Mississippian reef development in the Cracoe Limestone Formation of the southern Askrigg Block, North Yorkshire, UK

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Abstract: The southern margin of the Askrigg Block around Cracoe, North Yorkshire, shows a transition from carbonate ramp to reef-rimmed shelf margin, which, based on new foraminiferal/algal data, is now constrained to have initiated during the late Asbian. A late Holkerian to early Asbian ramp facies that included small mudmounds developed in comparatively deeper waters, in a transition zone between the proximal ramp, mudmound-free carbonates of the Scaleber Quarry Limestone Member (Kilnsey Formation) and the distal Hodderense Limestone and lower Pendleside Limestone formations of the adjacent Craven Basin. The ramp is envisaged as structurally fragmented, associated with sudden thickness and facies changes. The late Asbian to early Brigantian apron reefs and isolated reef knolls of the Cracoe Limestone Formation include massive reef core and marginal reef flank facies, the latter also including development of small mudmounds on the deeper water toes of back-reef flanks. The position of the apron/knoll reefs is constrained to the south (hangingwall) of the North Craven Fault, but it is syn-depositional displacement on the Middle Craven Fault that

accounts for the thick reefal development. Subsequent inversion of this structure during the early Brigantian caused uplift and abandonment of the reefs and consequent burial by the Bowland Shale Formation.

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The Cracoe Limestone Formation of the Great Scar Limestone Group, of early to mid Mississippian age (Lower Carboniferous), forms a series of inliers located south of the North Craven Fault along a roughly E–W-trending tract extending 20 km eastwards from Settle to Burnsall (Fig. 1). The formation is recognized as comprising mainly Cracoean reefs that formed an abrupt southern margin to the Askrigg Block carbonate shelf. The origin of these reefs was a focus of several publications in the first half of the twentieth century, which discussed the potential origins of these knoll-like structures (see next section). The aims of this study were: a) to appraise the morphology of the Mississippian reefs and associated flank deposits in the eastern development of the Craven Reef Belt in the vicinity of the type area of Cracoe (Fig. 1b) in the light of recent decades of research into reef formation; and b) provide improved constraints on the timing of reef development at the southern part of the Askrigg Block, principally based upon biostratigraphical determinations using foraminifers and algae/problematica. The origin and timing of the transition from carbonate ramp (Kilnsey Formation) to reef-rimmed platform (Cracoe Limestone Formation) was investigated, as was the northward lateral passage into the typical back-reef successions of the Malham Formation. Evidence is also considered as to what extent the current form of the ‘reef-knolls’ represents the original reef topography or is a function of syn-sedimentary or late Viséan tectonic disturbance.

History of geological research and survey

Mississippian reef facies in northern England have been traditionally subdivided into ‘Waulsortian’ mudmounds and ‘Cracoean’ apron reefs, with Cracoe (Fig. 1b) considered the type area for the latter. The Waulsortian mudmounds derive their name from Waulsort, Belgium. They are representative of a facies of late Tournaisian to early Viséan carbonate buildups found in northern and central England, south Wales, Ireland and the U.S.A. as well as Belgium (Lees & Miller 1985). They are characterized by discrete buildups with a significant proportion (>30%) of carbonate mud or peloidal mud and lacking a skeletal framework (Bridges *et al*. 1995). They developed in quiet water, low-energy environments on the distal parts of carbonate ramps, in the sub-photic zone or deeper parts of the photic zone, from 130 to greater than 300 m water depth (Lees & Miller 1985). Waulsortian mudmounds are well developed in the Clitheroe area within the Craven Basin, 30 km SW of Cracoe (Miller & Grayson 1982; Miller 1986; Lees & Miller 1985, 1995).

The younger Cracoean apron reefs form what is commonly referred to as the Craven Reef Belt (e.g. Hudson 1930). The western part of the Craven Reef Belt, from Settle to Malham (Fig. 1a), was the focus of detailed studies by Garwood & Goodyear (1924), Hudson (1930) and Arthurton *et al*. (1988). The current study area, located in the east of the exposed reef belt, has been studied extensively by previous workers (e.g. Marr 1899; Tiddeman 1901; Vaughan 1916; Hudson 1938; Bond 1950; Black 1958; Mundy 1980, 2000; Cossey *et al*. 2004). The term ‘Cracoean’ was first used by Bisat (1928), and then described as a reef facies by Hudson & Philcox (1965) to distinguish such ‘knoll reefs’ from the older Waulsortian mudmounds in Ireland.

Tiddeman (1901) considered that the steep dips present in the flanks of the reef knolls developed at the time of deposition, whereas Marr (1899) thought these steep dips to be purely tectonic, failing to recognize the presence of a distinct limestone facies within the reefs (Black 1958). Despite subsequent agreement that the structures represented reef knolls, there has been much disagreement as to how much the current isolated nature of the knolls is indicative of the original reef topography, or results from late-stage collapse of more laterally extensive apron reefs (e.g. Hudson 1932), or is a consequence of tectonism at the end of the Viséan (e.g. Bond 1950, Black 1958, Gawthorpe 1987). Hudson (1938) believed that the knoll topography of the reefs was a product of late Viséan erosion during a phase of tectonic uplift. Black (1958) recognized uplift and minor faulting during the Brigantian to early Pendleian, which he related to the development of boulder beds in the younger Bowland Shale Formation (Black 1957). Bond (1950), in contrast, sought to link the geometry of the knolls to a series of *en échelon* ENE–WSW to NE–SW trending anticlines, terminated or offset by WNW–ESE-trending faults, probably with dominant strike-slip displacements, that occur as post-reef development and before deposition of the Bowland Shale Formation ($P_{1a\text{-}1b}$).

Booker & Hudson (1926) recognized a reefal flank facies of fine fragmental material washed southwards to form the rapidly southward-thinning limestones of the Craven Basin, including the Pendleside Limestone Formation (Fig. 2). Poorly bedded or massive porcellanous limestones with overlying and marginal coarse crinoidal limestone were described as characteristic of the reef cores, with a distinctive fauna of bryozoans, gastropods, bivalves and brachiopods (Black 1958). Subsequently, the reef structure of Stebden Hill (Fig. 1b) was resolved into six biogenic associations (Mundy 1980), and presented as three generic facies (Brunton & Mundy 1988; Mundy 1994; Rigby & Mundy 2000): a bank facies forming the poorly bedded core of the build-up; a flank facies forming a basin-facing slope with depositional dips up to 35^{o} and with diverse biota; and a stromatolitic and sponge-rich framework facies developed in the shallowest water at the top of the build-up and typically preceding or following emergence. The latter is identified by erosive and fissured surfaces (Brunton & Mundy 1988; Mundy 1994). The reef topography, in excess of 120 m in the Craven Reef Belt, was completely onlapped by the Bowland Shale Formation. A short time interval between the highest reef carbonate of latest Asbian (P_{1a}) age and earliest Brigantian shales (P_{1b}) was identified by Black (1958), which Brunton & Mundy (1988) associated with a phase of emergence and generation of boulder beds and olistoliths on the reef flanks.

Black (1954) divided the reefs at Cracoe into the elevated "asymmetric" structures, such as Elbolton Hill and Byra Bank, which formed the marginal flank to the shallow water shelf carbonates present to the north, and 'symmetrical' knolls, such as Butter Haw, Skelterton, and Carden hills, developed in deeper waters (Fig. 1b). Mundy (1980) considered the reefs in this area to occur in three groupings: 1) Swinden reef of NE–SW trend, which may have developed on the northeastern extent of the syn-depositional Hetton Anticline (Arthurton *et al*. 1988); 2) Elbolton, Thorpe Kail (also known as Kail Hill) and Byra Bank of WNW–ESE trend parallel with, but located south of, the North Craven Fault; and 3) Skelterton, Carden, Butter Haw and Stebden hills, located south of the other reef structures (Fig. 1b).

A pre-reefal limestone succession has been described from the areas between the knolls. The Skelterton Limestone of Booker & Hudson (1926) was considered by Black (1958) as an Asbian basinal succession developed south of the reefs. This would now be interpreted as the Pendleside Limestone Formation, in agreement with Fewtrell & Smith (1980; Fig. 2), although these authors also included the reef facies within the ostensibly basinal succession. Mundy (1980, 2000) identified and mapped out the extent of two pre-reefal limestone units, the Rylstone and Threapland limestones of Arundian age and the Skelterton Limestone of

Holkerian age (Table 1). The Threapland Limestone comprises dark grey cherty packstones with interbedded mudstones (Bond 1950). The Rylstone Limestone consists of dark grey, thinly-bedded limestone and argillaceous limestone interbedded with calcareous mudstone restricted in extent to the Hetton Anticline (Harrison 1982). The Skelterton Limestone at Skelterton Hill to Skelterton Beck consists of a rapidly southward thinning succession of medium to dark grey cherty bioclastic packstones to crinoidal rudstone (Mundy 2000). Cossey *et al*. (2004) reproduced the map from Mundy (2000), assigning these limestones to the basinal succession of the Worston Shale Group (now Craven Group).

There have been attempts to subdivide the reef succession lithostratigraphically. Hudson (1938) considered that the reef limestones could be subdivided into 'Upper and Lower Reef Limestone' (Table 1). The two limestones were described as separated by brashy limestones, the lateral equivalent of the *Davidsonina (Cyrtina) septosa* Beds in which corals and brachiopods are common and typical reef fauna are subordinate (Hudson 1938; Hudson & Cotton 1944). Hudson & Cotton (1944) identified a distinctive pebbly ooidal and conglomeratic shell-reef limestone, with *Davidsonina (Cyrtina) septosa* at its base, which they interpreted as accumulating on a slight seaward slope of the reef. The Lower Reef Limestones were described by Hudson (1938) as comprising structureless limestone that includes fauna typical of the lower part of the B_2 subzone (early Asbian age). Hudson & Cotton (1944) described a *c.* 90 m thickness of pale grey to buff, poorly fossiliferous, fine-grained and bedded limestones with lenses of shell-reef limestone of equivalent age. The Upper Reef Limestones of Hudson (1938) contain abundant well-preserved productid brachiopods, locally forming shell breccias, indicative of the upper part of the B_2 (late Asbian) subzone. Towards the top they are darker grey and more rubbly and contain goniatites indicating a P_{1a} subzone (latest Asbian) age. Bond (1950) recognized a lower

‘Threaplands Limestone Series’ of late Arundian to Holkerian (S_{1-2}) age, followed by an upper ‘Elbolton Limestone Series’ of Holkerian to Asbian (S_2-D_1) age, the latter comprising in ascending order: the Loup Scar Beds, the Porcellanous Beds, the Tufa Beds, the *Davidsonina (Cyrtina) septosa* Beds and the ‘*Michelinia-Emmonsia* Beds’ (Table 1). However, the approach of Bond (1950) has proved too simplistic as it disregards rapid lateral facies variations and the scheme has not been used subsequently. Arthurton *et al*. (1988) referred to the Cracoean reefs as Marginal Reef Limestones of the Malham Formation. This has been redefined subsequently as the Cracoe Limestone Formation of the Great Scar Limestone Group (Dean *et al*. 2011; Fig. 2), the term preferred in this study. The back-reef limestones of this group, present to the north of the Cracoean reefs, are described in detail by Waters *et al*. (2016) and are not described further here, other than in the context of their relationship to the reef structures.

Revised lithostratigraphy and biostratigraphy

Given the complex non-stratiform nature of the reefs, no attempt has been made to identify component members. However, the reef complex comprises three distinct mappable facies: 1) pre-apron reef mudmound and intermound facies; 2) the large Cracoean apron reef core (bank) facies, and 3) associated apron reef flank facies. The stromatolitic and sponge-rich framework facies of Mundy (1994) and Rigby & Mundy (2000) is a minor component, not investigated during the current study, but would be incorporated in the mapped bank facies. Each facies is described in turn, below.

