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Biostratigraphy, microfacies and depositional environments of Upper Viséan limestones from the Burren region, County Clare, Ireland

S.J. GALLAGHER[1]*, C.V. MACDERMOT[2]†, I.D. SOMERVILLE[3], M. PRACHT[2] and A.G. SLEEMAN[2]

[1]School of Earth Sciences, The University of Melbourne, Victoria, Australia
[2]Geological Survey of Ireland, Dublin, Ireland
[3]UCD School of Geological Sciences, University College Dublin, Dublin, Ireland

The Burren region in western Ireland contains an almost continuous record of Viséan (Middle Mississippian) carbonate deposition extending from Chadian to Brigantian times, represented by three formations: the Chadian to Holkerian Tubber Formation, the Asbian Burren Formation and the Brigantian Slievenaglasha Formation. The upper Viséan (Holkerian–Brigantian) platform carbonate succession of the Burren can be subdivided into six distinct depositional units outlined below. (1) An Holkerian to lower Asbian unit of skeletal peloidal and bryozoan bedded limestone. (2) Lower Asbian unit of massive light grey *Koninckopora*-rich limestone, representing a shallower marine facies. (3) Upper Asbian terraced limestone unit with minor shallowing-upward cycles of poorly bedded *Kamaenella*-rich limestone with shell bands and palaeokarst features. This unit is very similar to other cyclic sequences of late Asbian age in southern Ireland and western Europe, suggesting a glacio-eustatic origin for this fourth-order cyclicity. (4) Lower Brigantian unit with cyclic alternations of crinoidal/bryozoan limestone and peloidal limestone with coral thickets. These cycles lack evidence of subaerial exposure. (5) Lower Brigantian bedded cherty dark grey limestone unit, deposited during the maximum transgressive phase of the Brigantian. (6) Lower to upper Brigantian unit mostly comprising cyclic bryozoan/crinoidal cherty limestone. In most areas this youngest unit is truncated and unconformably overlain by Serpukhovian siliciclastic rocks. Deepening enhanced by platform-wide subsidence strongly influenced later Brigantian cycle development in Ireland, but localized rapid shallowing led to emergence at the end of the Brigantian.

A Cf5 Zone (Holkerian) assemblage of microfossils is recorded from the Tubber Formation at Black Head, but in the Ballard Bridge section the top of the formation has Cf6 Zone (Asbian) foraminiferans. A typical upper Asbian Rugose Coral Assemblage G near the top of the Burren Formation is replaced by a lower Brigantian Rugose Coral Assemblage H in the Slievenaglasha Formation. A similar change in the foraminiferans and calcareous algae at this Asbian–Brigantian formation boundary is recognized by the presence of upper Asbian Cf6γ Subzone taxa in the Burren Formation including *Cribrostomum lecomptei, Koskinobigenerina* sp., *Bradyina rotula* and *Howchinia bradyana,* and in the Slievenaglasha Formation abundant *Asteroarchaediscus* spp., *Neoarchaediscus* spp. and *Fasciella crustosa* of the Brigantian Cf6δ Subzone. The uppermost beds of the Slievenaglasha Formation contain a rare and unusual foraminiferal assemblage containing evolved archaediscids close to *tenuis* stage indicating a late Brigantian age. Copyright © 2006 John Wiley & Sons, Ltd.

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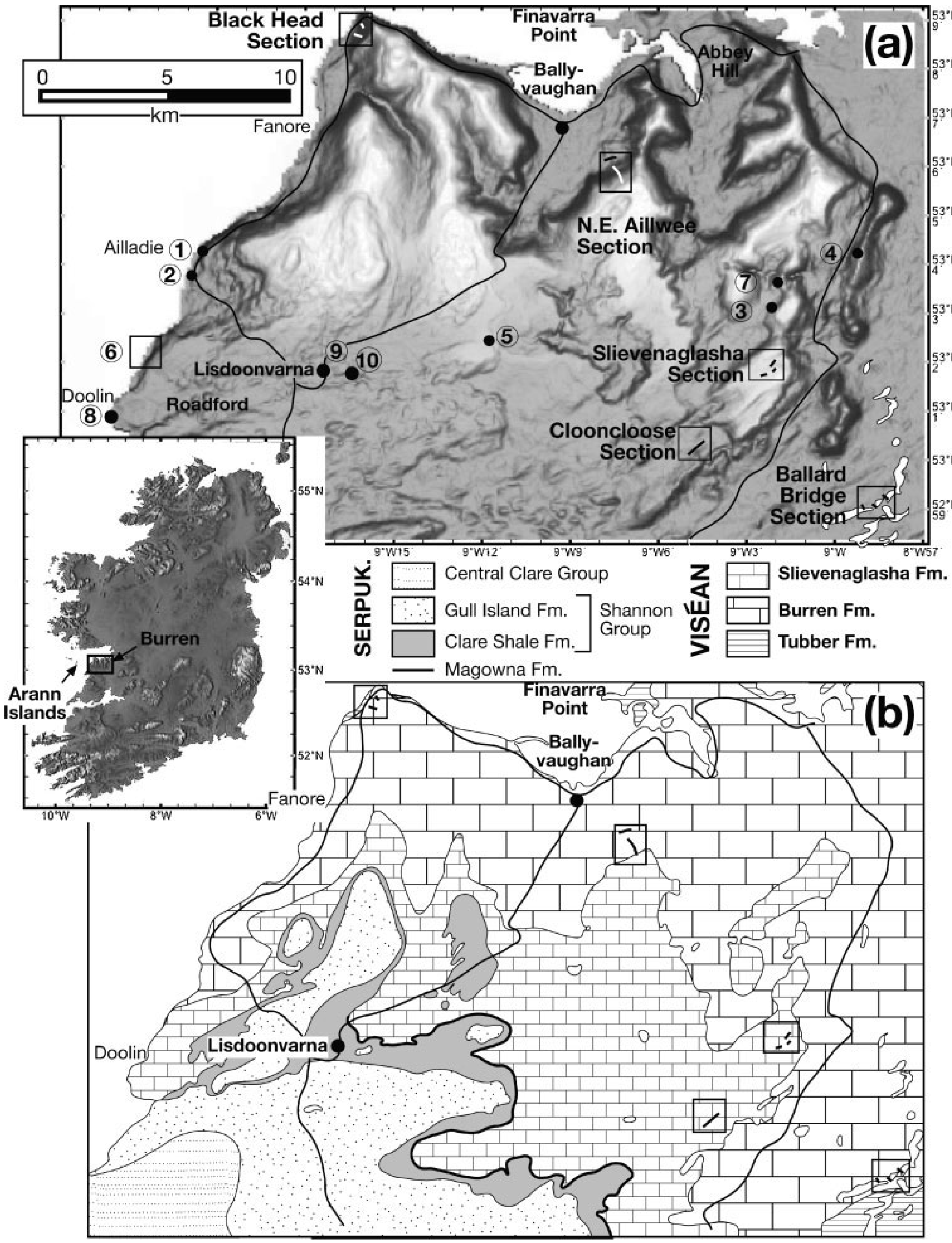
1. INTRODUCTION AND SUMMARY OF PREVIOUS WORK

The Burren region (Figure 1) is one of the most extensive limestone karst regions in northwest Europe covering *c*. 600 km^2 of north County Clare. Limestone plateaus are characteristic (especially in the northern part), rising to

*Correspondence to: S. J. Gallagher, School of Earth Sciences, The University of Melbourne, Victoria 3010, Australia.
E-mail: sigall@unimelb.edu.au
†Deceased


Black Head Section
Finavarra Point
Bally-vaughan
Abbey Hill
(a)
0 5 10
km
Fanore
N.E. Aillwee Section
Ailladie
Lisdoonvarna
Doolin
Roadford
Slievenaglasha Section
Databases
Clooncloose Section
Ballard Bridge Section
9°W15′ 9°W12′ 9°W9′ 9°W6′ 9°W3′ 9°W 8°W57′
Burren
Arann Islands
55°N
54°N
53°N
52°N
10°W 8°W 6°W
SERPUK.
Central Clare Group
Gull Island Fm.
Clare Shale Fm.
Shannon Group
Magowna Fm.
VISÉAN
Slievenaglasha Fm.
Burren Fm.
Tubber Fm.
(b)

over 300 m (Figure 1a). The area is bounded to the east by the limestone of the Gort Lowlands (maximum topography 30 m) and to the south by poorly exposed sandstone and shale, that produces a subdued topography (maximum elevation 100 m) in the southern half of County Clare (Figure 1a). (Grid references of locations referred to in the text are given in the Appendix.)

The Geological Survey of Ireland (GSI) initially mapped the Burren area in the mid-nineteenth century and published the first 1 inch-to-1 mile (1:63 360) maps (Sheets 114 and 123) in 1862. This work revealed outcrops of 'Upper Limestone' in the northern part with shallow dips (0 to 5°S). The overlying 'Shale Series' (Yoredale Beds) and 'Flagstone Series' (Millstone Grit) are present in the southern part of County Clare. The first detailed description of the stratigraphy and fossils of the Viséan (= Middle Mississippian of Work 2004) platform carbonates of the Burren area was by Douglas (1909).

Douglas (1909) used the Vaughanian (1905) divisions of the Lower Carboniferous of the Bristol area, SW England, modified by Sibly (1908) from his work in Derbyshire, in the Burren region. He described a thick succession of limestone ranging in age from the S_1 to D_3 zones (Arundian to Brigantian) using Vaughan's coral and brachiopod zonal scheme. Douglas described black compact crystalline and crinoidal limestone with some chert and oolitic beds in the S_2 (*Seminula*) Zone. The succeeding *Dibunophyllum* (D) Zone strata that form most of the Burren region are typified in the lower part (D_1 subzone) by dark grey, partly dolomitized crinoidal limestone overlain by pale grey, finely crystalline-bedded limestone with rare chert. The limestones of the upper D_2–D_3 subzones are crinoidal and overlain by black compact limestone with chert horizons. The lower D_1 subzone strata include the lower Burren Formation, as well as the pale grey bedded limestone with rare chert of the upper Burren Formation; the upper D_2–D_3 subzone strata are referred to as the Slievenaglasha Formation.

Clarke (1966a,b) described the coral fauna of the Burren, including the first recognition of the colonial rugose coral genus *Orionastraea* in Ireland from the upper D_3 subzone from Clare County Council Roadstone Quarry (in the townland of Ballyinsheen More), 1.6 km north of Lisdoonvarna (locality 9, Figure 1). Conil (1976) described and figured upper Viséan foraminiferans from Roadford, County Clare (Figure 1). George *et al*. (1976) reported diagnostic corals from the Burren limestones assigned to the Holkerian, Asbian and Brigantian stages. Nudds (1979) collected *Orionastraea* with *Lithostrotion* from the upper part of the Burren succession at Lisdoonvarna. Self (1981) and Drew (2001) described the karstic nature of the Burren region and also alluded to the presence of shale horizons in the limestone from the exploration of caves.

Gallagher (1992) documented the petrology and fossils from the Burren area and broad correlations were made between the Burren and other upper Viséan areas in southern Ireland by Gallagher (1996), Gallagher and Somerville (1997, 2003) and by Cózar and Somerville (2005a). The lithofacies, macrofauna and microfossils, particularly conodonts, were documented from the upper Viséan offshore Arann Island of Inishmore (Figure 1) and compared to the mainland Burren section (Somerville 1999). Sampling was undertaken for this project with the help of the late Conor MacDermot using his detailed field logs. Finally, Pracht *et al*. (2004) published a geological map of the Burren region and accompanying booklet (Figure 1b) in which previously described limestone units were formalized into members and formations (Figure 2).

The purpose of this contribution is to describe in detail the lithofacies of the formally defined members, in particular their microfacies and macro- and microfossil content, and to document evidence for environmental change preserved in the > 450 m of well exposed upper Viséan carbonate strata of the Burren region. The litho- and biostratigraphy of the Burren region is then compared and correlated to other parts of Ireland and western Europe.

Figure 1(a). A digital terrain map of the Burren region in north County Clare made using GeoMapApp 1.2_05 obtained from the Marine Geoscience Data Management System (http://www.geomapapp.org/). The sun illumination is vertical and there is a 7 × vertical exaggeration. The white regions have elevations > 250 m. The black shading matches the 50–100 m contours. The grid reference of the key sections and locations is listed in Appendix 1. The localities and sections are indicated (see Appendix 1 for grid references). (**b**) A geological map of the Burren region adapted from Pracht *et al.* (2004)

2. LITHOSTRATIGRAPHY, MICROFACIES AND DEPOSITIONAL ENVIRONMENTS OF THE BURREN SUCCESSION

The succession of the Burren region (Figure 2) has been lithostratigraphically divided into three formations based on lithofacies, age and topographic expression (see Gallagher 1996; Pracht *et al*. 2004).