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 *et al*. (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 *et al*. (1980), Strank (1981), Laloux (1987), and subsequent modifications mostly in Conil *et al*. (1991), Riley (1993) and Cózar & Somerville (2004). Sample numbers are italicized, with location details provided in Table 2. Biostratigraphical ranges of foraminifers and algae/problematica are shown in Table 3.

Pre-apron reef mudmound and intermound facies

Lithostratigraphy

Three sections were investigated in detail: Carden Hill, Butter Haw Hill and Threapland Gill, north of Skelterton Hill (Fig. 1b).

Carden Hill (Fig. 3a): The lowermost bed (*Pc4834*) comprises a crinoidal/bryozoan packstone with minor intraclasts and shows parallel lamination and fining-upward sequences. Irregular geopetal fill orientations may reflect rotated boulders/blocks. Mundy (2000) described allochthonous (post-reef) gravity-flow deposits of the Pendleside Limestone Formation at this location.

Mudmound facies are represented by (1) a possibly rotated brachiopod/bryozoan mudstone with parallel lamination, with brachiopods in life position and stromatactis cavities (*Pc4836*), and (2) a crinoidal/foraminifer/ostracod micropeloidal wackestone to packstone with large stromatactis cavities (*Pc4837*) and orientations of bioclasts and cavities oblique to the way up, possibly representing original palaeodip. A mudmound flank facies is represented by an ostracod mudstone comprising large intraclasts (ostracod mudstones) with large *in situ* encrusting bryozoans and bioturbated ostracod/bryozoan/crinoidal mudstone/wackestone

(*Pc4838*). Strongly bioturbated crinoidal/ostracod wackestone/packstone (*Pc4835*) and crinoidal/bryozoan/peloidal wackestone/packstone with micritized intraclasts and bioclasts (*Pc4839*) may represent intermound facies. This succession was interpreted by Mundy (2000) as the pre-reefal facies, with the summit of the hill (not sampled in this study) as the basal ("foundation") facies of the Cracoean apron reefs (Fig. 3a), characterized by northward prograding stacked lenses of bioclastic-peloidal packstones.

Butter Haw Hill: A mudmound facies in the lower slopes of the southern flank of Butter Haw Hill (Fig. 1b) is represented by a bryozoan-rich micropeloidal mudstone to cementstone with entire cavities filled by radiaxial calcite cements, passing into micropeloidal bryozoan wackestone with small stromatactis (*Pc4840−1*). An adjacent mudmound flank facies is represented by a micropeloidal bryozoan and crinoidal wackestone, with large flattened stromatactis filled by blocky cement, passing into crinoidal/bryozoan grainstone with some large cavities (*Pc4842*). The remainder of the hill was described as comprising reef knoll limestones of late Asbian (B_{2b}) age showing quaquaversal dips up to 45^{o} in the peripheral flank limestones with steep original depositional dips (Mundy 1980, 2000). Although this may be true for most of the hill, the sample localities appear consistent with the pre-apron reef facies present to the south on neighbouring Carden Hill.

Threapland Gill: A mudmound facies north of Skelterton Hill (Fig. 1b) is represented by a micropeloidal wackestone (*Pc4845*) and micropeloidal/bryozoan wackestone (*Pc4846*), both with large stromatactis. Probable mudmound flank facies are also evident in a bioturbated peloidal wackestone/packstone (*Pc4843*), and an intraclastic/crinoidal packstone with irregular cavities between the crinoids and intraclasts, filled by blocky cement and micropeloids (*Pc4844*). These observations are not consistent with the interpretation of these exposures by Mundy (2000) as part of the Pendleside Limestone Formation, comprising a massive boulder bed with wackestone or crinoidal rudstone matrix and clasts of reefal and pre-reefal characteristics. The overlying basal facies of the Cracoean reefs is present farther to the south at Skelterton Hill, comprising mainly NE-dipping bedded cherty wackestones with crinoids, bryozoans and lithostrotionid corals (Mundy 1980).

Biostratigraphy

Carden Hill: The basal bed (*Pc4834*) includes the foraminifers *Archaediscus* at *angulatus* stage?, *Nodosarchaediscus demaneti, N. viae, Planoarchaediscus* sp. and *Valvulinella youngi* (Fig. 4; Table 3). Overlying beds (*Pc4835–9*) include the foraminifers *Archaediscus* at *angulatus* stage? and at *concavus* stage*.* The foraminiferal assemblages suggest a late Holkerian−early Asbian age (upper Cf5 to Cf6α), consistent with a pre-apron reef development for the sampled succession.

Butter Haw Hill: In the lower part of the hill (*Pc4840−2*), sparse foraminifers include *Archaediscus* at *angulatus* stage, *Archaediscus* at *concavus* stage and *Archaediscus* sp. (Table 3). All the samples are consistent with an early Asbian age (Cf6α-β). A B_{2b} or late Asbian age, based upon a goniatite assemblage (Mundy 1980, 2000), appears to relate to a younger reef-flank facies present higher up the hill.

Threapland Gill: The foraminiferal assemblages (*Pc4843–6*; Table 3) are not particularly rich, probably due to a hostile environment for foraminifers. The foraminiferal assemblage (*Pc4843*) including *Archaediscus* at *concavus* stage suggests a late Holkerian age. The occurrences of *Archaediscus* at *angulatus* stage (rare) and *Nodosarchaediscus* sp., *N. demaneti* and *Endothyranopsis compressa* transitional to *E. crassa* (Fig. 4.11) (*Pc4844–6*) suggest an early Asbian age (Conil *et al*. 1980; Strank 1981). There is only one possible late Asbian marker, *Ungdarella*? (*Pc4844*), but its identification is uncertain. A late Holkerian–early Asbian age (upper Cf 5 to Cf6β) would be inconsistent with the Threaplands Gill section representing a late-stage flank facies to the apron reefs, and a deeper water ramp setting is preferred. This is not consistent with Booker & Hudson (1926) who considered their 'Skelterton Limestones' to be Brigantian (D_2) age, and Fewtrell & Smith (1978) who suggested an Asbian-Brigantian (D_1–D_2) age. Ramsbottom (*in* Mundy 1980) reported late Asbian foraminiferal assemblages and Strank (*in* Mundy 2000) considered the foraminifers to be of Holkerian 'aspect'.

Fewtrell & Smith (1978) reported the presence of *Howchinia* from Skelterton Hill knoll reef (stratigraphically above Threaplands Gill), and *Bradyina rotula* and *Archaediscus moelleri* from nearby Skelterton Beck (now Town Beck) within the overlying Bowland Shale Formation, which would suggest a latest Asbian to early Brigantian age (upper Cf6γ to lower Cf6δ) for the apron reef formation.

Apron reef core (bank) facies

Lithostratigraphy

At Swinden Quarry (Fig. 1b), located 1.25 km north of Cracoe, the upper part of the northeastern face shows a distinct, thick-bedded succession, described by Mundy (2000) as non-reefal dark grey packstones with muddy partings containing *Saccamminopsis.* He considered this as probably correlative of the lower part of the Brigantian Coldstones Limestone (= Alston Formation) seen at Coldstones Quarry. The uppermost unit at Swinden Quarry is underlain by bedded coarse-grained crinoidal packstones (Mundy 2000), which may be represented by the unaccessed succession at the top of Figure 3b. These crinoidal packstones are in turn underlain by a massive, pale and dark grey, brecciated, micritic limestone with common *in situ* brachiopods and bryozoa, interpreted as an unbedded bank facies by Mundy (2000). Crinoid and mud-rock filled neptunean dykes are present within this facies. Mundy (2000) interpreted a broad northeastward-dipping packstone succession as pre-reefal limestones; the current study cannot support that observation. The bedded succession, evident in Figure 3b, occurs between two massive intervals and may represent a back-reef slope succession, overridden by backstepping reef core facies.

The Swinden Quarry No. 2 and No. 4 boreholes extend through much of the thickness of the reef-knoll facies (Figs 3b, 5). In the latter borehole, the facies comprises an upper, dominantly pale grey, thinner bedded, medium- to coarse-grained and coarse-grained, poorly sorted, skeletal framestone (*RBH7−8; RBH10−11*) and intraclastic-skeletal packstone (locally a grainstone, rudstone, boundstone or wackestone; *RBH9*); cavities with abundant radiaxial fibrous cement and geopetal sediment, oncoids and wackestone intraclasts are common. This passes down to a mainly medium grey, thicker bedded, intraclastic-skeletal wackestone (*RBH12*), packstone/grainstone/floatstone (*RBH13−14; RBH16*) or skeletal grainstone/rudstone/boundstone (*RBH15; RBH17*); peloids and geopetal cavities are common.

In Swinden No. 2 Borehole, well bedded, mainly medium grey biocalcarenites are locally present. This facies is represented by crinoidal grainstones/packstones with sharp bases, fining upwards to micrites with possible microbial laminae (11.05−8.65 m), medium- to coarse-grained, normal- and reverse-graded with abundant crinoid, coral and brachiopod debris and subordinate wackestone interbeds (52.9−44.5 m) and thinly interbedded fine and coarse calcarenites with common crinoid plates, bryozoa, colonial and solitary corals and brachiopod valves (60.0−56.2 m). These may represent bioclastic sands developed marginal to the framework. Much of the remainder of the borehole consists of medium and medium to dark grey wackestone and micrite. These are thick bedded/massive with disseminated mainly crinoid debris and common vugs (29.1−11.05 m), thin-bedded, vuggy and stylolitic, dominated by crinoids and brachiopod valves (36.95−29.1 m); medium- to thick-bedded with both articulated and disarticulated brachiopods, common *Siphonodendron* in growth position with orthocones present at the top (44.5 −36.95m). The last facies may equate with the *Lithostrotion* (=*Siphonodendron*) colonies observed by Mundy (1980, 1994) on Stebden Hill at the summit of the knoll reef. The same facies equates to the skeletal framestone and packstones present in the upper part of Swinden No. 4 Borehole (Fig. 5) and corresponds to the lower "massive" reef core shown in Figure 3b. Thick-bedded wackestone/packstone with large crinoid plates, bryozoa and mainly disarticulated brachiopod debris (56.2−52.9 m) is similar to the *Koninckopecten* Association of Mundy (1980), which on Stebden Hill is developed in bedded flank deposits in water depths inferred by Mundy (1980) as greater than 73 m.

Biostratigraphy

Macrofossils: The main apron reef core (bank) facies were recognized to be mainly late Asbian (B_{2b}) age by Mundy (1980, 1994, 2000). The goniatites *Goniatites hudsoni*, *Beyrichoceras* aff. *vesiculiferum* and *Bollandoceras micronotoides*, consistent with a late Asbian (B_2) age,were recorded from the Swinden reef by Bisat (1934). Arthurton *et al.* (1988) described ammonoids recovered from Swinden Quarry ranging from the B_{2a}–P_{1b} subzones (Asbian–early Brigantian), but a pre-Asbian age was not established. In Swinden No. 4 Borehole, *in situ* upright *Syringopora* corallites (e.g. *RBH7 & RBH11*), *Siphondendron* *sociale* (e.g. *RBH8*) and *S. pauciradiale* and *S. irregulare* (e.g. *RBH10 & RBH12*) colonies form a framestone of Asbian–early Brigantian age.

Microfossils: At Swinden Quarry No. 4 Borehole (Fig. 5, Table 3) the foraminifers and algae suggest a late Asbian age (Cf6γ) for the entire thickness of the borehole. *Archaediscus* at *angulatus* stage and *A.* at *concavus* stage are common throughout. Highlighted is the occurrence of *Archaediscus* ex gr. *karreri* in most samples, including at its base, and *Endothyranopsis crassa* from the lower part of the borehole (*RBH16–17*). Previous studies on Swinden No.1 Borehole, drilled to a depth of 45 m in the floor of the quarry, and Swinden No. 3 Borehole drilled from the top of the quarry to a depth of 77 m, yielded a similar Asbian foraminiferal assemblage (Fewtrell & Smith 1978). In Swinden No. 1 Borehole, *Koskinobigenerina* sp., *Omphalotis* sp., *Palaeotextularia* sp., *Pseudolituotuba gravata*, and near the top of the borehole, *Archaediscus* ex gr. *karreri* and *Eostaffella parastruvei* are noteworthy. Younger rocks in Swinden No. 3 Borehole yielded *Valvulinella* and ?*Howchinia* (Fewtrell & Smith 1978).