2.1. *The Tubber Formation*

This predominantly Chadian to Arundian unit is described by Pracht *et al*. (2004), although they suggest that it may well be Holkerian in the upper part. However, in the north Burren area at Black Head and near Ballyvaughan (Figure 1) it is represented by the basal exposed unit (Finavarra Member) of the Burren succession (Figure 2), and may extend to the earliest Asbian stage (Gallagher 1992, 1996). The lower part of the Tubber Formation is recorded in the Gort Borehole (G-1) and in the Gort Lowlands to the east (Pracht *et al.* 2004). The formation is not described further here.

2.2. *The Burren Formation*

This 365 to 386 m thick formation crops out extensively in the north Burren region of County Clare (Figure 1b). The lower boundary of the Burren Formation is marked by a laterally continuous dolomite horizon parallel to

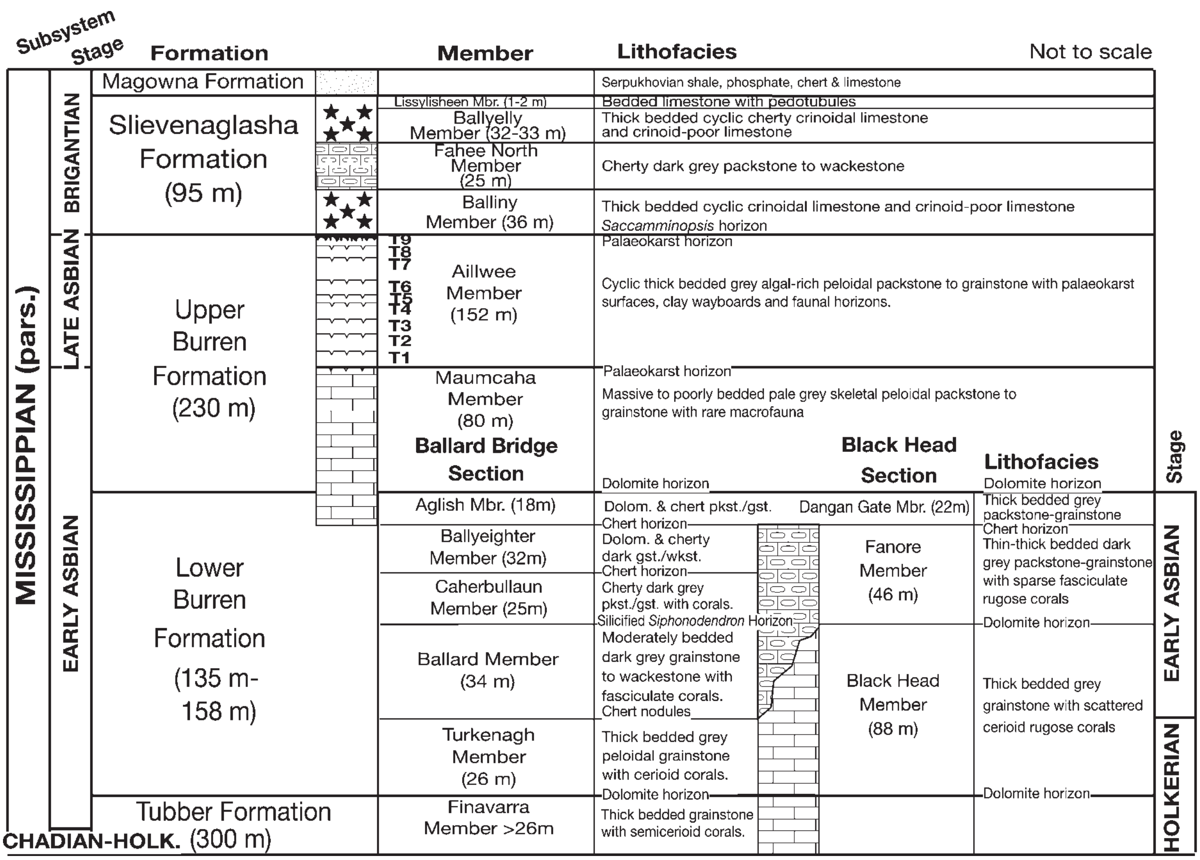


Figure 2. A schematic summary of the stratigraphy of the upper Viséan carbonates of the Burren region. T1 to T9 are numbered terraces in the Aillwee Member.

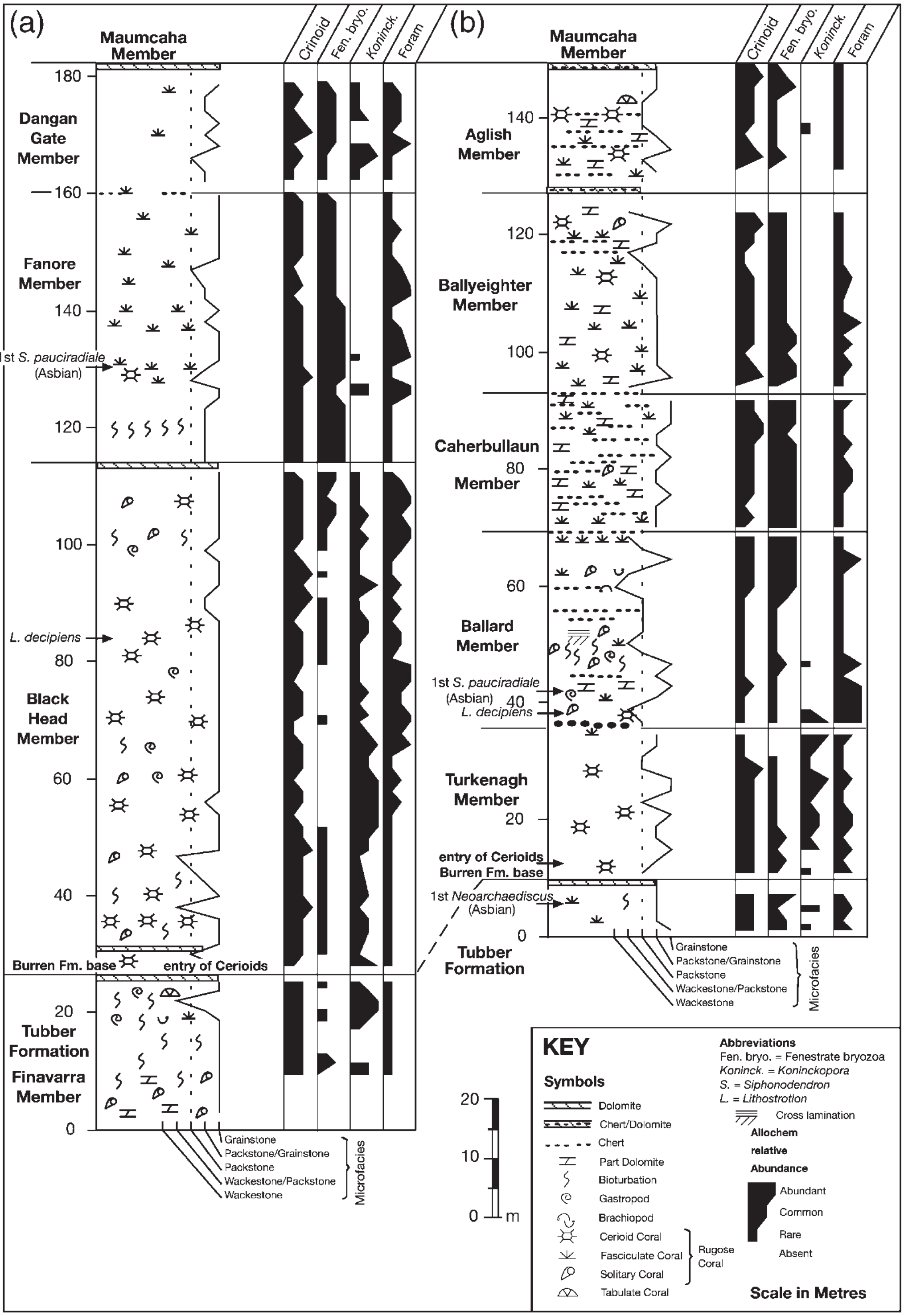


Figure 3. A log of the lower part of the Burren Formation (and upper part of the Tubber Formation), including (a) the Black Head and (b) the Ballard Bridge Sections. See Table 1 for allochemical abundance key.

Table 1. The semi-quantitative basis of the allochemical abundance data in Figures 3, 4 and 7

Code	Allochems per 50 mm × 10 mm thin section
Absent	0 specimens
Rare	1–30 fronds of bryozoans, 1–30 foraminiferans, crinoids and pseudo-thalli of kamaenids and *Ungdarella*, 1–6 fragments of *Koninckopora*
Common to Abundant	> 30 fronds of bryozoans, > 30 foraminiferans, crinoids and pseudo-thalli of kamaenids and *Ungdarella*, > 6 fragments of *Koninckopora*

bedding, which is found below the first occurrence of cerioid lithostrotionid corals (Gallagher 1992, 1996; Pracht *et al*. 2004). The dolomite unit separates the thick-bedded (1–3 m thick) grainstone (with abundant fasciculate *Siphonodendron martini* corals of the underlying Tubber Formation) from the thicker bedded (2–5 m thick) grainstone of the base of the Burren Formation (Figure 2). This boundary is located near the base of the Ballard Bridge and Black Head sections (Figure 3). A pronounced irregular palaeokarst surface marks the top of the Burren Formation (as seen at Locality 6 on the coast, Figures 1, 2, 6.4). This surface is overlain by a *Saccamminopsis* band and crinoidal limestone of the succeeding Brigantian Slievenaglasha Formation. The type section of the Holkerian–Asbian Burren Formation is a composite section, involving a combination of the Black Head and northeast Aillwee sections (Figures 3 and 4). The Burren Formation can be subdivided into two stratigraphic intervals: (i) the lower Burren Formation comprising three members in the Black Head (northwest) section and five in the Ballard Bridge (southeast) section (Figure 3); and (ii) the upper Burren Formation comprising the Maumcaha and Aillwee members, best exposed in the northeast Aillwee Section (Figure 4).

The Black Head Section

The lower Burren Formation in the Black Head Section (156 m thick) can be subdivided into three members: the Black Head, Fanore and Dangan Gate members (Gallagher 1992, 1996; Pracht *et al*. 2004; Figures 2, 3a).

Black Head Member (88 m). Cerioid *Lithostrotion* coral bands appear in the lower limestones of the Black Head Member (Figure 3). The microfacies consists of coarse-grained moderate- to well-sorted, skeletal peloidal grainstone (Figure 5.1) with common dasyclad algae (*Koninckopora*), crinoids, brachiopods, molluscs, foraminiferans and some extensively micritized skeletal grains. Fenestrate bryozoans are mostly absent to rare (Figure 3). Most of the bioclasts are micrite-coated. The Black Head Member was deposited in an open-marine, shallow-water subtidal environment in the zone of normal wave action, inferred from the presence of green algae and *in situ* cerioid colonial colonies. Constant reworking of allochems at shallow photic depths is suggested by the well-sorted nature of the limestone, and the frequent well-rounded bioclasts.

Fanore Member (46 m). The lower boundary of the Fanore Member is placed above a dolomite horizon at log level 114 m (Figures 3 and 6.3). The limestones have a sparse fauna of *in situ* fasciculate *Siphonodendron* and *Solenodendron* coral thickets with very rare *Lithostrotion* colonies. The microfacies consists of fine- to medium-grained skeletal peloidal packstone to grainstone with abundant fenestrate bryozoans (sheets and fragments) (Figures 3 and 5.2) and common crinoids, trepostome bryozoans, sponge spicules and foraminiferans. Many of the bioclasts are bored and micrite-coated. *Koninckopora* is mostly absent or rare. The Fanore Member was deposited in subtidal, open-marine conditions, below normal wave-base (but still in the photic zone). The preservation of *in situ* fasciculate rugose colonies, fenestrate bryozoan sheets, trepostome bryozoans, sponge spicules and the virtual absence of dasyclad algae is typical of quiet water, lower energy environments in a slightly deeper water shelf setting (Somerville and Rodríguez 2005).

Dangan Gate Member (22 m). The lower boundary of the Dangan Gate Member is marked by a chert horizon at log level 160 m (Figure 3). The upper boundary is a thin, laterally continuous dolomite horizon marking the base of the succeeding Maumcaha Member, that can be correlated for 30 km, from the Black Head to the Ballard Bridge

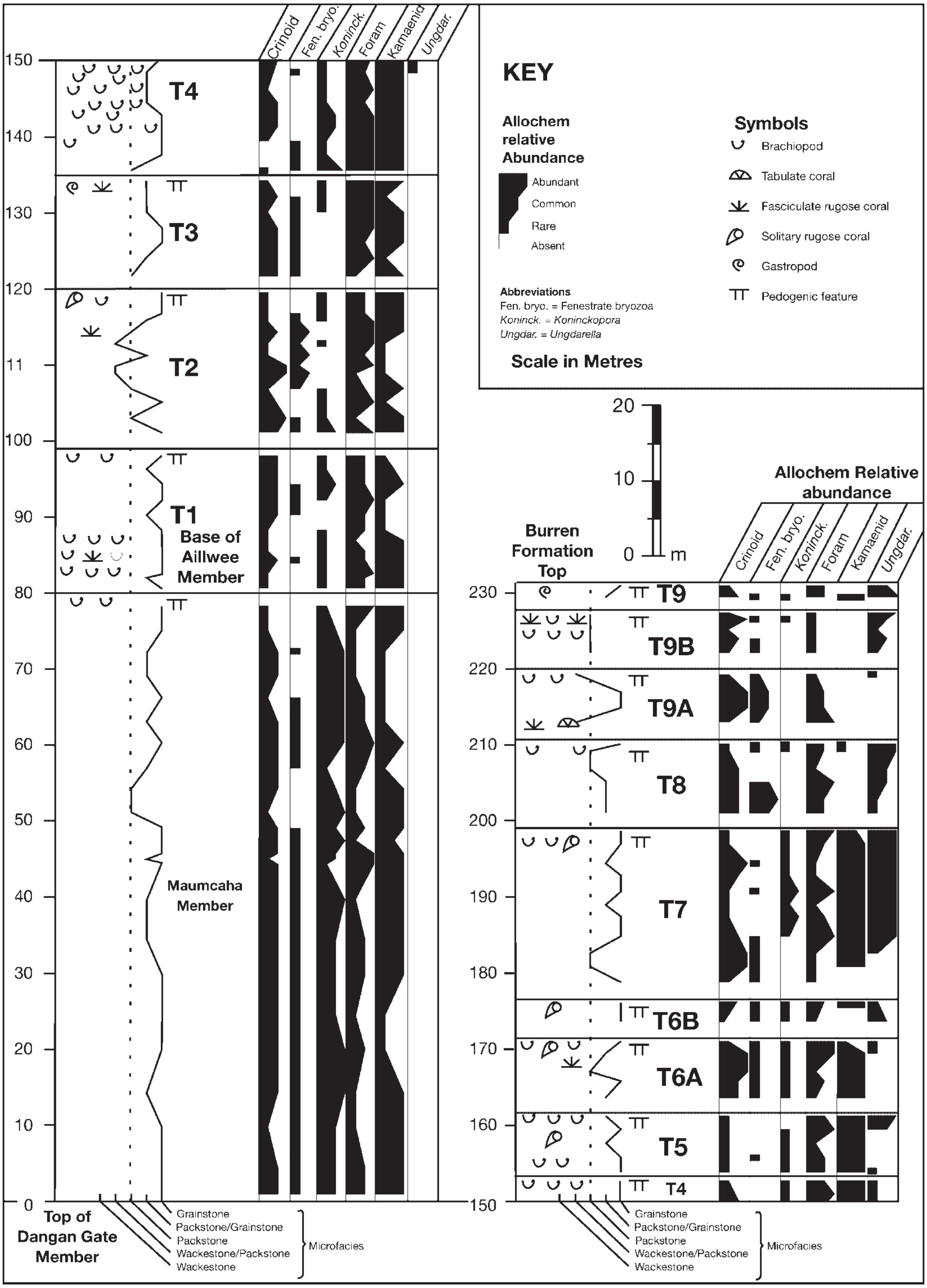


Figure 4. A log of the upper part of the Burren Formation in the northeast Aillwee Section. See Table 1 for allochemical abundance key.

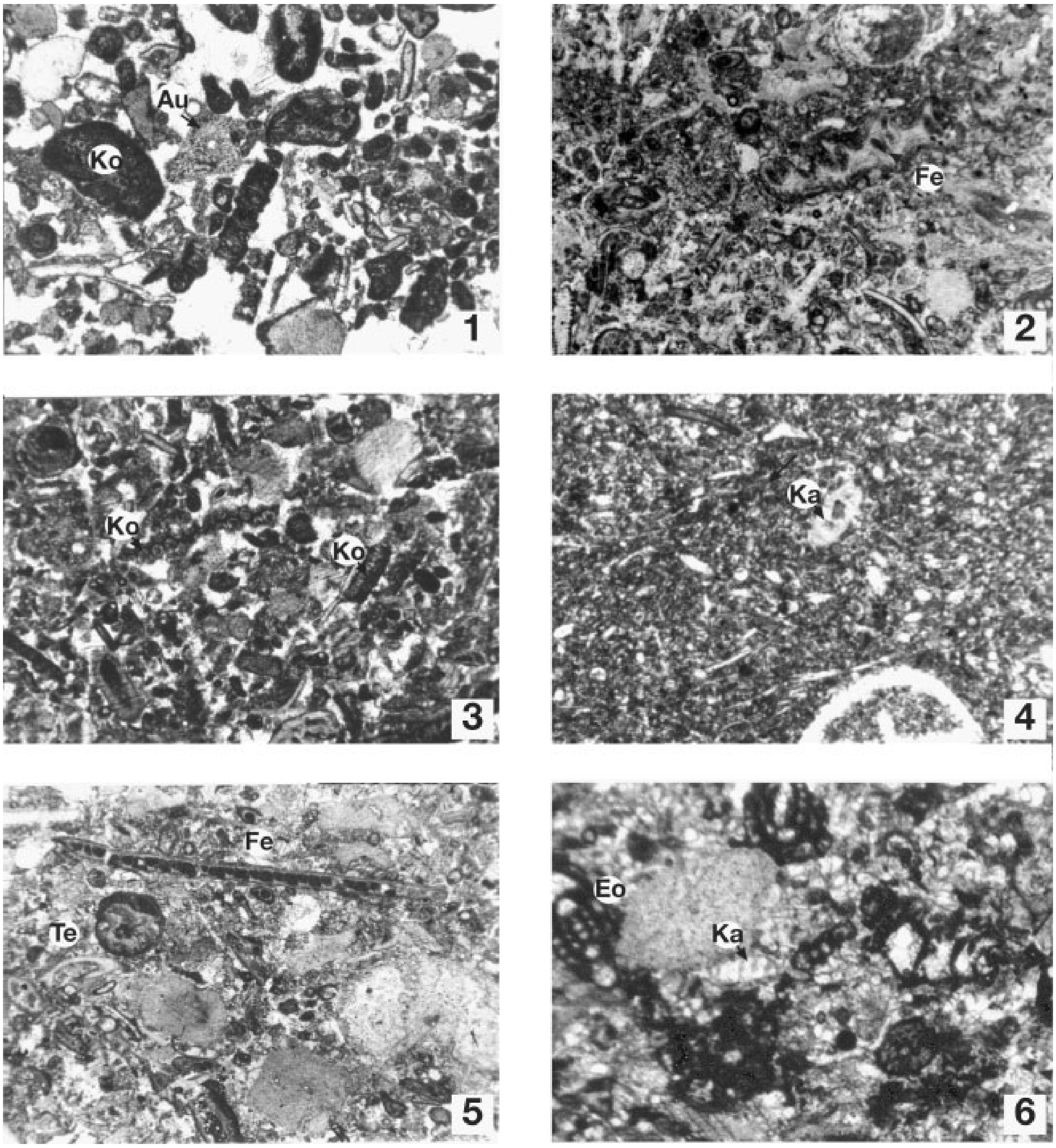


Figure 5. Microfacies of the Burren succession (all figures × 7). **(1)** Medium-grained, moderately well-sorted skeletal peloidal grainstone with micrite-coated bioclasts, e.g. aoujgaliids (Au) and *Koninckopora* (Ko). Black Head Member, lower Burren Formation, GSI No. 78-2929 log level 78.7 m, Black Head Section (Figures 1 and 3). **(2)** Fine-grained skeletal packstone with fenestrate bryozoans (Fe) and crinoids. Fanore Member, lower Burren Formation, GSI No. 79-1343, log level 136.4 m, Black Head Section (Figures 1 and 3). **(3)** Medium- to fine-grained peloidal packstone/grainstone with abundant *Koninckopora* (Ko). Dangan Gate Member, Lower Burren Formation, GSI No. 79-1558, log level 168 m (Figures 1 and 3). **(4)** Fine-grained spicule-rich wackestone, with bivalves and *Kamaenella* (Ka), Ballard Member, lower Burren Formation, GSI No. 80-0335 log level 50.2 m, Ballard Bridge Section (Figures 1 and 3). **(5)** Coarse-grained, crinoid-fenestrate, bryozoan-rich (Fe) packstone with *Tetrataxis* spp. (Te). Caherbullaun Member, Lower Burren Formation, GSI No. 80-0359, log level 77.6 m (Figures 1 and 3). **(6)** Fine-grained foraminiferan (Eo = *Eostaffella*) and *Kamaenella* (Ka) packstone to grainstone. Aillwee Member, upper Burren Formation, GSI No. 78-1573, log level 146.5 m in T4, northeast Aillwee Section (Figures 1 and 4).