Apron reef flank facies

Lithostratigraphy

Elbolton Hill and Stebden Hill have been the most intensively studied reefs in the Cracoe area, with a definitive palaeoecological study by Mundy (1980, 1994, 2000), and no attempt is made in the current study to reinvestigate these structures. On Elbolton Hill, the massive reef core present on the southern side passes northwards to bedded flank facies that include peloids and oncoids; geopetal studies show these beds to have been horizontal at the time of deposition (Mundy 1980). In addition to the main Elbolton reef structure of the B_{2b} subzone, steeply dipping peripheral lowstand, richly fossiliferous flank deposits of the P_{1a} subzone, locally comprizing rudstone coquinas intercalated with microbialite veneers, are found on the lower slopes on the west, south and east of the hill (Mundy 1980). Stebden Hill comprises limestones of the B_{2b} subzone with quaquaversal dips (Bond 1950), with the peripheral flank limestones orientated approximately in their original depositional dip (Mundy 1980, 2000). Further lowstand flank deposits of the P_{1a} subzone occur on the northern side of the hill.

Swinden Quarry: In the southwest corner of Swinden Quarry, a boulder bed of limestone clasts with a black shale matrix occurs with a steep margin against black shales of the Bowland Shale Formation (Fig. 3c). This passes abruptly downwards and eastwards into a brecciated, heterogeneous limestone ranging from coarse, crinoidal grainstone to pale grey micrite. Previously interpreted as a faulted margin (Mundy 2000), it is proposed here to represent a talus slope on the forereef margin. Similar deposits were described by Black (1957) within the Bowland Shale Formation, located immediately to the south of the Cracoean reefs. However, they occur in strata of late Brigantian (P_{2a-2b}) and early Namurian (E_1) age, and as such, would post-date the reef genesis and probably represent erosion of the relic reef structure.

Langerton Hill (Linton): Located northwest of Butter Haw Hill (Fig. 1b), Mundy (2000) recorded boulder beds and bedded crinoidal rudstone calciturbidites and debrites from this locality, which he interpreted as part of the Pendleside Limestone Formation. A crinoidal/bryozoan/brachiopod grainstone/packstone with minor intraclasts (*Pc4849*), possibly deposited as a shallow water tempestite, would appear consistent with that interpretation. The succession includes a mudmound facies comprising cementstone with pockets of micropeloidal wackestones (*Pc4847*), with a mudmound flank facies of intraclastic crinoidal brachiopod rudstone with a micrite matrix (*Pc4848*).

Byra Bank: The flank facies developed at Byra Bank, near Burnsall (Fig. 1b), is a highly bioclastic limestone recorded in loose (brash) material. The limestone includes common black phosphatic clasts as well as abundant brown-stained mudstone forming the matrix material. This mudstone is probably also rich in phosphate.

Loup Scar: At Loup Scar (Figs 1b, 6), a scarp face >10 m high is developed at a prominent bend in the River Wharfe. It consists of two massive limestone units separated by a thinly-bedded limestone unit. The basal massive beds (*RBH1, RBH42−44*) comprise pale to medium–dark grey, coarse-grained, well sorted intraclastic-skeletal grainstone/boundstone with occasional ooids, peloids, micritized shells, or skeletal wackestone/packstone with oncoids and geopetal cavities. This massive unit has been cut by a channel with about 4 m of erosional relief (Fig. 6). The thin-bedded unit filling the channel is typically a coarse-grained, poorly sorted, intraclastic-skeletal (crinoidal-algal) packstone/floatstone with patches of pelsparite and large oncoids (*RBH2*). The beds are asymmetrically folded (verging eastwards), interpreted as slumping within the channel. These limestones include geopetal cavities and radiaxial fibrous cement. A second phase of erosion of the channel-fill succession was followed by a return to deposition of the upper massive limestone unit. Exposure from the river bank adjacent to this youngest part of the succession includes cross-bedded crinoidal packstone/grainstone (*Pc4855*). It is interpreted that the background carbonate supply at Loup Scar reflected material avalanching down the back slope of a reef knoll, possibly Byra Bank which crops out *c.* 1 km to the southwest (Fig. 1b).

Kail Hill: On the northern flank of Kail Hill (*RBH40*, Fig. 1b), a pale grey, medium-grained, poorly sorted, skeletal-intraclastic packstone/grainstone includes common crinoids and brachiopods, large geopetal cavities and wackestone intraclasts. *RBH45* is a pale grey, coarse-grained, poorly sorted, intraclastic-skeletal (crinoidal-rich) wackestone with wackestone intraclasts. These form part of the bedded limestones present in the central and northern parts of the hill, flanking the more massive reef limestones including microbial boundstones present in the south of the hill (Mundy 1980).

North of Hartlington Kail and Byra Bank: At Barben Beck (*RBH52*, Fig. 1b), the facies comprises pale grey, poorly sorted, medium-grained, skeletal-peloidal packstone/boundstone with common crinoids and brachiopods and abundant geopetal cavities. Typically pale grey, poorly sorted, massive fine- to medium-grained, peloidal skeletal packstone and 'algal' boundstone with spar-filled cavities with radiaxial fibrous cement were recorded at Skuff Road (*RBH3*), Hippings Lane Quarry (*RBH6*) and 400 m southeast of Langerton Hill (Burnsall) (*RBH49*). These localities occur in a back-reef location, considered to be reef flank associated with mudmound development.

Biostratigraphy

The flank deposits present on the northwestern side of Elbolton Hill contain the goniatites *Bollandoceras micronotum*, *Beyrichoceras rectangularum* and *Goniatites globostriatus* of the B_{2b} subzone (Hudson & Cotton 1944). Lowstand flank deposits of the P_{1a} subzone include the guide goniatites *Beyrichoceratoides truncatum* and *Goniatites crenistria* (Bisat 1928; Mundy 2000).

Langerton Hill (Linton) (Fig. 1b): The succession (*Pc4847–9*; Table 3) contains *Howchinia bradyana* (Fig. 4.16) and large *Archaediscus* ex gr. *karreri* (Fig. 4.10), consistent with a late Asbian age (Cf6γ) (Laloux 1987; Riley 1993; Cózar & Somerville 2004). There is one hybrid form between the *Archaediscus* and *Tubispirodiscus*, identified as *T.* aff. *cornuspiroides* (Fig. 4.7) (*Pc4849*). It is not the nominal species, which first occurs in later Brigantian times; however, the degree of evolution of that specimen would only be possible in the Brigantian (Cf6δ). The ammonoid *Goniatites spirifer* was recorded by Riley (1983), 30 m northeast of Far Langerton House [^{3}9965 ^{4}6120], confirming that reef growth continued into the earliest Brigantian (P_{1b}). Nearby, Mundy (1980, 1994, 2000) recognized the presence of fossiliferous limestones of the P_{1a} subzone forming steeply dipping flank deposits on the south and west side of Elbolton Hill and north side of Stebden Hill.

Byra Bank (Fig. 1b): The succession (*WMD16359–16384* from loose blocks) includes the brachiopods *Antiquatonia antiquata,* ?*A. hindi wettonensis, A.* spp., ?*Dictyoclostus multispiniferus,*?*Overtonia fimbriata* and *Spirifer* ex gr. *striatus.* Range data for *Antiquatonia* suggest an Asbian or Brigantian age. The possible record of *Antiquatonia hindi wettonensis* suggests the late Brigantian. An Asbian or Brigantian age is consistent with most of the remainder of the fauna. Hudson (1938) described goniatite faunas from the southern flank of Byra Bank in Badger Beck indicative of the upper B_2 and the P_{1a} subzones (late Asbian age) and belonging to his Upper Reef Limestone.

Loup Scar (Fig. 1b): Macrofossils found beneath the channel at this locality (*WMD16446–16459*), including the coral *Michelinia* sp. (cf. *M. megastoma*) and brachiopod *Leptagonia analoga*, suggest an age no younger than Asbian. Bond (1950) showed the *'Michelinia – Emmonsia* Beds' in D_{1-2}, but his 'Loup Scar Beds' are significantly older (S_2–lower D_1). In contrast, the presence of the brachiopods *Angiospirifer* ex gr. *trigonalis* and *Antiquatonia antiquata* are more consistent with a level at or above the Brigantian. Amongst the fauna listed by Bond (1950) from Loup Scar are the brachiopods *Pugnax pleurodon* (=

Pleuropugnoides pleurodon) and *Sinuatella sinuata*, the co-occurrence of which is indicative of a Brigantian age.

Microfossils found in the basal massive beds at Loup Scar (*RBH1, RBH42–44*; Table 3) include *Archaediscus karreri grandis*, *Cribrostomum*, *Euxinita efremovi* (Fig. 4.9), *Endothyranopsis* aff. *crassa*, *Howchinia bradyana*, *Neoarchaediscus* (Figs 4.6, 4.8), *Pseudoendothyra sublimis* (Fig. 4.13), *Palaeotextularia*, *Protoinsolentitheca fundamenta* and *Ungdarella uralica*. This assemblage, along with that from the middle bedded limestones (*RBH2*) with *Nodasperodiscus* and *Ungdarella uralica,* can be assigned to the late Asbian (Cózar & Somerville 2004, 2005, 2013). In the uppermost beds (*RBH41*), assemblages also record *Archaediscus karreri grandis* and *Neoarchaediscus*, representative of the late Asbian (Cf6γ).

Kail Hill: On the northern flank of Kail Hill (*RBH40*, Fig. 1b), the foraminifers include *Archaediscus* at *angulatus* stage, *Endostaffella* sp., *Endothyranopsis* aff. *crassa, Eostaffella* sp., *Globoendothyra* sp., *Palaeotextularia* spp., *Plectogyranopsis ampla* and the algospongia *Ungdarella uralica.* This assemblage is indicative of a late Asbian age (Cf6γ).

North of Hartlington Kail and Byra Bank (Fig. 1b): At Barben Beck (*RBH52*) the foraminifers include *Archaediscus* at *angulatus* stage, *Euxinita efremovi*, *Hemidiscopsis* sp. (Fig. 4.17), *Neoarchaediscus stellatus, Omphalotis* sp., *Palaeotextularia*? sp. and *Vissariotaxis longa* (Fig. 4.15), with the alga *Hortonella uttingi* (Table 3). The presence of *Neoarchaediscus stellatus*, allows an assignment to the late Asbian (Cf6γ).

At Skuff Road Quarry (*WMD16460–16465*, see Table 2 for locality details), the presence of the bivalve *Aviculopecten murchisoni?* suggests a D_1 or D_2 subzone (= Asbian and Brigantian age) (Saddler & Merriam 1967, fig. 1). Foraminifers from this locality (*RBH3*, Table 3) include *Archaediscus* at *angulatus* stage, *Nodasperodiscus* sp., *Praeostaffellina macdonaldensis, Pseudoendothyra sublimis*, accompanied by the algae/algospongia *Fasciella kizilia, Fourstonella johnsoni,* and *Girvanella wetheredii.* The occurrence of *Archaediscus* at *angulatus* stage, *Nodasperodiscus* and *Pseudoendothyra sublimis* suggest a later part of the early Asbian or more probably a late Asbian age (Cf6γ) (Somerville & Cózar 2005; Cózar & Somerville 2013).

Hippings Lane Quarry (^{4}02605 ^{4}61989) is the type locality of the goniatites *Beyrichoceras phillipsi* and *Goniatites maximus* var. 'b' of the lower B_2 subzone (early Asbian age) (Hudson 1938). The presence of the coral *Palaeosmilia murchisoni* and a brachiopod fauna mainly of *Gigantoproductus* (*Productus) maximus* led Hudson & Cotton (1944) to propose that this location was in the basal beds of the upper D_1 subzone, close to the level of the *Davidsonina (Cyrtina) septosa* Beds and above the level recorded at Loup Scar. The mudmound facies contains sparse foraminifers (*RBH6*, Fig. 1b, Table 3), including large *Archaediscus* such as *A.* aff. *chernoussovensis*, and *Archaediscus* at *angulatus* stage, confirming an Asbian age (Conil *et al*. 1980). The most enigmatic taxon is *Haplophragmina* aff. *beschevensis* (Fig. 4.19), which was first recorded from the latest Asbian and later (≥ upper Cf6γ) (Pille 2008).

Southeast of Langerton Hill (Burnsall) (Fig. 1b): The disused quarry has recorded finds of *Beyrichoceras* aff. *delicatum* and *B.* cf. *phillipsi* of the upper B_2 subzone, lying just below the *Davidsonina (Cyrtina) septosa* Beds (Hudson & Cotton 1944). Farther down the slope, additional small disused quarries include the ammonoids *Goniatites hudsoni* and *G.*

antiquatus of the lower B_2 subzone. The presence in the upper disused quarry (*RBH49*, Table 3) of the foraminifers *Archaediscus* at *angulatus* stage, *Eostaffella* ex gr. *parastruvei*, *Palaeotextularia* and *Pseudoendothyra* is consistent with the upper part of the early Asbian to late Asbian (Cf6β-γ) (Conil *et al*. 1980, 1991; Laloux 1987).

Discussion on the deposition of the Cracoe Limestone Formation

Environments of deposition

The earliest reef structures, located at the southern margin of the reef complex near Carden Hill (Fig. 7a), are small, comparatively massive mudmounds, typically up to about 10 m high and tens of metres across. Similar to the 'Waulsortian' mudmounds described in earlier literature (see above), they are dominated by brachiopod/bryozoan/ostracod-rich micropeloidal mudstones and wackestones with well-developed stromatactis cavities. The mudmounds have marginal flank facies of inclined and well-bedded, faunally diverse and rich, wackestone/packstone and ostracod mudstones with common intraclasts.

Crinoidal/bryozoan/peloidal wackestone/packstones, parallel laminated in fining-upward sequences, may represent an intermound facies. The peloidal nature of the micrites may be a product of microbial processes (Dix & James 1987; Bridges & Chapman 1988). The common stromatactis cavities are a calcite cement fill of labyrinthine cavities with radiaxial fibrous calcite, the product of early submarine cementation in mudmounds (Bathurst 1982).

The dimensions and principal biotic components are typical of a Type-3 mudmound of Bridges *et al*. (1995), commonly developed during Holkerian–Brigantian times in intra-shelf ramp development in moderately shallow waters compared with true Waulsortian mudmounds (Type 1 of Bridges *et al*. 1995). These late Holkerian to early Asbian mudmounds developed in the gradually southward deepening waters on a gently south-sloping ramp (Mundy 2000), e.g. Carden Hill, Butter Haw Hill and Threaplands Gill (Fig. 7a). This required no development of a structural discrimination along the Craven Fault System between the Askrigg Block and Craven Basin at that time. However, in the Craven Basin it is thought that mudmounds nucleated around fault-controlled intrabasinal highs (Gawthorpe 1986, 1987).

The Cracoean reefs that developed on the southern margin of a carbonate shelf occur as both laterally extensive 'apron reefs' or isolated reef (knolls) mounds (Rigby & Mundy 2000), defining an abrupt transition into deeper water facies of the Craven Group rocks along the forereef.

Mudmound facies that are comparable to those developed on pre-reefal ramp settings are also recognized north of Hartlington Kail Hill, within late Asbian back-reef flank facies deposits (Fig. 7b). At Langerton Hill (Linton), the mudmounds are associated with late Asbian to early Brigantian carbonates formed during the final stage in reef development, immediately prior to burial by the Bowland Shale Formation. The Langerton Hill mudmounds appear to have developed within the relatively deeper water toe of a reef talus slope, on the western flank of the Butter Haw Hill reef knoll (Fig. 7c). At that time, a flat-topped carbonate shelf flanked by marginal reefs was well established. The shelf-top back-reef environment is likely to have had poor circulation and limited exchange of waters with the adjacent Craven Basin, and so consequently the shallow-water Asbian mudmounds are found in the fully marine environments present in shelf margins (Bridges *et al*. 1995).

The structure and reefal assemblages recognized in Cracoean apron reefs were described fully by Mundy (1980). The proposed Cracoean reef flank facies is marked by highly bioclastic and faunally rich limestones, with phosphatic clasts and possible phosphatic mudstone. This is consistent with high productivity and restricted sedimentation by either lack of supply or reworking under a moderate to high-energy regime.

Where seen in section at Swinden Quarry, the reef core appears to display a well-bedded back-reef facies overlain by further reef core carbonates, interpreted as backstepping of the reef. Sea-level oscillations, which started during the late Asbian and have been estimated to range in the order of 10−50 m (Wright & Vanstone 2001), are unlikely to have been of sufficient magnitude to have forced such back-stepping; unless stressed, reefs would be expected to aggrade almost vertically in pace with glacio-eustatic sea level rises. Such elevated platform rims have a strong tendency to stack vertically (Schlager 1992). The proposed backstepping could be a function of subsidence and importantly a component of tilting within the hangingwall of the Middle Craven Fault.

Correlation with the back-reef succession of the Great Scar Limestone Group

The Rylstone-Threapland limestones, developed on the Hetton Anticline along the northern flank of the Craven Basin (not studied here), comprise dark grey cherty limestones and mudstones, interpreted by Mundy (2000) as late in Arundian in age. These would represent the southerly lateral age-equivalent of the Chapel House Limestone Formation, the local basal formation of the Great Scar Limestone Group (Fig. 2). The Chapel House Limestone Formation consists of a succession that includes intertidal−supratidal deposits (Waters *et al*. 2016) and is lithologically very different to the Rylstone-Threapland limestones. The succeeding Scaleber Force Limestone Member (Kilnsey Formation) is lithologically much more similar to the Rylstone-Threapland limestones and both were probably deposited in a relatively deep-water ramp environment (Arthurton *et al*. 1988; Waters *et al*. 2016). This may suggest that the Rylstone-Threapland limestones should be re-investigated to see if a Holkerian age, as now determined for the equivalent Scaleber Force Limestone Member by Waters *et al*. (2016), can be demonstrated.

The pre-apron reef succession observed at Carden Hill, Butter Haw Hill and Threapland Gill comprises medium to dark grey limestones with common mudmounds of the Skelterton Limestone of Mundy (2000). The foraminiferal assemblage suggests a late Holkerian−early Asbian age for this succession. Ramsbottom (1973) considered the early Asbian succession (the lower part of his fifth mesothem), which commonly contains abundant *Daviesiella llangollensis*, to be absent across the Askrigg Block, suggesting that a prominent non-sequence coincident with a major lowstand developed at this time. However, the current study recognizes strata of this age within these mudmounds. These limestones appear to have developed on a more distal, southerly position on a carbonate ramp than the laterally equivalent Scaleber Quarry Limestone Member (Kilnsey Formation) of the Kilnsey Crag area. The Scaleber Quarry Limestone Member farther to the north lacks development of mudmounds (Arthurton *et al*. 1988; Waters *et al*. 2016), but otherwise is lithologically similar to the succession observed beneath the Cracoean reefs. The presence of these mudmounds in the Cracoe area is considered to represent deposition in slightly deeper water on the carbonate ramp.

Evidence for structural modification of the pre-reefal and apron reef successions

Two main episodes of tectonic activity have been recognized in the Craven Basin (Bowland Sub-basin), during the late Chadian/early Arundian and late Asbian/early Brigantian

(Gawthorpe 1986, 1987). Both episodes were considered to result in the development of slump and slide structures, gravity flow carbonate deposits, increased terrigenous mud deposition and a decline in carbonate production (Gawthorpe & Clemmey 1985). But did these deformation events result in disturbance of the carbonate ramp and shelf during their evolution?

The earliest of these tectonic events coincides with development of the carbonate turbidites of the early Arundian Embsay Limestone Member (Hodder Mudstone Formation) within the Craven Basin (Fig. 2) and the onset of shallow marine conditions on the southern flank of the Askrigg Block associated with deposition of the Chapel House Limestone Formation (Waters *et al*. 2016).

The late Arundian to Asbian Hodder Mudstone Formation to Pendleside Limestone Formation succession developed in the Craven Basin during a phase of relative tectonic quiescence. It is marked by a southeastward transition from proximal, relatively shallow-water, carbonate-rich intervals to thicker, distal, argillaceous units with finer-grained carbonates (Gawthorpe 1986, 1987). Gawthorpe (1987) attributed this relationship to formation of a marked carbonate shelf profile from marginal/upper slope through to lower slope. However, subsequent revisions to the timing of development of the ramp-to-shelf transition on the Askrigg Block (Waters *et al*. 2016) suggest that much of this succession developed within the middle to distal parts of a southward-facing carbonate ramp. A setting of a fragmented ramp with localized 'lows' and 'highs', as proposed by Riley (1990), may be a more realistic interpretation. The deposition of the Hodderense Limestone Formation during the Holkerian represents a phase of more extreme sediment starvation with slow accumulation of hemi-pelagic cephalopod limestones (Riley 1990). This is age-equivalent to the deepest water ramp carbonate deposition (Scaleber Force Limestone Member) on the Askrigg Block and probably coincides with a marine transgression. A phase of displacement on the Middle Craven Fault is inferred by the abrupt southward thickening of the Kilnsey Formation in the vicinity of Settle (Arthurton *et al*. 1988), which from the age constraints of Waters *et al*. (2016) would be of Holkerian to early Asbian age.

Carbonate turbidite development was reinstated in the northern part of the Craven Basin during the early Asbian with deposition of the Pendleside Limestone Formation. This succession is coincident with the formation of the proximal ramp deposits of the Scaleber Quarry Limestone Member (Fig. 2). The succession seen at Carden Hill and Threapland Gill represents the transition zone from the ramp carbonates of the Kilnsey Formation and these deeper water deposits of the Craven Group. The possibility that the transition zone is abrupt and fault-induced is suggested by the sudden development of mudmounds in inferred deeper water conditions, a facies not seen in the Kilnsey Formation to the north. The succession at Carden Hill appears to include rotated blocks in the basal observed strata, possibly reflecting debris flows from a fault scarp.

The Craven Reef Belt occurs almost immediately south of the Middle Craven Fault in the Settle and Malham areas (Fig. 1a), but in part is up to 2.5 km south of the fault within the Cracoe study area (Fig. 1b). It appears probable that the late Asbian to early Brigantian development of the reef-rimmed shelf was at least in part constrained by a palaeotopography associated with displacement on this fault, with the reefs developing exclusively in the hangingwall (Fig. 7). Several authors, including Tiddeman (1889), Johnson (1967) and Ramsbottom (1974) have suggested that movement along the Middle Craven Fault generated the degree of subsidence required for the growth of the reef facies. The thick development of reefs at Swinden Quarry, in excess of 155 m during the late Asbian alone, appears to support that interpretation. The deformation may have been initiated during the latest Asbian, marked by significant southward increase in thickness of the Gordale Limestone Member across the Craven Fault System, and facies variations with shallow peritidal deposits on the tilt-block high and deepening successions immediately north of the North Craven Fault (Waters *et al*. 2016). This suggests footwall flexure during displacement on the North and Middle Craven Faults through down-to-the-south displacements. Subsidence to the south of the Middle Craven Fault could account for the back-stepping of the massive reef core facies evident in Swinden Quarry (Fig. 3b). The channeling and within-channel slumping at Loup Scar (Fig. 6) appear to have occurred at the time of, and may have been caused by, this late Asbian onset of deformation.