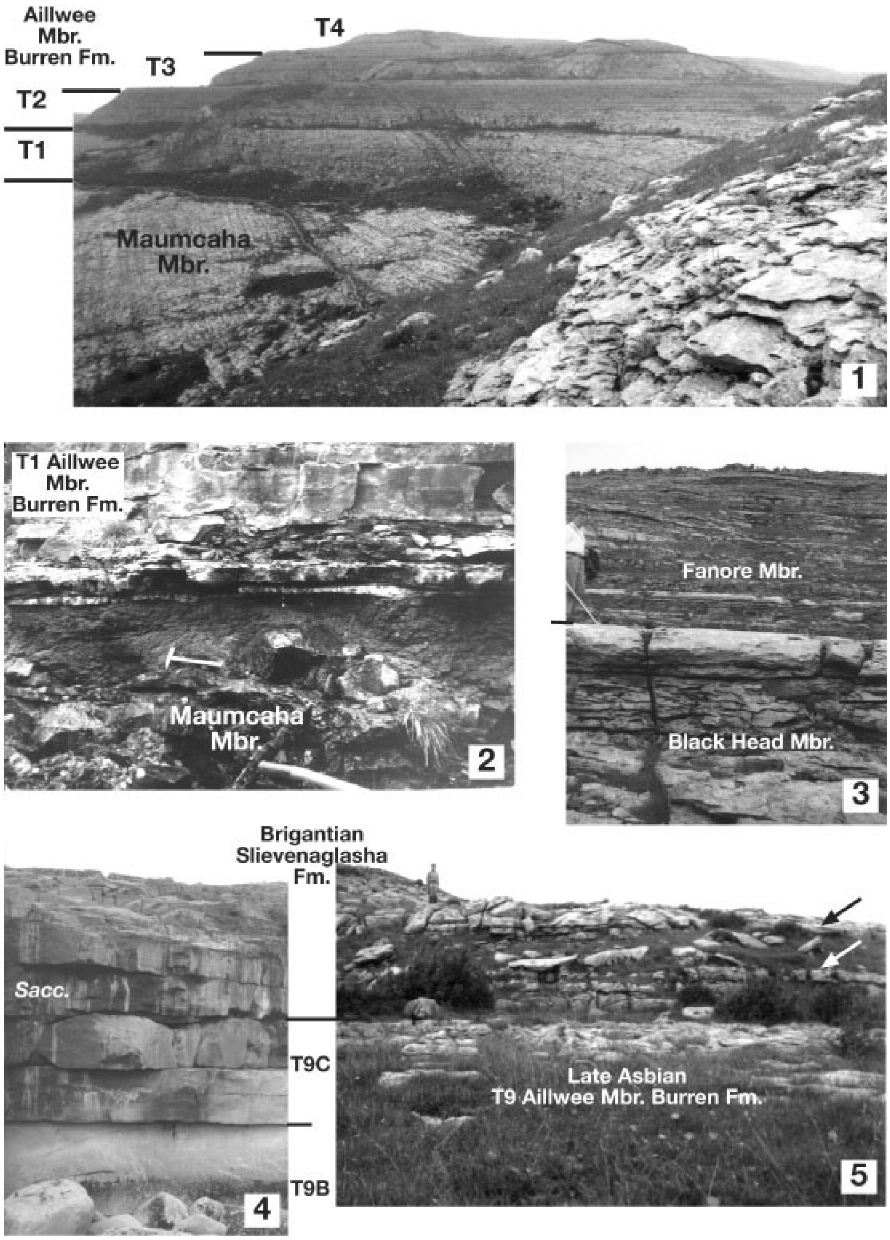


Figure 6. Outcrops in the Burren region. **(1)** The type section of the Aillwee Member and the contact with the Maumcaha Member (upper part of the Burren Formation) in the northeast Aillwee section (Figure 1). The first four minor cycles of the Aillwee Member (terraces T1 to T4) are indicated. T1 is approximately 20 m thick. **(2)** A palaeokarst surface and shale at the Maumcaha/Aillwee Member boundary in the northeast Aillwee section (Figure 1). The hammer is 0.4 m long. **(3)** The Black Head/Fanore Member boundary (lower part of the Burren Formation) in the Black Head type section (Figure 1). Note the laterally extensive dolomite unit defining the boundary. Scale: person is 1.78 m. **(4)** The Asbian/Brigantian boundary at locality 6 (Figure 1). The two upper cycles of the Burren Formation are shown T9B and T9C (3 m thick); the boundary is marked by an irregular palaeokarst surface. **(5)** The Asbian/Brigantian boundary in the Slievenaglasha section (Figure 1). The arrows indicate the position of the first two cycle boundaries in the Slievenaglasha Formation (Balliny Member) above the Burren Formation. Scale: person is 1.78 m.

sections (Figure 3). The microfacies consists of medium- to fine-grained, moderately to poorly sorted, skeletal peloidal packstone to grainstone. *Koninckopora*, crinoids, foraminiferans and fenestrate bryozoans (rare sheets occur) are present in most samples (Figures 3 and 5.3). The Dangan Gate Member was deposited in a shallow-water open-marine environment, similar to the Fanore Member.

Ballard Bridge Section

The lowest part of this section lies in the Tubber Formation (Figure 2). In the succeeding lower Burren Formation, five members can be distinguished (Gallagher 1992, 1996): the Turkenagh, Ballard, Caherbullaun, Ballyeighter and Aglish members (Figure 3b). These members, with a combined thickness of 135 m (Figure 2), were amalgamated into a single member (Hawkhill Member) by Pracht *et al.* (2004). The base of the Burren Formation in this section coincides with the first appearance of cerioid corals above a 1-m thick dolomite horizon (*c.* 1 m log level; 10 m above the base of the section; Figure 3b). The top of the Ballard Bridge Section is just above the dolomite marker bed, immediately below the Maumcaha Member of the upper Burren Formation. The Ballard Bridge Section is the lateral equivalent of the Black Head Section, although quite different in lithofacies (cf. Figure 3a, b). It comprises, generally, darker grey, slightly more dolomitized limestones, with more abundant bryozoans, sponge spicules and chert nodules. The transition between the two sections (30 km apart) is difficult to assess because of the lack of suitable exposure in the intervening area.

Turkenagh Member (26 m). The lower boundary of the Turkenagh Member sits on top of a dolomite horizon of the Tubber Formation below the first appearance of cerioid lithostrotionids (Figure 3b). The microfacies consist of bioturbated, medium- to coarse-grained, moderately to well-sorted, skeletal peloidal *Koninckopora* packstone to grainstone. Foraminiferans and crinoids are common, whereas fenestrate bryozoans are generally rare, except near the base (Figure 3). The Turkenagh Member was deposited in a shallow-water open-marine subtidal environment, above normal wave-base.

Ballard Member (34 m). The lower boundary of the Ballard Member is marked by the first thin-bedded limestone containing a horizon of irregularly shaped chert nodules at log level 34 m (Figure 3b). Cerioid lithostrotionids are present near the base. The lower 10 m of the member are characterized by fine-grained calcisphere-rich peloidal packstone to grainstone containing abundant foraminiferans with rare crinoids, fenestrate bryozoans and *Koninckopora*. The succeeding 12 m are fine-grained bioturbated, spicule-rich peloidal packstone to wackestone (Figure 5.4) with rare foraminiferans, fenestrate bryozoans and kamaenids. The upper 12 m are coarser-grained, skeletal peloidal packstone to wackestone with abundant fenestrate bryozoans (fragments and sheets) and crinoids, but foraminiferans are rare (Figure 3). The lower part of the Ballard Member was deposited in an open-marine, shallow-water subtidal environment (in the photic zone), above normal wave-base. Subsequently, lower energy, deeper water subtidal (below normal wave-base) conditions developed, inferred from the increase in the number of intact fenestellid sheets and absence of dasyclad algae.

Caherbullaun Member (25 m). The lower boundary of the Caherbullaun Member is defined by a laterally continuous silicified *Siphonodendron* horizon. Fasciculate and solitary (large caniniid) rugose corals are characteristic. The microfacies consists of medium- to coarse-grained, skeletal peloidal packstone to grainstone. The dominant bioclastic components are sheets of fenestrate bryozoans with common foraminiferans and crinoids (Figures 3b and 5.5). This microfacies is similar to the upper part of the Ballard Member, which is also marked by the absence of *Koninckopora*. Thus, a similar depositional environment to that for the Ballard Member is envisaged (see above).

Ballyeighter Member (32 m). The lower boundary of the mostly chert-free, grey, partly dolomitized limestone of the Ballyeighter Member is a chert horizon at log level 95.5 m. Fasciculate and cerioid colonies occur as well as solitary corals. The microfacies consist of packstone to grainstone which is similar to the Caherbullaun Member, although fenestrate bryozoans become rare in the upper 20 m (Figure 3b). The Ballyeighter Member was deposited in a similar depositional environment to the Ballard Member.

Aglish Member (18 m). A cherty dolomite marker bed at log level 127.5 m parallel to bedding is used to define the base of the Aglish Member. The upper boundary is a laterally continuous dolomite bed with chert nodules. The partly dolomitized cherty limestone of the member contains a sparse fauna of cerioid and fasciculate rugose corals.

The microfacies consists of medium- to coarse-grained, skeletal peloidal packstone to grainstone with common crinoids (Figure 3b). This member differs from other members in the Ballard Bridge Section since foraminiferans and fenestrate bryozoans (sheets and fragments) are rare, as is *Koninckopora*. The depositional environment of the Aglish Member is similar to that of the previous member. However, at the top of the member there must be a rapid shallowing event, to slightly higher energy, open-marine, subtidal conditions, as inferred from the abundance and diversity of calcareous algae at the base of the overlying Maumcaha Member (see below).

The northeast Aillwee Section

The northeast Aillwee Section of the upper Burren Formation is 232 m thick and can be subdivided into two stratigraphic units: the Maumcaha and Aillwee members (Figures 2 and 4).

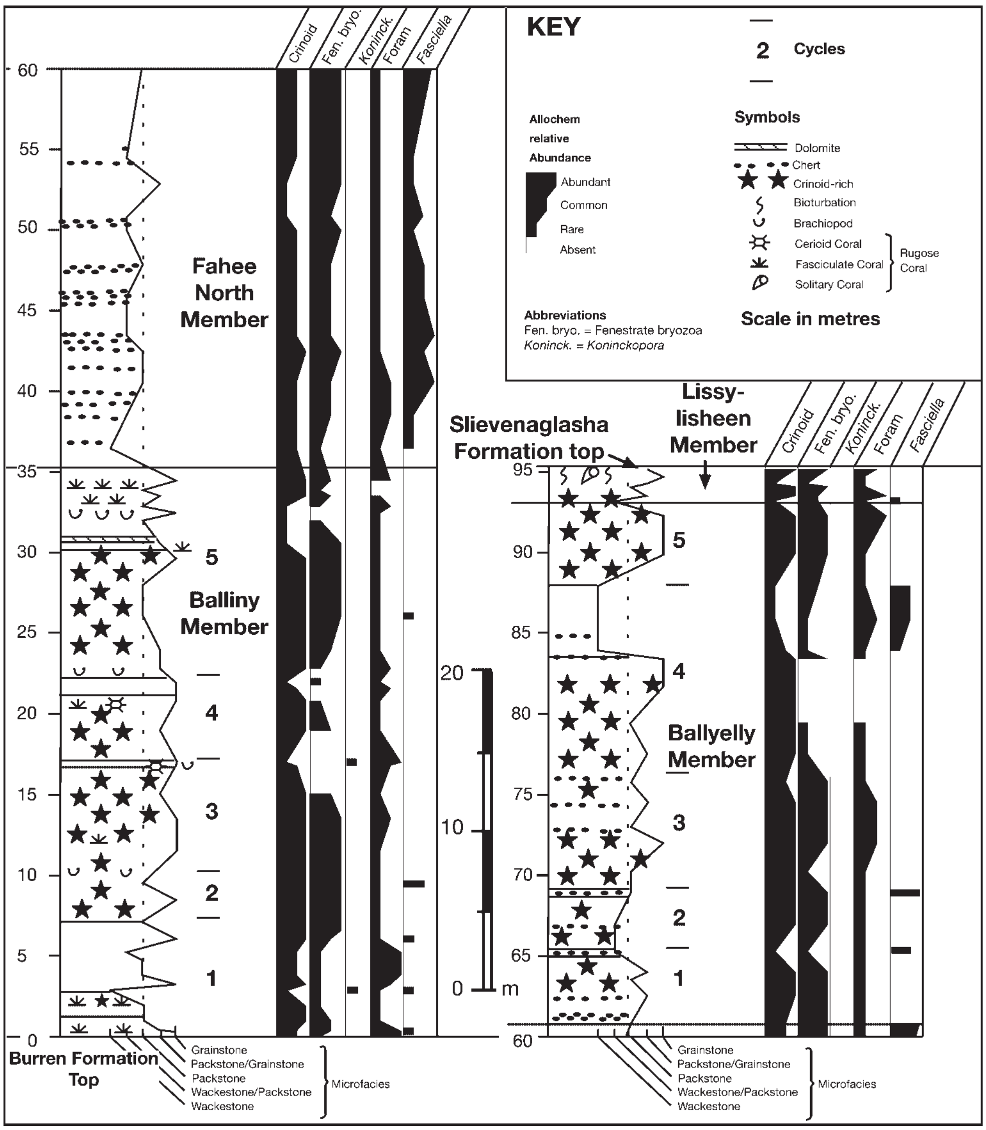


Figure 7. A log of the Slievenaglasha Formation. The boundaries between the members discussed in the text are indicated. See Table 1 for allochemical abundance key.

Maumcaha Member (80 m). The base of the massive limestone of the Maumcaha Member is placed above a thin, laterally continuous dolomite horizon. Macrofauna is rare except in the upper metre, with concentrations of brachiopods in bands, mostly concave-up, and in growth position. The microfacies comprises medium- to coarse-grained, skeletal peloidal packstone to grainstone with abundant *Koninckopora,* kamaenids *(Kamaena* and *Kamaenella)*, crinoids and foraminiferans (Figure 4). Fenestrate bryozoan fragments are rare or absent. The Maumcaha Member was deposited in a shallow marine subtidal environment, in the photic zone. The nearest modern analogue for this *Koninckopora*- and kamaenid-rich limestone is the *Halimeda* banks, off the coast of Florida (Aigner 1985) and behind the Great Barrier Reef in Australia (Tucker and Wright 1990).