A prominent conglomerate present within the Pendleside Limestone Formation evident in the Skipton Anticline, commonly referred to as Tiddeman's Breccia (Hudson & Mitchell 1937), broadly coincides with that transition from ramp to shelf, seen upslope as the transition from Kilnsey Formation to Malham Formation and the formation of apron reef at Swinden Quarry and reef flank facies at Langerton Hill, Linton (Fig. 2). Within the basin, this transition to development of a fringing reef is seen as a change in dominant supply from fine skeletal, pellet-ooidal carbonates to lithoclastic limestone breccias and development of an anoxic sea-floor during the *Goniatites hudsoni* (B_{2a}) Subzone (Riley 1990). The transition was considered by Riley (1990) to be associated with tectonic uplift.

The second phase of late Asbian/early Brigantian tectonic activity of Gawthorpe (1986, 1987) in the Craven Basin is evidenced in the Craven Reef Belt by a phase of earliest Brigantian inversion of the Middle Craven Fault. Deformation caused the local thickening of the oncolite-bearing part of the Lower Hawes Limestone Member to the north of the fault and condensed succession to the south (Arthurton *et al*. 1988, p.100). This event is significant in coinciding with the $P_{1a\text{-}1b}$ final burial of the Cracoean reefs by the Bowland Shale Formation (Fig. 2). The lowstand flank deposits of the P_{1a} subzone that accumulated in shallow waters on the lower slopes of Stebden and Elbolton Hills (Fig. 7c) were considered to indicate uplift to the south of the Middle Craven Fault by as much as 50 m (Mundy 1980). This uplift event also generated much limestone debris, shed south of the apron reef into the Craven Basin. Some of this debris may be evident as the P_{1b} subzone tempestites, boulder beds and debrites recorded at Langerton Hill (Linton). The megabrecciation and development of neptunean dykes evident at Swinden Quarry have been associated with this deformation event (Mundy 2000), which coincides with development of an unconformity at the base of the Lower Hawes Limestone Member (Fig. 2).

A late Brigantian ($P_{2a\text{-}b}$) phase of displacement on the Middle Craven Fault, throwing down to the south, is associated with the Bowland Shale Formation resting on a marked unconformity upon Asbian Malham Formation and early Brigantian Alston Formation and erosion of the reef limestones (Mundy 1980; Arthurton *et al*. 1988). Displacement on northwest-trending faults occurred during the late Brigantian phase of deformation (Hudson 1930), associated with transtension during dextral shear on both the North and Middle Craven Faults (Arthurton 1984). These displacements will have caused disruption of the original reef topography, producing tilting to the north of reefs such as Skelterton Hill and Stebden Hill, with geopetals showing that a component of the primary depositional dip underwent subsequent tilting on Butter Haw Hill and Elbolton Hill (Mundy 1980, 2000).

Intra-Pendleian displacement on the Middle Craven Fault is shown by onlap of Millstone Grit sandstones onto a south-facing scarp (Arthurton *et al*. 1988) and may be associated with the prominent unconformity at the base of the upper Pendleian Grassington Grit across the southern part of the Askrigg Block (Dunham & Wilson 1985). Limestone blocks present within the Bowland Shale Formation (Black 1957) post-date reef growth and must represent erosion of these structures.

Conclusions

The oldest reefal structures present in the Cracoe-Burnsall area comprise small mudmounds found on the lower slopes of Carden Hill, Butter Haw Hill and Threapland Gill. Foraminiferal-algal assemblages indicate a late Holkerian−early Asbian age for these mudmounds, consistent with their development on a carbonate ramp in a transitional zone between the proximal Scaleber Quarry Limestone Member (Kilnsey Formation) and distal Hodderense Limestone Formation and lower part of the Pendleside Limestone Formation of the Craven Basin. That transition may, in part, have been influenced by displacement on the Middle Craven Fault, with southward thickening in the hangingwall of this structure.

The apron reef facies present in the Cracoe-Burnsall area, e.g. Swinden Quarry, Elbolton, Kail Hill and Hartlington Kail Hill, developed mainly as a marginal rim to a flat-topped carbonate shelf, with a marked slope into the deeper water hemi-pelagic argillaceous successions and carbonate turbidites of the Pendleside Limestone Formation of the Craven Basin to the south. Foraminiferal-algal assemblages confirm that these reefs developed during the late Asbian–early Brigantian (B_{2a} – P_{1b} subzones). Distinct apron reef core (bank) and flank facies are recognized, the latter principally evident in a back-reef setting immediately north of the reef core, though local forereef talus deposits are preserved. The relatively deeper water toes of the back-reef flank facies show development of mudmounds of comparable scale and lithological and biotic composition as the mudmounds found on the older carbonate ramp succession. The thick marginal apron reef succession appears to have developed during further subsidence south of the Middle Craven Fault.

Latest Asbian to earliest Brigantian inversion of the Middle Craven Fault, with uplift of the hangingwall to the south produced a phase of lowstand flank deposits and caused erosion of the reefs, generating much debris that accumulated in the northern part of the Craven Basin. A subsequent post-reef phase of late Brigantian (P_{2a-b}) dextral shear on the Middle Craven Fault and formation of transtentional faults caused some tectonic dismembering of the apron reef morphology.

In summary, late Chadian/early Arundian deformation appears to have fragmented the southward deepening carbonate ramp, influencing the location of the growth of pre-apron reef mudmounds. Late Asbian deformation caused tilting and flexuring of the Askrigg Block, with displacement on the Middle Craven Fault constraining the growth location of the apron reef. Subsequent early Brigantian inversion of the Middle Craven Fault coincided with, and may have caused, final abandonment of the Cracoean reefs.

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Figures

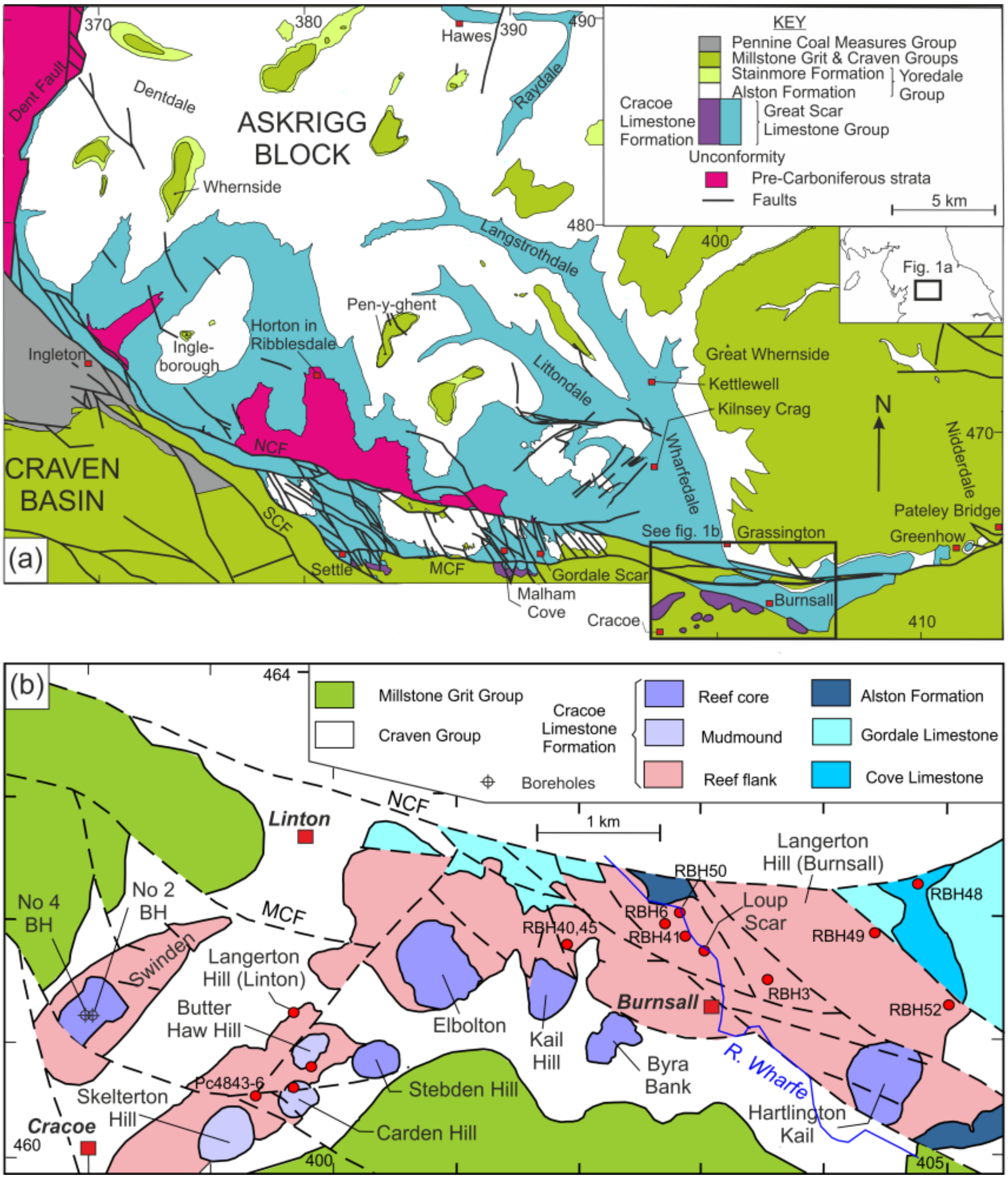
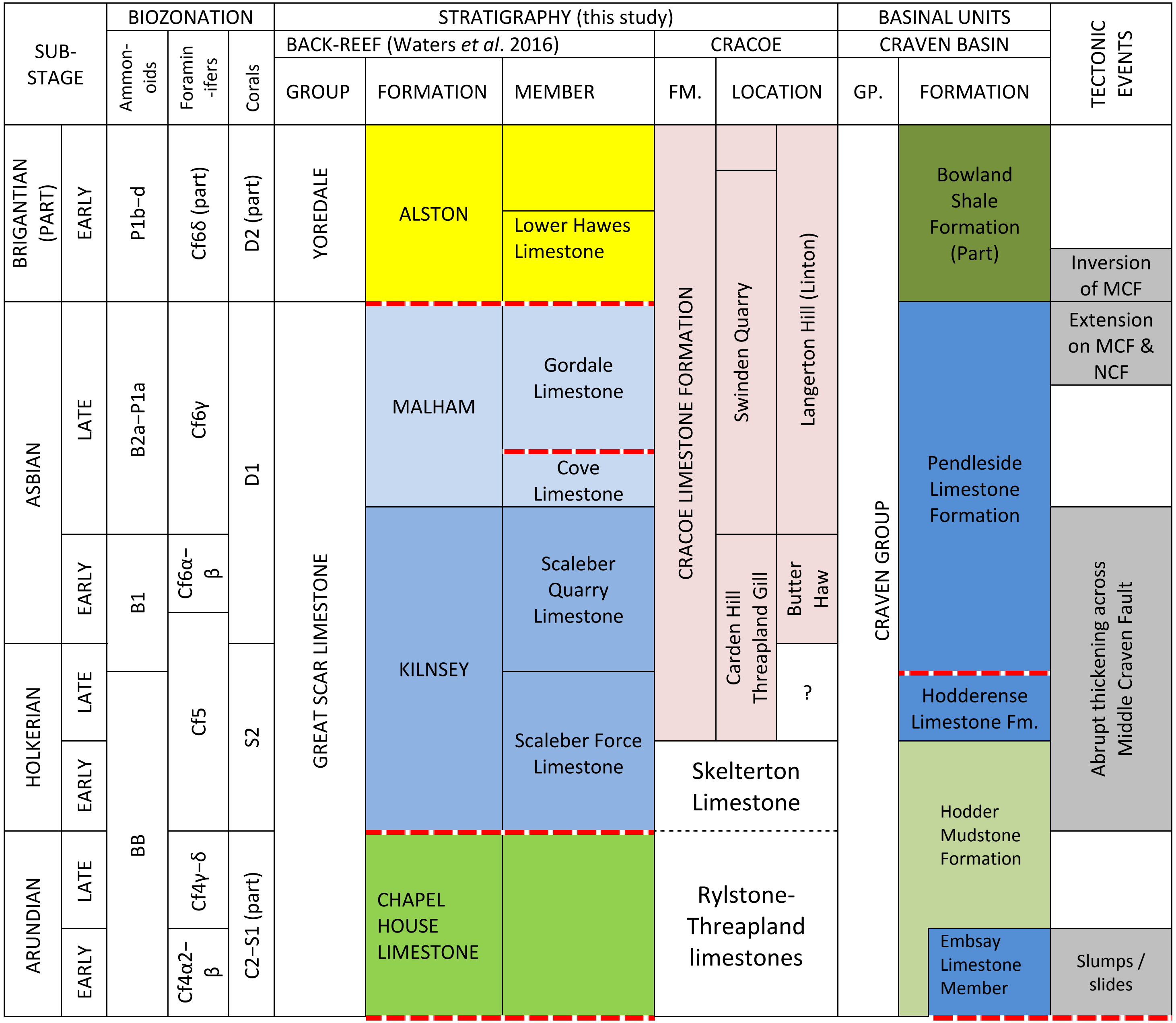


Fig. 1. a) Geological map showing the distribution of the Great Scar Limestone Group across the southern part of the Askrigg Block (based upon Waters & Lowe, 2013, figs 2.3 and 2.8); b) Geological map south of the North Craven Fault showing detail of the Cracoe Limestone Formation, including the position of selected biostratigraphical samples. MCF- Middle Craven Fault; NCF- North Craven Fault; SCF- South Craven Fault. Sourced from BGS revision mapping in 2011-2014.



SUB-STAGE
BIOZONATION
Ammon-oids
Foramin-ifers
Corals
STRATIGRAPHY (this study)
BACK-REEF (Waters et al. 2016)
GROUP
FORMATION
MEMBER
CRACOE
FM.
LOCATION
BASINAL UNITS
CRAVEN BASIN
GP.
FORMATION
TECTONIC EVENTS
BRIGANTIAN (PART)
EARLY
P1b–d
Cf6δ (part)
D2 (part)
YOREDALE
ALSTON
Lower Hawes Limestone
ASBIAN
LATE
B2a–P1a
Cf6γ
D1
MALHAM
Gordale Limestone
Cove Limestone
EARLY
B1
Cf6α–β
GREAT SCAR LIMESTONE
KILNSEY
Scaleber Quarry Limestone
HOLKERIAN
LATE
EARLY
Cf5
S2
Scaleber Force Limestone
ARUNDIAN
LATE
EARLY
BB
Cf4γ–δ
Cf4α2–β
C2–S1 (part)
CHAPEL HOUSE LIMESTONE
CRACOE LIMESTONE FORMATION
Swinden Quarry
Langerton Hill (Linton)
Carden Hill
Threapland Gill
Butter Haw
?
Skelterton Limestone
Rylstone-Threapland limestones
CRAVEN GROUP
Bowland Shale Formation (Part)
Pendleside Limestone Formation
Hodderense Limestone Fm.
Hodder Mudstone Formation
Embsay Limestone Member
Inversion of MCF
Extension on MCF & NCF
Abrupt thickening across Middle Craven Fault
Slumps / slides

Fig. 2. Revised biostratigraphical ages for the reef structures at Cracoe compared with the back-reef carbonate successions described by Waters *et al*. (2016). Basinal succession of the Craven Basin is based upon Waters *et al*. (2009). Prominent unconformities are identified by dashed lines.

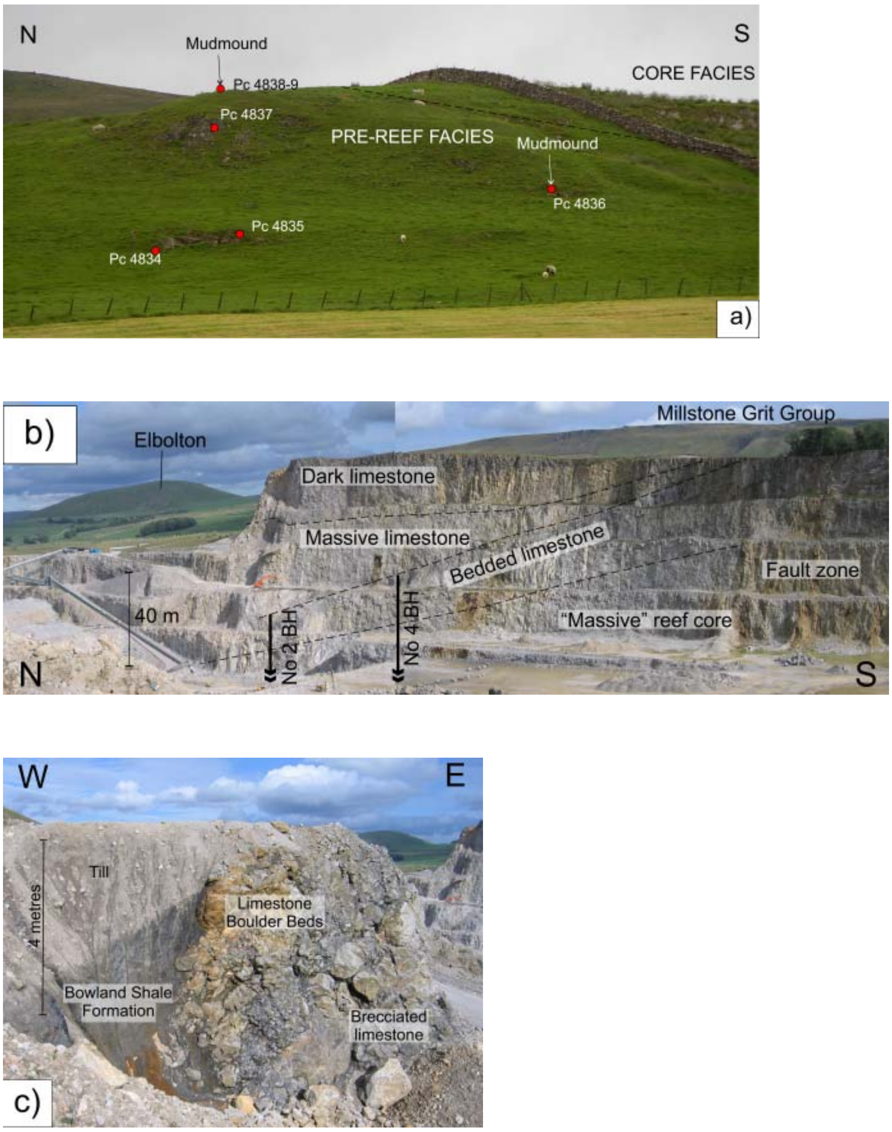


Fig. 3. Components of the Cracoe Limestone Formation: a) Carden Hill [3994 4606], showing the position of samples collected for biostratigraphical analysis from the pre-reefal succession; b) View of the Cracoean reef limestone at Swinden Quarry with a typical reef mound morphology evident at Elbolton Hill, in the background. The quarried limestones are mainly massive reef-core, but with well bedded possible flank facies. The dark limestone at the top of the quarry face has not been accessed. The approximate position of the boreholes in Fig. 5 are shown; c) Southwestern flank of the Swinden Cracoean reef [39761 46137] with a boulder bed of sub-rounded limestone clasts adjacent to basinal mudstones of the Bowland Shale Formation (Fig. 2).

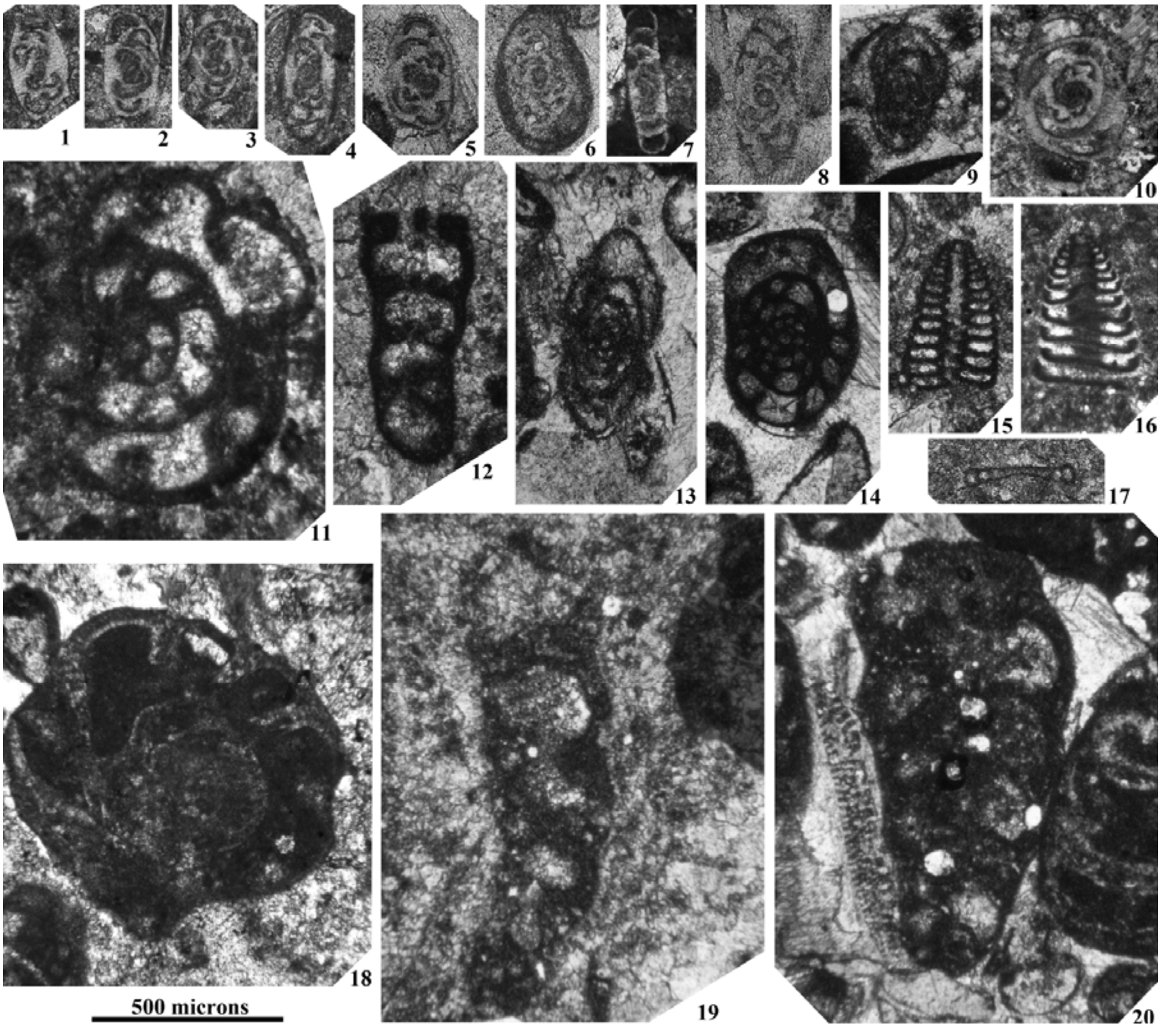


Fig. 4. Selected foraminifers from the Cracoe Limestone Formation. Scale bar consistent for all photomicrographs. **1.** *Archaediscus* at *angulatus* stage?, Carden Hill (Pc4834), late Holkerian-early Asbian. **2.** *Archaediscus* at *angulatus* stage?, Carden Hill (Pc4834), late Holkerian-early Asbian. **3.** *Nodosarchaediscus viae*, Carden Hill (Pc4834), late Holkerian-early Asbian. **4.** *Nodosoarchaediscus demaneti*, Carden Hill (Pc4834), late Holkerian-early Asbian. **5.** *Nodasperodiscus* sp., Loup Scarp (RBH1), late Asbian. **6.** *Neoarchaediscus* sp., Loup Scarp (RBH1), late Asbian. **7.** *Tubispirodiscus* aff. *cornuspiroides*, Langerton Hill, Linton (Pc4849), early Brigantian. **8.** *Neoarchaediscus* sp., Loup Scarp (RBH1), late Asbian. **9.** *Euxinita efremovi*, Loup Scarp (RBH1), late Asbian. **10.** *Archaediscus* ex gr. *karreri*, Langerton Hill (Pc4849), early Brigantian. **11.** *Endothyranopsis compressa* transitional to *E. crassa*, Threapland Gill (Pc4844), late Holkerian-early Asbian. **12.** *Mikhailovella* aff. *gracilis*, Loup Scarp (RBH42), late Asbian. **13.** *Pseudoendothyra sublimis*, Loup Scarp

(RBH1), late Asbian. **14.** *Eostaffella mosquensis*, Loup Scarp (RBH1), late Asbian. **15.** *Vissariotaxis longa*, Barben Beck (RBH52), latest Asbian. **16.** *Howchinia bradyana*, Langerton Hill, Linton (Pc4848), early Brigantian. **17.** *Hemidiscopsis* sp., Barben Beck (RBH52), latest Asbian. **18.** *Endothyranopsis crassa*, Langerton Hill (Pc4849), early Brigantian. **19.** *Haplophragmina* aff. *beschevensis*, Hippings Lane Quarry (RBH6), late Asbian. **20.** *Koskinobigenerina* sp., Loup Scarp (RBH1), late Asbian.