Aillwee Member (152 m). The lower boundary of the Aillwee Member is marked by a palaeokarst surface (Figure 6.1 and 6.2) and by a change in slope topography from the undulating surface of the pale grey massive limestone of the underlying member to the terraced, well-bedded morphology of the Aillwee Member (Figure 6.1). The boundary can be observed also at Abbey Hill (Figure 1) and Ailladie on the coast (locality 1, Figure 1). At Ailladie two clay horizons (= clay wayboards of Walkden 1972) are present at the boundary, underlain by a surface, with pedotubules (Figure 8.1) and a diverse macrofauna including *Chaetetes, Lithostrotion, Syringopora* and brachiopods. Several distinct terraces (T1 to T9) can be distinguished in the Aillwee Member, each representing a minor cycle. Other cycles such as T9A, T9B, T9C, T6A and T6B do not form terraces and are defined on the presence of a laterally extensive bedding plane near their top. The cycles have a palaeokarst surface with pedotubules and/or clay horizon near their top. In addition to the karst features, the cycles comprise thick- to very thick-bedded (1–8 m) dark grey limestone, mostly devoid of macrofauna, but usually with an upper coral and/or brachiopod horizon (Figure 4). These brachiopods include gigantoproductids and linoproductids, with *Davidsonina septosa* from terrace T5. Fasciculate and solitary rugose corals (*Siphonodendron* and *Palaeosmilia murchisoni*) are present with sponges (*Chaetetes*) and gastropods in some of the horizons, especially in T9. Brachiopods are common in T4 and near the base of T1. The top of each cycle forms a bench in the landscape (Figure 6.1) due to the differential erosion of clay horizons and recent karst dissolution. The microfacies of the Aillwee Member have variable components: fenestrate bryozoans are present in the lower and middle of each cycle, but are often absent near the top (Figure 4). Rare *Koninckopora* occurs typically near the top of cycles. In the lower four cycles (T1—T4) *Kamaenella* is abundant (Figure 5.6). Above T4, the problematic red alga *Ungdarella* is present near the top of cycles, and absent near the base. Typically, a cycle comprises (T7 in Figure 4) packstone facies near the base or middle, and near the top, packstone to grainstone facies. There are also distinct and repetitive shifts in the relative abundance of components (including presence/absence) up through each cycle (Figure 4) (see details in Gallagher 1992, 1996, figure 3). These macro- and microfacies characteristics of the Aillwee Member are typical of shallowing-upward cycles in upper Asbian platform rocks (Horbury and Adams 1996; Gallagher 1996; Gallagher and Somerville 1997, 2003; Cózar and Somerville 2005a). The presence of calcareous algae near the top and base of cycles and their absence near the middle suggest the initial transgressive events were shallow subtidal in nature. Subsequently, deeper subtidal conditions developed where crinoids and fenestrate bryozoans are most common. Shallowing to higher energy subtidal conditions and eventual emergence with pedogenesis concluded cycle deposition.

2.3. *The Slievenaglasha Formation*

The lower boundary of this formation at its type section (the combined Clooncloose and Slievenaglasha sections) (Figures 1, 6.4, 6.5, 7) lies below a thick-bedded, cyclic, crinoidal limestone containing a 2 m-thick *Saccamminopsis* horizon, developed above the last cycle of the Aillwee Member of the Burren Formation (Gallagher 1992, 1996; Pracht *et al*. 2004). On the coast, the base of the Slievenaglasha Formation with the *Saccamminopsis* band is marked by a palaeokarst surface at the top of the underlying Burren Formation (locality 6, Figure 1; Figures 2 and 6.4). Micro- and macrofossil data indicate a Brigantian age for the Slievenaglasha Formation (see Section 3). The upper 1–2 m of this 95-m-thick formation are slightly younger, with a possible late Brigantian age (Sevastopulo and Wyse Jackson 2001; Pracht *et al*. 2004). This formation crops out in the southeastern part of the Burren region and on the coast at Doolin (locality 8, Figure 1). The Slievenaglasha Formation is characterized by

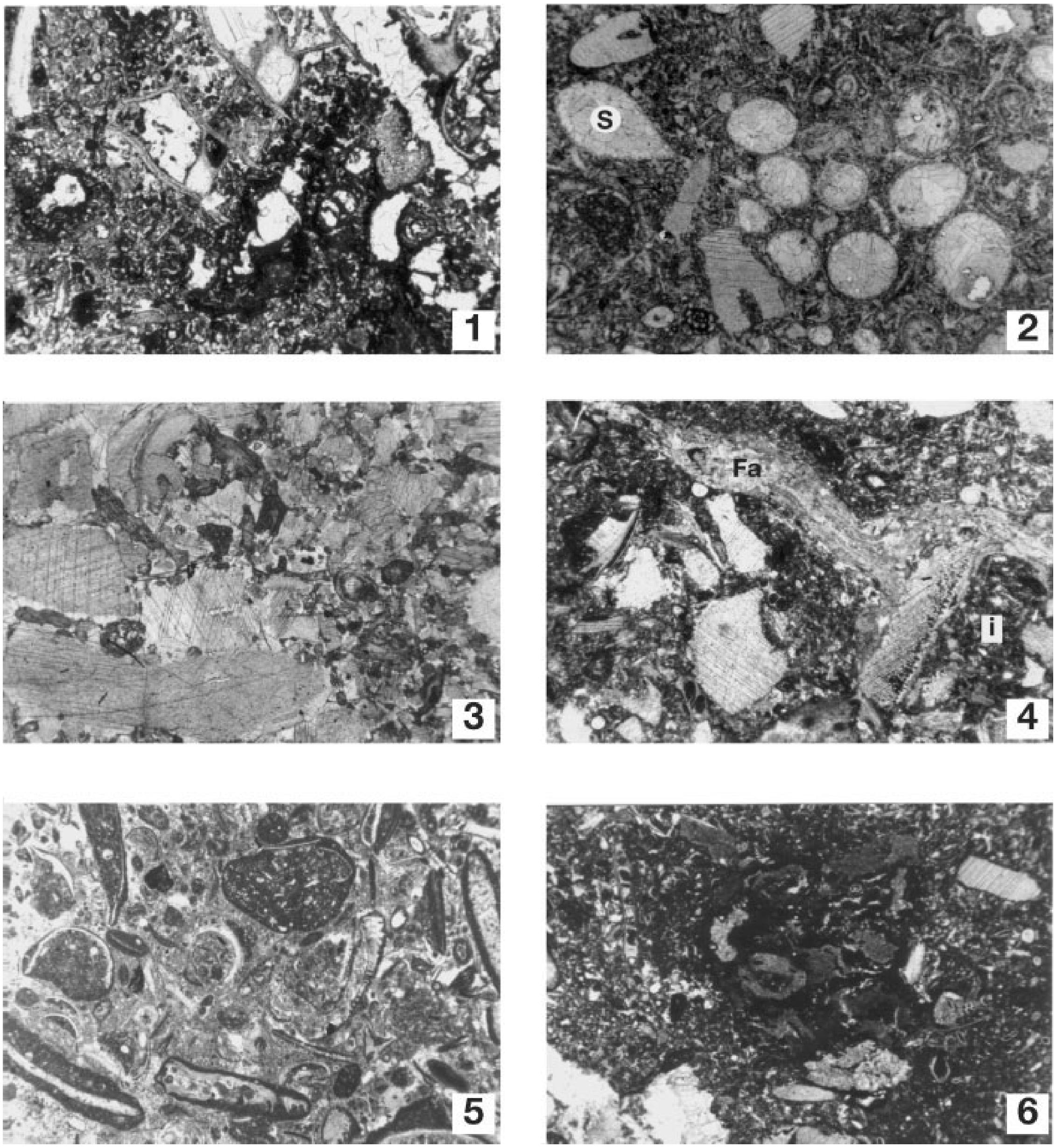


Figure 8. Microfacies of the Burren succession (all figures × 7). **(1)** Alveolar texture with calcified rootlets with micritic sheaths and septa in a fine-grained *Kamaenella* skeletal peloidal packstone/grainstone. Aillwee Member, upper Burren Formation, thin section No. 78-1545, log level 134.3 m, near the top of terrace T3, northeast Aillwee Section (Figures 1 and 4). **(2)** Fine-grained, spicule-rich, peloidal packstone/wackestone with abundant *Saccamminopsis* (S) and crinoids. *Saccamminopsis* band near the base of the Balliny Member, Slievenaglasha Formation, GSI No. 78-1558, log level 4.8 m (Figures 1 and 6). **(3)** Coarse-grained crinoidal grainstone, Balliny Member, Slievenaglasha Formation, GSI No. 78-1479, log level 11.4 m (Figures 1 and 7). **(4)** Fine-grained bryozoan and crinoidal wackestone/packstone, with large *Fasciella* (Fa) coating a crinoid and wackestone intraclast (i). Fahee North Member, Slievenaglasha Formation, GSI No. 79-1368, log level 42.4 m (Figures 1 and 6). **(5)** Intraclastic skeletal packstone, with rounded 'algal'-coated and micritized bioclasts. Lissylisheen Member, Slievenaglasha Formation GSI No. 78-2894, log level 94.3 m (Figures 1 and 7). **(6)** Alveolar pedogenic texture in a crinoid and fenestrate bryozoan-rich peloidal packstone/ wackestone. Lissylisheen Member, Slievenaglasha Formation, GSI No. 78-2891, log level 93.2 m (Figures 1 and 7).

Figure 9. A range chart of the macro- and microfossils in the Black Head Section of the lower part of the Burren Formation and Tubber Formation.

thick-bedded, pale grey crinoidal limestone that alternates with crinoid-poor limestone in its lower and upper parts. In the middle of the formation, bedded dark grey cherty limestone is common. Chert, however, is also present in the upper part. The Slievenaglasha Formation has been subdivided formally into four members (Pracht *et al*. 2004) (Figures 2, 7)—Balliny, Fahee North, Ballyelly and Lissylisheen members—that highlight the main differences in lithofacies described above. The Slievenaglasha Formation is overlain by a very thin unit (0.1–3 m) of phosphatic and cherty micrite and shale (the Magowna Formation) in south County Clare (Sleeman and Pracht 1999), but is not present in north County Clare, north of St. Brendan's Well/River Gowlaun section, near Lisdoonvarna (Pracht *et al*. 2004; Figure 1b, location 10).

Balliny Member (36 m)

This member is characterized by five cycles (ranging in thickness from 3 to 10 m, Figure 6.5) with each cycle comprising an alternation of thick-bedded crinoidal limestone and thin units of crinoid-poor limestone (Figure 7). The Balliny Member corresponds to Lithofacies Association 3 of Gallagher (1992, 1996) and Gallagher and Somerville (1997). Brachiopods and cerioid and fasciculate rugose corals are present near the top of cycles. The microfacies is variable including: fine- to medium-grained, *Saccamminopsis*-rich, skeletal peloidal packstone to wackestone (Figure 8.2) with rare fenestrate bryozoan fragments and common sponge spicules, and medium- to coarse-grained crinoidal and bryozoan packstone to grainstone (Figure 8.3). Foraminiferans and very rare *Koninckopora* together with rare bryozoans and crinoids are present in fine-grained peloidal grainstone near the top of cycles. The crinoidal limestones of the Balliny Member formed in a subtidal, open-marine environment, with thick layers of fenestrate bryozoans and crinoids accumulating *in situ*, and forming banks and sheets that were reworked and modified by bioturbation, current and storm processes (cf. Aigner 1985). The last process may have resulted in the concentration of crinoids at the base of graded beds settling from suspension after storm events. The facies at the top of cycles formed in shallow, open-marine, subtidal lagoonal conditions in the photic zone. The occasional wackestone facies near the top of cycles probably formed in sheltered areas in the lee of the crinoid/bryozoan bank facies. The cycles culminated in a shallow subtidal environment, but not in a subaerial environment, since no palaeokarstic features or pedogenic textures are found in the cycle top facies indicating emergence, similar to that for the underlying Burren Formation.

Fahee North Member (25 m)

Well-bedded, dark grey, bioturbated limestone with chert horizons is characteristic of the Fahee North Member that corresponds to Lithofacies Association 4 of Gallagher (1992, 1996) and Gallagher and Somerville (1997). The typical microfacies is a bioturbated, spicule-rich, intraclastic packstone to wackestone. Wackestone intraclasts (up to 100 μm in size) are partly coated with common *Fasciella*. This problematical alga also partly coats crinoids and bryozoans (Figure 8.4). Fenestrate bryozoans are common as sheets and fragments. Foraminiferans are rare. This facies is similar to the intraclastic microfacies described in the Brigantian successions elsewhere in southern Ireland by Gallagher (1992, 1996, 1997, 1998), Gallagher and Somerville (1997, 2003) and Cózar and Somerville (2005a, b, c). The chert-rich limestones of the Fahee North Member were deposited in a deep open-marine, subtidal environment, below normal wave-base, but above storm wave-base. A combination of bioturbation and intermittent storm events generated the wackestone intraclasts. These clasts were deposited partly buried and subsequently coated on the upper exposed surface by the problematic *Fasciella* alga (Gallagher 1998, figure 8.6). Similar encrustations by *Fasciella* in consortia with *Aphralysia* and *Girvanella* have been documented in oncoids (Cozar *et al*. 2003; Vachard *et al*. 2004).

Ballyelly Member (32 m)

Thick-bedded crinoidal limestone with chert horizons dominates the major parts of the five cycles in the Ballyelly Member. Thin intervals of crinoid-poor cherty limestone form the top of cycles, similar to those in the Balliny Member, except for the presence of chert. The Ballyelly Member corresponds to Lithofacies Association 5 of

Figure 10. A range chart of the macro- and microfossils in the Ballard Bridge Section of the lower part of the Burren Formation and Tubber Formation.

Figure 11. A range chart of the macro- and microfossils in the northeast Aillwee Section of the upper part of the Burren Formation.

Gallagher (1992, 1996) and Gallagher and Somerville (1997). Foraminiferans are rare in the fine- to medium-grained crinoidal packstone and grainstone facies of the Ballyelly Member where fenestrate bryozoan sheets and fragments are abundant. Fine-grained, spicule-rich, crinoid- and bryozoan-poor, peloidal packstone to wackestone facies is present near log level 65 m and between log levels 84 and 88 m (Figure 7). Wackestone intraclasts partly coated by *Fasciella* are common near the top of cycles. A low-energy, deeper water subtidal environment is

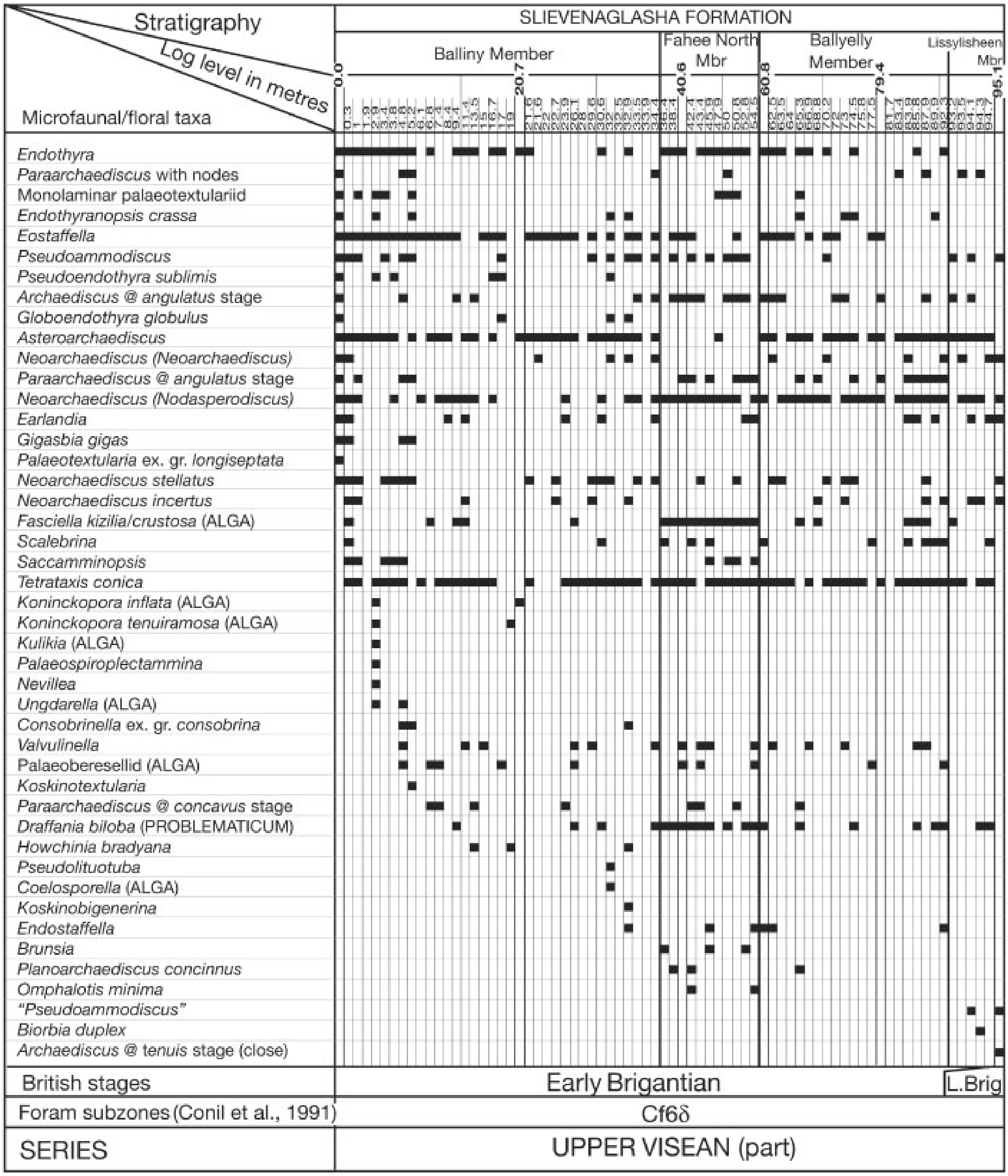


Figure 12. A range chart of the microfossils in the Slievenaglasha Formation. (L. Brig = Late Brigantian.)

suggested for the crinoidal microfacies of the Ballyelly Member. The top of the cycles terminated in lower energy, deep-water subtidal environments, similar to those of the Fahee North Member.

Lissylisheen Member (1–2 m)

This member at the top of the Slievenaglasha Formation is a bioturbated limestone with solitary rugose corals (*Cyathaxonia* and zaphrentids) and vertical pedotubules up to 600 μm long (Figure 8.6). The microfacies comprise

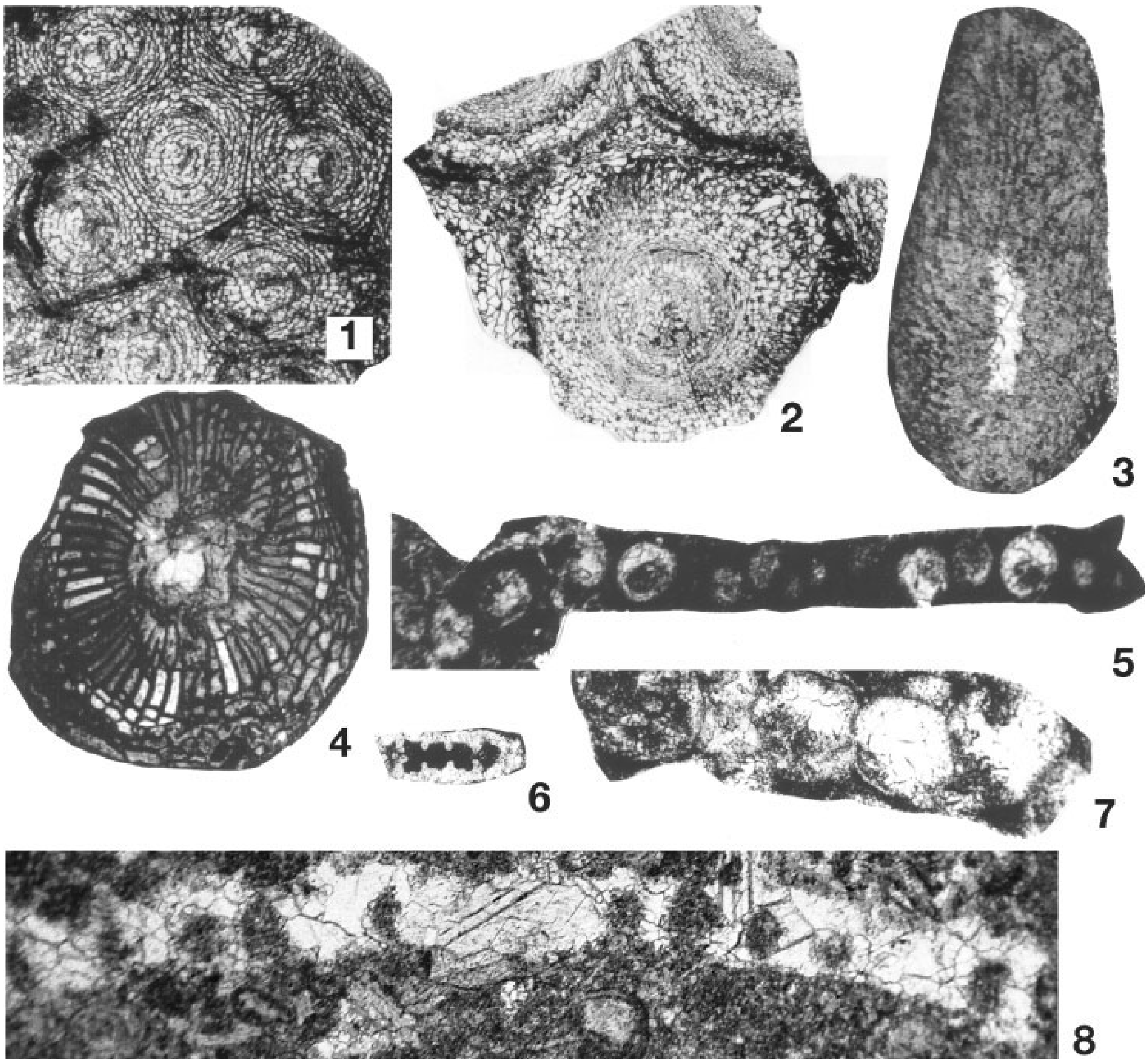
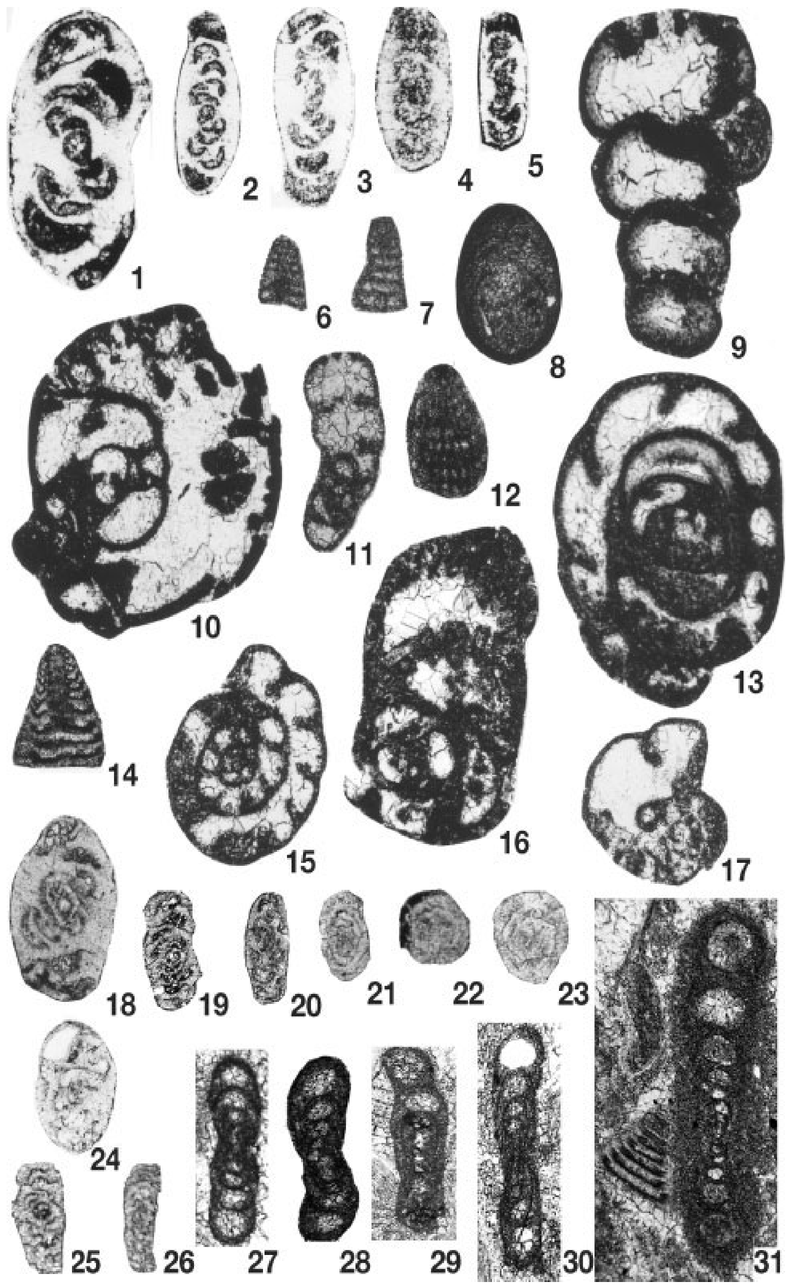