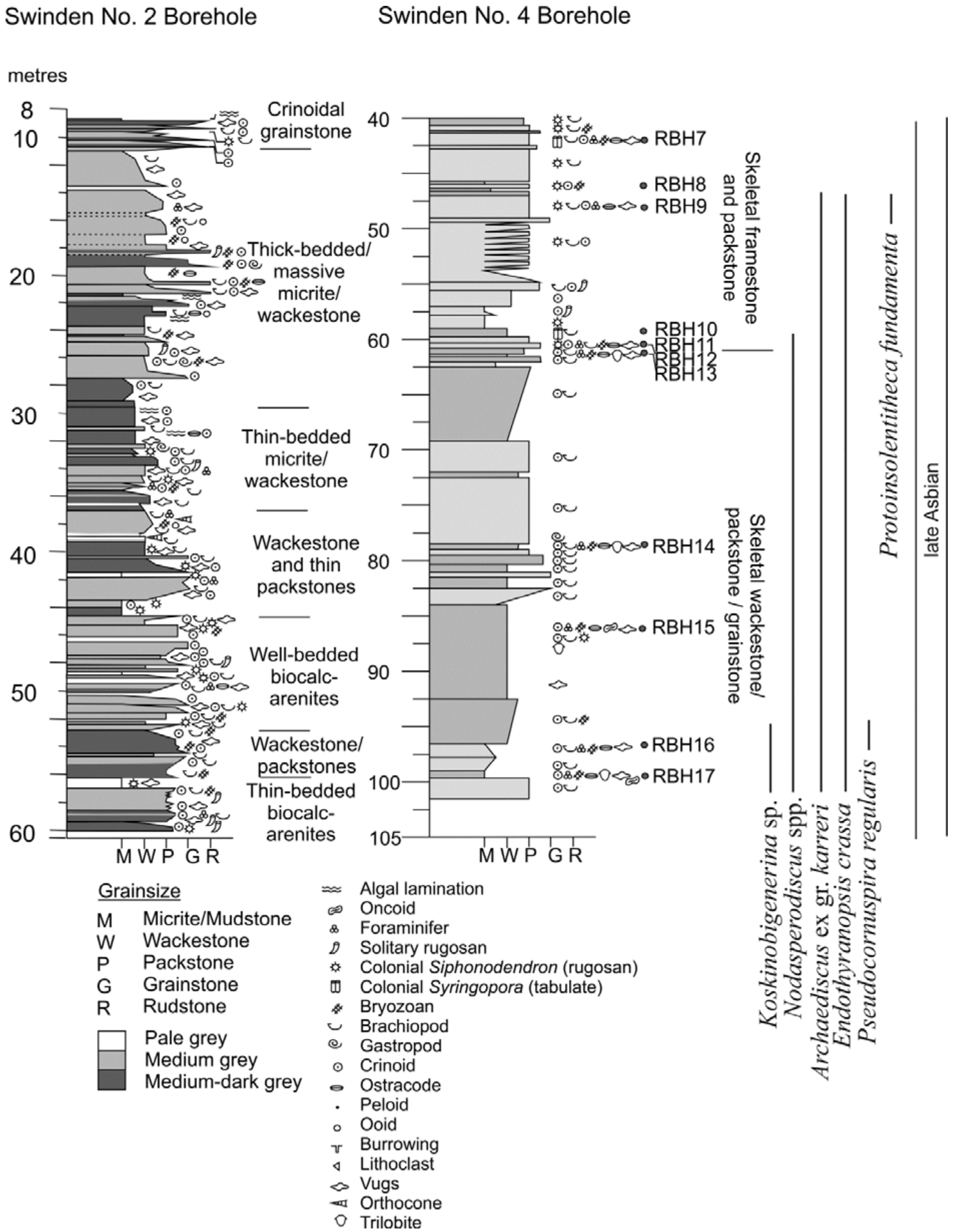


Fig. 5. Lithological logs of selected intervals from the Swinden No. 4 and Swinden No. 2 boreholes showing the position of biostratigraphical samples from the former. The range of selected foraminifers is indicated.

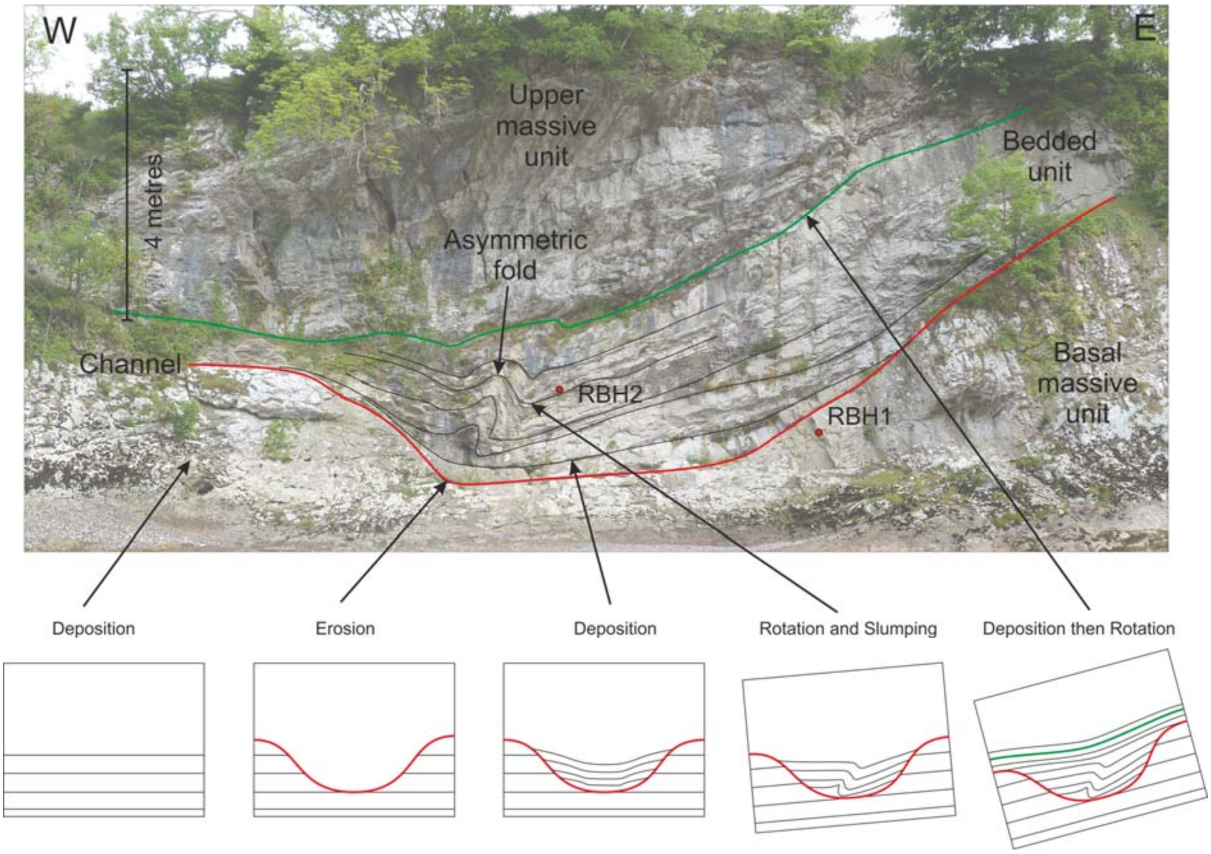


Fig. 6. Loup Scar section at a prominent bend in the River Wharfe [402979 461755] showing two massive limestone units. The lower is channelized and infilled by slumped thin bedded limestone as depicted in the cartoons.

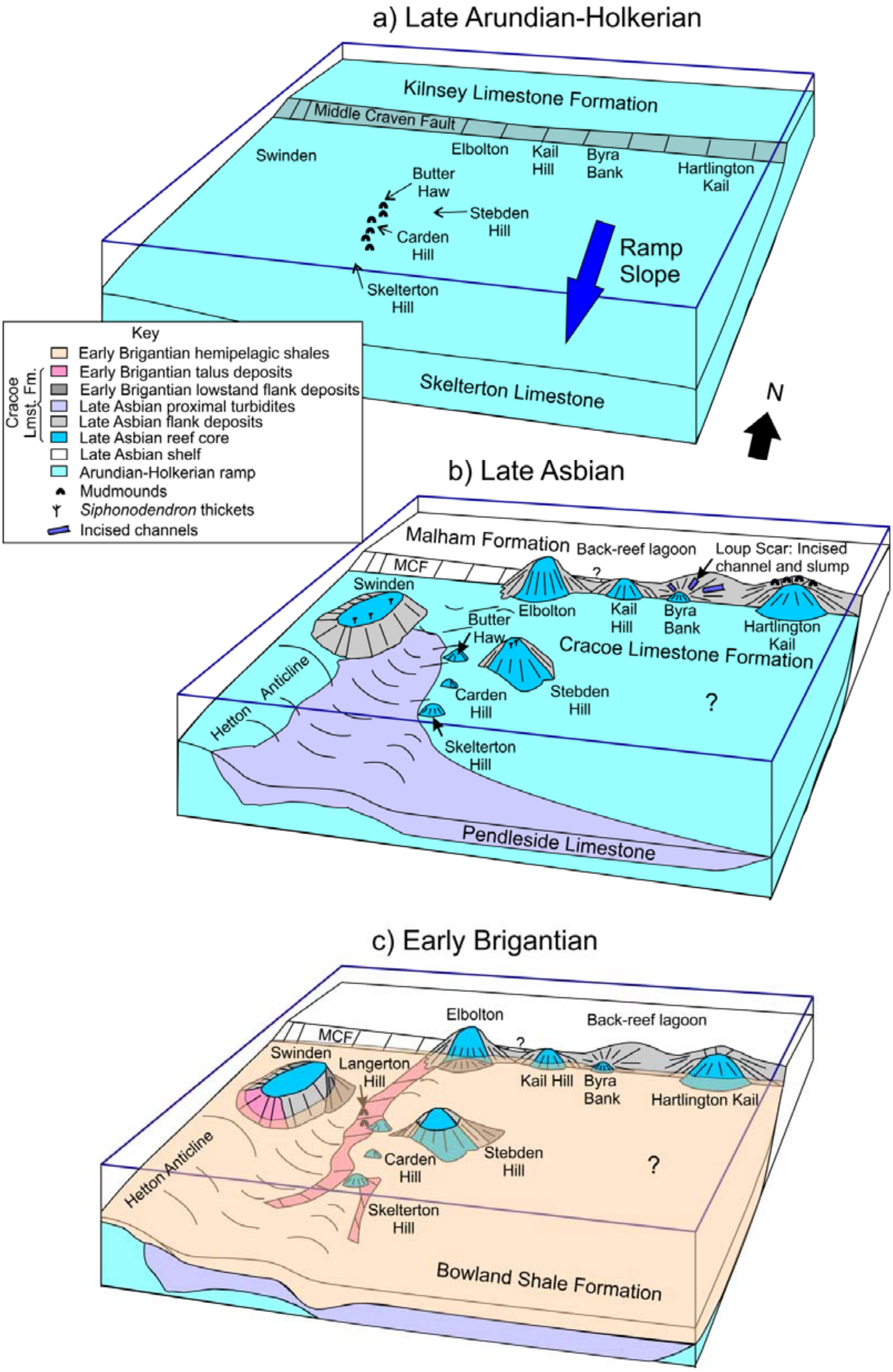


Fig. 7. Schematic perspective views showing: a) late Arundian-Holkerian development of ramp topography; b) the relationships of the late Asbian reef facies upon the existing ramp; and c) early Brigantian Bowland Shale Formation onlap onto the reef knolls.