Figure 13. Corals and algae in the Burren succession (1, 2 and 4 are corals): **(1)** *Lithostrotion araneum* (M'Coy, 1849), (×2), GSI No. 91-4002, log level 34.6 m, Ballard Bridge Section, lower Burren Formation. **(2)** *Palastraea regia* (Phillips, 1836), (×1), GSI No. 91-4076, Location 7 (Figure 1), Slievenaglasha Formation. **(3)** *Ungdarella* spp. (×50), GSI No. 78-1545, log level 134.3 m northeast Aillwee Section, upper Burren Formation. **(4)** *Siphonophyllia samsonensis* (Salée, 1911), (×1), GSI No. 91-4001, log level 255 m, Ballard Bridge Section, lower Burren Formation. **(5)** *Koninckopora* sp. B (×50), GSI No. 78-1591, log level 201.1 m, northeast Aillwee Section, upper Burren Formation. **(6)** *Kamaena* spp. (×50), GSI No. 80-0342, log level 64.4 m, Ballard Bridge Section, lower Burren Formation. **(7)** *Koninckopora mortelmansi* (Mamet, 1973), (×50), GSI No. 78-2916, log level 53.8 m, Black Head Section, lower Burren Formation. **(8)** *Coelosporella jonesii* (Wood, 1940) (×40), GSI No. 78-1495, log level 32 m, Slievenaglasha Formation.

medium- to coarse-grained crinoid-rich intraclastic skeletal packstone (Figure 8.5) to grainstone, with interbeds of crinoid-poor peloidal wackestone. At this level, many of the bioclasts are bored and some have cryptalgal coats, and rare ooids are recorded at Vigo Cave (IGR R260 903), 15 km SE of Lisdoonvarna. Pedogenic alveolar textures (cf. Esteban and Klappa 1983) are seen in some of the samples (Figure 8.6). The Lissylisheen Member was deposited in a higher energy, shallow-water, subtidal open-marine environment with low sedimentation rate, which permitted the rolling and rounding of bioclasts and their intense boring, micritization and cyanobacterial encrustation. Subaerial exposure signified by pedogenic features terminated deposition of the Slievenaglasha Formation.



3. BIOSTRATIGRAPHY

The biostratigraphic data documented in this section from the upper Viséan rocks of the Burren region, are compared to the biostratigraphic frameworks in George *et al*. (1976), Conil *et al*. (1980), Fewtrell *et al*. (1981), Somerville and Strank (1984), Mitchell (1989), Conil *et al*. (1991), Jones and Somerville (1996), Gallagher (1996, 1997, 1998) and Gallagher and Somerville (1997, 2003). The foraminiferan zonation follows the Franco-Belgian zonation of Conil *et al*. (1980, 1991) with further refinements in Riley (1993), Jones and Somerville (1996), Cózar and Somerville (2004, 2005a) and Somerville and Cózar (2005). The rugose coral assemblage zones are those of Mitchell (1989) and Conil *et al*. (1991), with additions in Jones and Somerville (1996), and Rodríguez and Somerville (2005). The chronostratigraphic stages and divisions of the Carboniferous used here are those of George *et al*. (1976) and Gradstein *et al*. (2004). The macrofaunal data collected are shown in Figures 9, 10 and 11. The foraminiferan and algal data are shown in Figures 9, 10, 11 and 12. Selected coral and algal species are illustrated in Figure 13, and important foraminiferan taxa are illustrated in Figure 14.

3.1. Macrofauna

Previous macrofaunal studies

In the Burren, previous studies on corals and brachiopods were carried out by Douglas (1909), Clarke (1966a, b) and Nudds (1979), with palaeontological notes in George *et al*. (1976).

Douglas (1909) subdivided Vaughan's (1905) S (*Seminula*) Zone into the S_1 (Arundian) and the S_2 (Holkerian) subzones. The S_2 subzone was based mostly on the presence of *Nematophyllum minus* (= *Lithostrotion portlocki* or *L. vorticale*). He also subdivided the *Dibunophyllum* (D) Zone into the D_1, D_2 and D_3 subzones. The D_1 (Asbian) subzone was recognized based on the presence of *Dibunophyllum Ø* (= *Dibunophyllum bourtonense*), *Dibunophyllum muirheadi* (= *Dibunophyllum bipartitum*), *L. junceum* (= *Siphonodendron junceum*) and *Productus* aff. *giganteus* (= *Gigantoproductus* aff. *giganteus*). The D_2 and D_3 (Brigantian) subzones were based on the occurrence of *Lonsdaleia duplicata, Cyathophyllum regium* (= *Palastraea regia*) and *Caninia* aff. *cornucopiae,* associated with the brachiopods *Productus* (= *Gigantoproductus*) *giganteus* and *Cyrtina septosa* (= *Davidsonina septosa*). The latter species has, however, been regarded normally as being diagnostic of an upper D_1 (late Asbian) age (George *et al*. 1976; Somerville and Strank 1984; Riley 1993).

Clarke (1966a) studied the distribution of two *Aulina* species in the Burren succession. *Aulina hibernica* (= *Solenodendron hibernicum*) was found to first appear near the base of the D_1 subzone and *A. furcata* (= *Solenodendron furcatum*) above 'the *Davidsonina septosa* band' in the D_2 subzone. However, according to

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Figure 14. Foraminiferans in the Burren Formation (1–8, 10–12, 14, 16–18); foraminiferans in the Slievenaglasha Formation (9, 13, 15, 19–31): **(1)** *Paraarchaediscus@concavus* stage, (×90), GSI No. 80-0274, Ballard Bridge Section, log level 20.8 m. (2) *Paraarchaediscus* plus nodes, (×90), GSI No. 78-2943, Black Head Section, log level 107 m. **(3)** Archaediscid@*angulatus* stage, (×90), GSI No. 78-2919, Black Head Section, log level 59.8 m. **(4)** *Neoarchaediscus (Nodasperodiscus)* spp. (×90), GSI No. 80-0397, Black Head Section, log level 145.7 m. **(5)** *Paraarchaediscus* with nodes (×90), GSI No. 78-2869, Black Head Section, log level 13 m. **(6)** *Vissariotaxis* spp. (×50), GSI No. 78-1541, northeast Aillwee Section, log level 26.1 m. **(7)** *Vissariotaxis* spp. (×50), GSI No. 78-1543, northeast Aillwee Section, log level 130.1 m. **(8)** *Gigasbia gigas* Strank, 1983, (×50), GSI No. 79-1346, Black Head Section, log level 142 m. **(9)** *Cribrostomum lecomptei* (Conil and Lys, 1964) (×50), GSI No. 78-1527, northeast Aillwee Section, log level 101.2 m. **(10)** *Cribrospira panderi* (von Möller, 1878) (×50), GSI No. 78-2847. **(11)** *Haplophragmella* spp. (×50), GSI No. 78-1544, northeast Aillwee Section, log level 132.1 m. **(12)** *Valvulinella youngi* (Brady, 1876) (×50), GSI No. 79-1366, log level 43.4 m. **(13)** *Globoendothyra globulus* (Eichwald, 1860) (×50), GSI No. 78-1545, northeast Aillwee Section, log level 134.3 m. **(14)** *Howchinia bradyana* (Howchin, 1888) (×50), GSI No. 79-1366, log level 43.4 m. **(15)** *Endothyranopsis crassa* (Brady, 1876) (×50), GSI No. 80-0323, Ballard Bridge Section, log level 26.8 m. **(16)** *Nevillea dytica* (Conil and Lys, 1977) (×50), GSI No. 78-1590, northeast Aillwee Section, log level 198.8 m. **(17)** *Cribrospira* spp. (×50), GSI No. 78-1590, northeast Aillwee Section, log level 198.8 m. **(18)** *Neoarchaediscus (Nodasperodiscus) stellatus* (Bozorgnia, 1973) (×90), GSI No. 78-2898, log level 62.5 m. **(19)** Archaediscid approaching *tenuis* stage × 140, GSI No. 78-2896, log level 95.1 m. **(20)** *Paraarchaediscus* with nodes (×90), GSI No. 78-2892, log level 93.5 m. **(21, 22)** *Asteroarchaediscus baschkiricus* (Krestovnikov and Theodorovich, 1936) (×120), GSI No. 78-2896, log level 95.1 m. **(23)** *Asteroarchaediscus baschkiricus* (Krestovnikov and Theodorovich, 1936) (×120), GSI No. 78-2898, log level 62.5 m. **(24)** *Neoarchaediscus (Nodasperodiscus) stellatus* (Bozorgnia, 1973) (×90), GSI No. 78-1500, log level 34.4 m. **(25, 26)** *Neoarchaediscus incertus* (Grozdilova and Lebedeva, 1954) (×90), GSI No. 78-2896, log level 95.1 m. **(27, 28, 29, 30, 31)** *'Pseudoammodiscus'* spp. (×100), GSI No. 78-2896, log level 95.1 m.

Sevastopulo and MacDermot (1991), *Solenodendron furcatum* lies some distance below the first *D. septosa* band and first appears in the Fanore Member. Clarke (1966b) also noted the presence of *Orionastraea phillipsi* (indicating an upper D_2 age) in the upper Viséan succession. Nudds (1979) discussed the stratigraphic implications of *Orionastraea* in Ireland and he reassigned the *O. phillipsi* specimen collected by Clarke (1966b) to *O. rete* and accurately located its stratigraphic horizon close to the top of the Brigantian succession in the quarry north of Lisdoonvarna (Figure 1). Nudds (1979) suggested that not only is the Brigantian succession complete in the Burren, but the upper 6 m of strata in the quarry section and below the shales of the Namurian (Serpukhovian) Clare Shale Formation might represent a condensed Brigantian succession. In the Magowna Formation that directly and apparently conformably succeeds the Slievenaglasha Formation in the Magowna and Shallee areas northwest of Ennis, south County Clare, the basal Pendleian (Serpukhovian) ammonoid *Cravenoceras leion* (E_{1a} subzone) is recorded (Hodson and Lewarne 1961; Sleeman and Pracht 1999; Sevastopulo and Wyse Jackson 2001).

New macrofaunal data

The Tubber and Burren Formations. Lithostrotion araneum and *L. vorticale* both appear near the base of the Burren Formation in the Black Head Member of the Black Head section at log level 34.8 m (Figures 3, 9, 13.1). In the laterally equivalent Ballard Bridge Section, *L. araneum* first appears at the base of the Turkenagh Member at log level 10.8 m. These species are characteristic of and first appear in Rugose Coral Assemblage Zone E of Mitchell (1989) and Jones and Somerville (1996), of Holkerian age. In the Ballard Member *Siphonodendron pauciradiale* with *S. 'irregulare'* (*sensu* Poty 1981) first appear at log level 40.8 m (Figures 3, 10). These taxa are commonly used as Asbian (George *et al*. 1976; Nudds 1980) and RC6 Zone (Conil *et al*. 1991) indicators. Moreover, *Lithostrotion decipiens,* first recorded at log level 38.6 m, is indicative of an Early Asbian age, and is assigned to Rugose Coral Assemblage Zone F (Rodríguez and Somerville 2005). Higher in the Ballard Member *Siphonophyllia samsonensis* (= *S. benburbensis* auct.) is recorded at 55 m. This is followed by the first appearance of *Solenodendron furcatum* at log level 77.6 m in the Caherbullaun Member and *Siphonodendron intermedium* at the top of this member (Figure 10).

In the Black Head Section *Lithostrotion decipiens* is first recorded at log level 84.2 m, in the Black Head Member. *Solenodendron furcatum* first appears near the base of the Fanore Member at log level 114 m, *Siphonodendron intermedium* at 130.2 m and *S. pauciradiale* at log level 131 m (Figure 3). Thus, the upper part of the Tubber Formation and the lowest part of the Burren Formation are Holkerian in age, with the remaining part of the lower Burren Formation of Early Asbian age.