Tables

<table>
<tr><th>Hudson (1938)</th><th colspan="2">Bond (1950)</th><th>Mundy (2000)</th><th>Sub-stage</th><th>Index</th></tr>
<tr><td>Upper Reef Limestone</td><td rowspan="5">Elbolton Limestone Series</td><td>Michelinia–Emmonsia Beds</td><td rowspan="3">Cracoean Reefs</td><td rowspan="3">Late Asbian</td><td>P_{1a}</td></tr>
<tr><td>Cyrtina septosa Band</td><td>Davidsonina (Cyrtina) septosa Beds</td><td>B_2</td></tr>
<tr><td>Lower Reef Limestone</td><td>Tufa Beds</td><td>B_2; mid D_1</td></tr>
<tr><td rowspan="4"></td><td>Porcellanous Beds</td><td rowspan="2">?</td><td rowspan="2">Early Asbian</td><td>Lower D_1</td></tr>
<tr><td>Loup Scar Beds</td><td>S_2-D_1</td></tr>
<tr><td rowspan="2">Threapland Limestone Series</td><td rowspan="2"></td><td>Skelterton Limestone</td><td>Holkerian</td><td rowspan="2">S_{1-2}</td></tr>
<tr><td>Rylstone-Threapland limestones</td><td>Late Arundian</td></tr>
</table>

Table 1. Former stratigraphical nomenclatures used for the Cracoean reefs and pre-reef successions.

Sample Number	Easting	Northing	Location	Facies
Pc4834	^{3}99443	^{4}60650	Carden Hill, western flank	intermound
Pc4835	^{3}99423	^{4}60632	Carden Hill, western flank	intermound
Pc4836	^{3}99408	^{4}60601	Carden Hill, western flank	mudmound core
Pc4837	^{3}99432	^{4}60605	Carden Hill, western flank	mudmound core
Pc4838	^{3}99448	^{4}60590	Carden Hill, summit	mudmound flank
Pc4839	^{3}99448	^{4}60590	Carden Hill, summit	intermound
Pc4840	^{3}99585	^{4}60792	Butter Haw Hill, southern flank	mudmound core
Pc4841–2	^{3}99585	^{4}60792	Butter Haw Hill, southern flank	mudmound flank
Pc4843–4	^{3}99107	^{4}60532	Skelterton Hill, Threapland Gill (west)	mudmound flank
Pc4845–6	^{3}99107	^{4}60532	Skelterton Hill, Threapland Gill (east)	mudmound core
Pc4847	^{3}99425	^{4}61223	Langerton Hill (Linton)	mudmound core
Pc4848–9	^{3}99425	^{4}61223	Langerton Hill (Linton)	mudmound flank
Pc4855	^{4}02925	^{4}61772	Upstream of Loup Scar on right bank at river level	reef flank
RBH01–2	^{4}02979	^{4}61755	Loup Scar, north bank of the River Wharfe, 366m NW of Burnsall church	reef flank
RBH03	^{4}03481	^{4}61520	Skuff Road Quarry, 233m east of Burnsall church	reef flank
RBH06	^{4}02605	^{4}61989	Hippings Lane, 780m to the north east of Burnsall church	reef flank
None	^{3}97900	^{4}61370	Swinden No. 2 Borehole	reef core
RBH07−17	^{3}97788	^{4}61363	Swinden No. 4 Borehole	reef core
RBH40	^{4}01773	^{4}61823	Kail Hill flank, 460m east of Thorpe	reef flank
RBH41	^{4}02778	^{4}61880	235m upstream from Loup Scar. south bank of the River Wharfe	reef flank
RBH42–4	^{4}02978	^{4}61755	Loup Scar, south bank of the River Wharfe	reef flank
RBH45	^{4}01773	^{4}61823	Kail Hill flank, 460m east of Thorpe	reef flank
RBH49	^{4}04405	^{4}61915	400m SE of the top of Langerton Hill (Burnsall)	reef flank
RBH52	^{4}05031	^{4}61288	Hartlington Hall, Barben Beck	reef flank
WMD16359–16384	^{4}02728	^{4}61722	Byra Bank, 560m west of Burnsall church (loose material)	reef flank
WMD 16446–16459	^{4}02978	^{4}61755	Loup Scar, south bank of the River Wharfe, 366m NW of Burnsall church	reef flank
WMD16460–5	^{4}03480	^{4}61520	Skuff Road Quarry, 233m east of Burnsall church	reef flank

Table 2. List of specimens and locality details for the key macropalaeontological and micropalaeontological determinations.

Group	Taxon	Carden Hill						Butter Haw Hill			Threapland Gill				Swinden Quarry No. 4 Borehole										Langerton Hill			Loup Scarp							Kail Hill		Borben Beck	Skelf Road By.	Hippings Lane
		Pc4834	Pc4835	Pc4836	Pc4837	Pc4838	Pc4839	Pc4840	Pc4841	Pc4842	Pc4843	Pc4844	Pc4845	Pc4846	RBH17	RBH16	RBH15	RBH14	RBH13	RBH12	RBH11	RBH9	RBH8	RBH7	Pc4847	Pc4848	Pc4849	RBH1	RBH42	RBH43	RBH44	RBH2	Pc4855	RBH41	RBH40	RBH45	RBH52	RBH3	RBH6
Foraminifers	*Archaediscus* at *angulatus* sta	?	?	?	?	?	?	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
	A. concavus trans. *angulatus*											X																											
	Archaediscus at *concavus* stage		X	X	X		X	X			X			X	X	X		X			X	X		X					X	X	X	X	X				X		X
	Archaediscus chernoussovensis																																						aff
	Archaediscus karreri														gr	gr		gr	gr	gr	gr	gr				gr	gr		gr					gr					
	Cepekia sp.															X																							
	Consobrinella spp.													X		X				X		X										X	X						
	Cribrostomum sp.																											?											
	Earlandia elegans		X		X				X							X								X									X						
	Earlandia minima								X		X				X	X					X																	X	
	Earlandia moderata										X				X					X	X			X												X	X		
	Earlandia vulgaris				X										X	X		X	X	X		X												X					
	Endostaffella fucoides																											X											
	Endostaffella spp.															X								X									?		X				
	Endothyra bowmani	gr										gr				X					X	X				X		X			X		gr		gr		X	gr	
	Endothyra similis		gr									gr				X					X	X		X	X				X			X							X
	Endothyra prisca								X																														
	Endothyra spp.		X	X	X	X	X		X	X	X			X				X	X	X		X		X			X			X	X		X	X			X		
	Endothyranopsis compressa														X				X	X	X	X																	
	E. compressa trans. *crassa*											X																											
	Endothyranopsis crassa														X	X						X					X	aff							aff				
	Endothyranopsis sp.														X																								
	Eostaffella mosquensis																											X											
	Eostaffella parastruvei																											X						gr					
	Eostaffella proikensis															X															X								
	Eostaffella spp.																											X							X				
	Euxinita efremovi																											X					X				X	?	
	Forschia mikhailovi															X		?										X		?									
	Forschia parvula																											X											
	Globoendothyra globulus																											X		X									
	Globoendothyra spp.																	X				X		X							X				X				
	Haplophragmina beschevensis																																						aff
	Hemidiscopsis sp.																																				X		
	Howchinia bradyana																								X	X	X		X										
	Howchinia gibba																												?										
	Koskinotextularia sp.																																X						
	Koskinobigenerina spp.														?	X												X											
	Lituotubella magna											X																											
	Mediocris breviscula																																					X	
	Mediocris mediocris																	X										X											
	Mikhailovella gracilis																												aff										
	Neoarchaediscus sp.																											?						X					
	Neoarchaediscus stellatus																																				X		
	Nodosarchaediscus demaneti	X																																					X
	Nodosarchaediscus viae	X																																					
	Nodosarchaediscus spp.											X												X				X					X						
	Nodasperodiscus spp.														?						X											X						X	
	Omphalotis frequentata														X																								
	Omphalotis minima															X			X	X								X											
	Omphalotis spp.				X											X		X										X									X		
	Palaeotextularia spp.																	X										X	X					X	X		?		
	Planoarchaediscus spirillinoides															X						X															X		
	Planoarchaediscus sp.	X										X						X						X															
	Plectogyranopsis ampla																	X																	X				
	Plectogyranopsis convexa															X																							
	Plectogyranopsis sp.											X																											
	Praeostaffellina macdonaldensis																																					X	
	Protoinsolentitheca fundamenta																					X							X	X									
	Pseudoammodiscus volgensis	X	X									X																				X							
	Pseudoammodiscus spp.			X	X	X		X		X	X			X	X	X	X		X	X	X	X				X		X	?	X	X				X			X	
	Pseudoendothyra bona																											X											
	Pseudoendothyra sublimis																											X										X	
	Pseudoendothyra spp.															X												X											
	Pseudolituotuba gravata											X		X	X	X	X	X	X	X		X		X							X	X							X
	Pseudolituotuba sp.										X																			X				X					
	Pseudotaxis eominima																									X		X											
	Scalebrina sp.															X								X								X							X
	Tetrataxis spp.	X			X			X		X	X	X			X	X	X	X	X	X	X	X		X				X	X		X		X	X	X		X	X	X
	Tubispirodiscus cornuspiroides																										aff												
	Valvulinella youngi	X													X	X	X	X	X	X	X	X	?	X								X	?	X			X		X
	Vissariotaxis longa																																				X		
Dasycladales	*Anatolipora carbonica*																											X				X							
	Koninckopora inflata										X	X			X	X						X																	
	Koninckopora minuta														X																								
	Koninckopora tenuiramosa											X			X	?						X								X									
	Kulikia sphaerica																											X											
	Windsoporella tulayae																											X											
	Windsoporella pareyni																											X											
Aoujgaliids	*Aoujgalia variabilis*																											X					X						
	Aoujgalia regularis																												X										
	Aoujgalia sp.				X							X																											
	Aphralysia sp.												?		X	?						X							X		X	X	X				X		
	Asphaltinella horowitzi															X								X															
	Epistacheoides sp.						X					X			X		X	X	X	X	X	X																	
	Fasciella kizilia																											X	X	X	X	X		X			X	X	X
	Kamaena delicata	X														X			X	X											X	X							
	Kamaena sp.																				?																	X	
	Kamaenella denbighi																																	X					
	Kamaenella tenuis																		X			X									?								
	Fourstonella johnsoni																												X		X							X	
	Fourstonella skimoensis																											?	?										
	Palaeoberesella lahosenii																		X									X											X
	Pseudostacheoides loomisi																											X											
	Roquesselsia radians																											X											
	Sinustacheoides meandriformis	?														X						X																	
	Stacheia marginuloides																									X													
	Stacheoides tenuis															X					X																		
	Ungdarella uralica											?																X				X			X				
	Zidella maxima											?																			X	X							
	Girvanella wetheredii																														X	X						X	X
	Ortonella sp.																											X											
	Hortonella uttingi																												X								X		
	Draffania biloba											X				X		X	X																				

Table 3. Foraminifer and algae/problematica taxa in the Cracoe Limestone Formation.