In the upper part of the Burren Formation, the following diagnostic brachiopod taxa first appear: the late upper Asbian *Davidsonina septosa* (George *et al*. 1976) first appears at log level 147 m in T4 (Figure 11), and *Gigantoproductus edelburgensis,* a Brigantian brachiopod (Pattison 1981), appears just below the top of the Burren Formation at log level 227.5 m. Rare late upper Asbian coral taxa collected include *Siphonodendron junceum* from T2 onwards. This indicates a probable RC7α (i.e. a late Asbian) age (Conil *et al*. 1991) for the Aillwee Member. Elsewhere, *S. junceum* is first recorded in the Dromdowney Member (Ballyclogh Formation) of north County Cork (Gallagher 1992; Gallagher and Somerville 1997), the Dromkeen Limestone Formation of east County Limerick (Somerville *et al.* 1992) and the upper Bricklieve Limestone Formation of northwest Ireland (Cózar *et al*. 2005). All these horizons are assigned to the Rugose Coral Assemblage G of Mitchell (1989), and Rodríguez and Somerville (2005) of late Asbian age.

The Slievenaglasha Formation. Near the base of the Slievenaglasha Formation (locality 7, Figure 1), the following rugose corals were collected: *Lithostrotion vorticale*, *Palastraea regia* (Figure 13.2), *Siphonodendron intermedium*, *S.* cf. *intermedium*, *S. 'irregulare'*, *S. junceum*, *S. martini* and *S. pauciradiale*. The first appearance of *Palastraea regia* near the base of the Slievenaglasha Formation confirms the Brigantian age for this formation. The Brigantian coral *Lonsdaleia* (*Actinocyathus) floriformis* (*sensu* Poty and Hecker 2003) is present in the lower half of the Slievenaglasha Formation. This species has also been recorded from the Slievenaglasha Formation on the Arann Islands (Somerville 1999). Both *P. regia* and *L.* (*A*)*. floriformis* are diagnostic species of Rugose Coral Assemblage H and I of early Brigantian age, whereas species of *Orionastraea* in the upper part of the formation are typical of Assemblages I–K of late Brigantian age (Mitchell 1989; Jones and Somerville 1996).

Microfossils

Previous microfossil studies

Prior to this work, published foraminiferan/algal studies in the Burren region have been limited. Austin *et al*. (1970) recorded a foraminiferan/conodont assemblage from a Viséan succession in south County Clare and north County Limerick (nearly 40 km to the south of the present study area) suggesting a V3bγ–V3c (latest Asbian to Brigantian) age and including the biostratigraphically important taxa *Cribrostomum* spp., *Howchinia bradyana, Neoarchaediscus incertus* and *Archaediscus* spp. Conil (1976) described foraminiferans from the Burren succession at Roadford (northwest County Clare; Figure 1) belonging to the V3bγ subzone (late Asbian). Taxa include *Lituotubella magna, Cribrostomum* sp. nov., *Archaediscus* aff. *karreri, Nodosoarchaediscus* spp. (*Paraarchaediscus* with nodes), *Nodasperodiscus* spp. (*Neoarchaediscus*) and *Plectogyranopsis* sp. nov. (*Latiendothyranopsis*). Other taxa from the upper part of the V3bγ subzone (latest Asbian/ to Brigantian) include *Haplophragmella fallax* (*Nevillella* (=*Nevillea*) *dytica,* the type locality for the species), *Eostaffella* spp., *Bradyina rotula* and *Cribrospira panderi*. Somerville and Strank (1984) noted that the calcareous algal genus *Koninckopora* had been found in the dark grey limestone above the Asbian/Brigantian boundary in the Burren. Sevastopulo and MacDermot (1991) recorded a band of *Girvanella* oncoids together with *Saccamminopsis* in the basal beds of the Slievenaglasha Formation.

Conodonts recorded from the uppermost limestone of the Slievenaglasha Formation and thin limestone beds in the overlying Magowna Formation in the Kilnamona area, 6 km NW of Ennis (Meischner *in* Skompski *et al*. 1995), have yielded *Lochriea cruciformis*, *L. ziegleri* and *L. senckenbergica*. These taxa elsewhere in Europe are recognized as markers for the Viséan/Namurian (Serpukhovian) boundary, and recently Nemyrovska (2005) has proposed that *L. ziegleri* be used to define the base of the Serpukhovian.

New microfossil data

Over 350 thin sections from the Burren succession stored in the GSI collection were examined as part of this study. The samples were collected at regularly spaced 1 to 2 m intervals, using the field logs of C. MacDermot. The foraminiferan taxonomy follows that of Vissarionova (1948), Loeblich and Tappan (1964, 1988), Hallet (1971), Conil *et al*. (1980), Fewtrell *et al*. (1981), Strank (1981, 1983), Nolan (1986), Brenckle *et al*. (1987) and Athersuch and Strank (1989). The calcareous algae and problematica were identified using Petryk and Mamet (1972), Rich (1974), Mamet and Roux (1974, 1975, 1976), Perret and Vachard (1977), Skompski (1981, 1984, 1986, 1996), Mamet (1991), Vachard *et al.* (2004), plus plates in Hallet (1971), Termier *et al.* (1977), Conil *et al.* (1980), Skompski *et al.* (1989), Adams *et al.* (1992), and Cózar and Somerville (2005a, b, c). Important taxa are shown in the logs (Figures 9–12).

The Tubber and Burren Formations. The majority of the foraminiferan and alga taxa in the Black Head Section are long-ranging Holkerian to Brigantian forms (Figure 9). However, in the Tubber Formation, the presence of *Paraarchaediscus* at *concavus* stage, *Paraarchaediscus* with nodes and monolaminar palaeotextulariids suggest a Cf5 Zone (Conil *et al.* 1991) Holkerian age. In the succeeding lower Burren Formation (Black Head Member), a richer and more diverse assemblage is recorded including the first occurrence of *Draffania biloba*, *Endothyranopsis crassa* and *Koninckopora mortelmansi*, also of Cf5 Zone Holkerian age. The first appearance of rare archaediscids at *angulatus* stage at log level 61.8 m, in the middle of the Black Head Member (Figure 9), may indicate the base of the early Asbian Cf6 α and β subzones (Conil *et al.* 1991).

However, in the Ballard Bridge Section, although many taxa typical of the Cf5 Zone are present in the Tubber Formation (e.g. *Paraarchaediscus* at *concavus* stage and monolaminar palaeotextulariids), they are accompanied by *Archaediscus* at *angulatus* stage, *Neoarchaediscus (Nodasperodiscus)* spp. and *Neoarchaediscus (Neoarchaediscus)* spp., confirming an early Asbian Cf6α and β subzonal age (Figure 10). The same taxa occur in the lower Burren Formation (Turkenagh and Ballard members) that shows a marked increase in diversity and abundance of taxa. Few biostratigraphically diagnostic microfossil taxa appear in the Maumcaha Member (Figure 11), that has a generally low diversity assemblage similar to that in the lower Burren Formation.

Undoubted late Asbian (Cf6γ subzone of Conil *et al.* 1991) microfossil taxa first appear near the base of the Aillwee Member in terrace T1 and lower T2, including *Palaeotextularia* ex. gr. *longiseptata, Plectostaffella* spp., *Koskinobigenerina* spp. (92.2 m), bilaminar palaeotextulariids (94.4 m), *Cribrostomum lecomptei* (101.2 m) and *Vissariotaxis compressa* (108.9 m). Other important forms in T4 include *Ungdarella* spp. (132.1 m) and *Haplophragmella* spp. (142.8 m), suggesting a lower late Asbian/Cf6γ1a subzonal age (Gallagher and Somerville 2003). In terraces T6–T7 endothyrids with cribrate apertures such as *Cribrospira* spp. (176.3 m) and *Nevillea* spp. (198.8 m) first occur, suggesting a middle late Asbian/middle Cf6γ1b subzonal age. In T8 significant first appearances include *Howchinia bradyana* and *Koninckopora* sp. B (201.1 m), *Neoarchaediscus (Nodasperodiscus) stellatus* (202.8 m) and in T9 *Saccamminopsis* spp. (213 m). These taxa indicate an upper late Asbian/upper Cf6γ2 subzonal age (Gallagher and Somerville 1997, 2003) for T8 and T9 of the northeast Aillwee section. Other important species recorded in T9 at locality 6 (Figure 1) are *Bradyina rotula*, *Cribrospira panderi* and *Cribrospira mira*, taxa typical of the upper part of the Late Asbian substage in the Burren. A similar assemblage has been recorded from the top of the Dromdowney Member (Ballyclogh Formation) in north County Cork (Gallagher 1992; Gallagher and Somerville 1997), and from the top of the Ballyadams Formation in County Carlow (Cózar and Somerville 2005a; Somerville and Cózar 2005).

Slievenaglasha Formation. The Brigantian Slievenaglasha Formation (Figure 12) lacks typical 'diagnostic' Brigantian foraminiferans such as *Warnantella, Loeblichia* and *Janischewskina,* although as demonstrated by Cózar and Somerville (2004) from the Brigantian stratotype section in northern England, these taxa are usually rare and in the case of *Janischewskina* do not first appear until the late Brigantian. The typical microfossil assemblages recorded in the Balliny Member include an increase in the abundance and diversity of large archaediscids (*Archaediscus* at *angulatus* stage), and stellate archaediscids (*Asteroarchaediscus* spp., *Neoarchaediscus* (*Neoarchaediscus*) spp., *Neoarchaediscus* (*Nodasperodiscus*) spp., *Neoarchaediscus* (*Nodasperodiscus*) *stellatus* and *Neoarchaediscus* (*Neoarchaediscus*) *incertus*). The member is also characterized by the last occurrence of *Koninckopora inflata* and *K. tenuiramosa, Ungdarella* spp. and rare *Kulikia* spp. It is also notable for the presence of *Fasciella crustosa* and *F. kizilia* coating wackestone intraclasts and bioclasts. A striking feature of this member (and younger members) is the local abundance of *Saccamminopsis* spp. (forming 'floods'). Other important elements of the assemblage are *Howchinia bradyana, Koskinobigenerina* spp., *Endostaffella* spp. and the rare dasyclad alga *Coelosporella.*

In the Fahee North Member are recorded abundant *Fasciella*, *Draffania* and *Saccamminopsis*, but foraminiferan are scarce (Figure 12). The Ballyelly Member has a similar composition and diversity to the Balliny Member, although algae are much sparser. The micro- and macrofaunal data confirm a Brigantian (Cf6δ) subzone age for this formation. Many of these taxa are also recorded from the Slievenaglasha Formation on the Arann Islands (Somerville 1999).

The microfossil assemblage in the Balliny Member is closely comparable with that recorded from units 3 and 4 of the Clogrenan Formation in the Carlow area (Cózar and Somerville 2005a, b; Somerville and Cózar 2005) and in the Templemary Member of the Liscarrol Formation of north County Cork (Gallagher and Somerville 1997), both of early Brigantian age. Particularly noteworthy is the similar rich abundance of *Neoarchaediscus*, *Asteroarchaediscus*, *Eostaffella*, *Pseudoammodiscus* and tetrataxids, and the presence of large *Archaediscus karreri* in all three formations. Another feature of all three formations is the local abundance of *Saccamminopsis* in thin discrete bands. This characteristic has been noted elsewhere in Brigantian rocks: in the Deer Park Formation in Kingscourt, County Meath (Strogen *et al.* 1995; Somerville 1999), in northern England (Hallet 1971; Cózar and Somerville 2004) and in Poland (Skompski 1986, 1996). Another interesting aspect of the Balliny Member is the rarity of the alga *Coelosporella,* which has a similar sparse development in the Carlow (Cózar and Somerville 2005a, b, c) and north Cork (Gallagher and Somerville 1997) areas. The absence of diagnostic late Brigantian indicators (e.g. *Loeblichia paraammonoides*, *Janischewskina typica*, *Climacammina* spp., *Endothyranopsis sphaerica* and the alga *Calcifolium okense*, see discussion in Cózar and Somerville 2004) in the Fahee North and Ballyelly members is unusual as most of these taxa are recorded in the coeval Clogrenan Formation at Carlow, in a similar cherty crinoidal limestone facies (Cózar and Somerville 2005a, b; Figure 15).

The Lissylisheen Member yields an unusual and important assemblage including *Asteroarchaediscus baschkiricus* and evolved archaediscids approaching *tenuis* stage. Other species at this level include evolved howchiniids and *'Pseudoammodiscus'* spp. (cf. Skompski *et al.* 1989). Skompski *et al.* (1989) reported *'Pseudoammodiscus'*

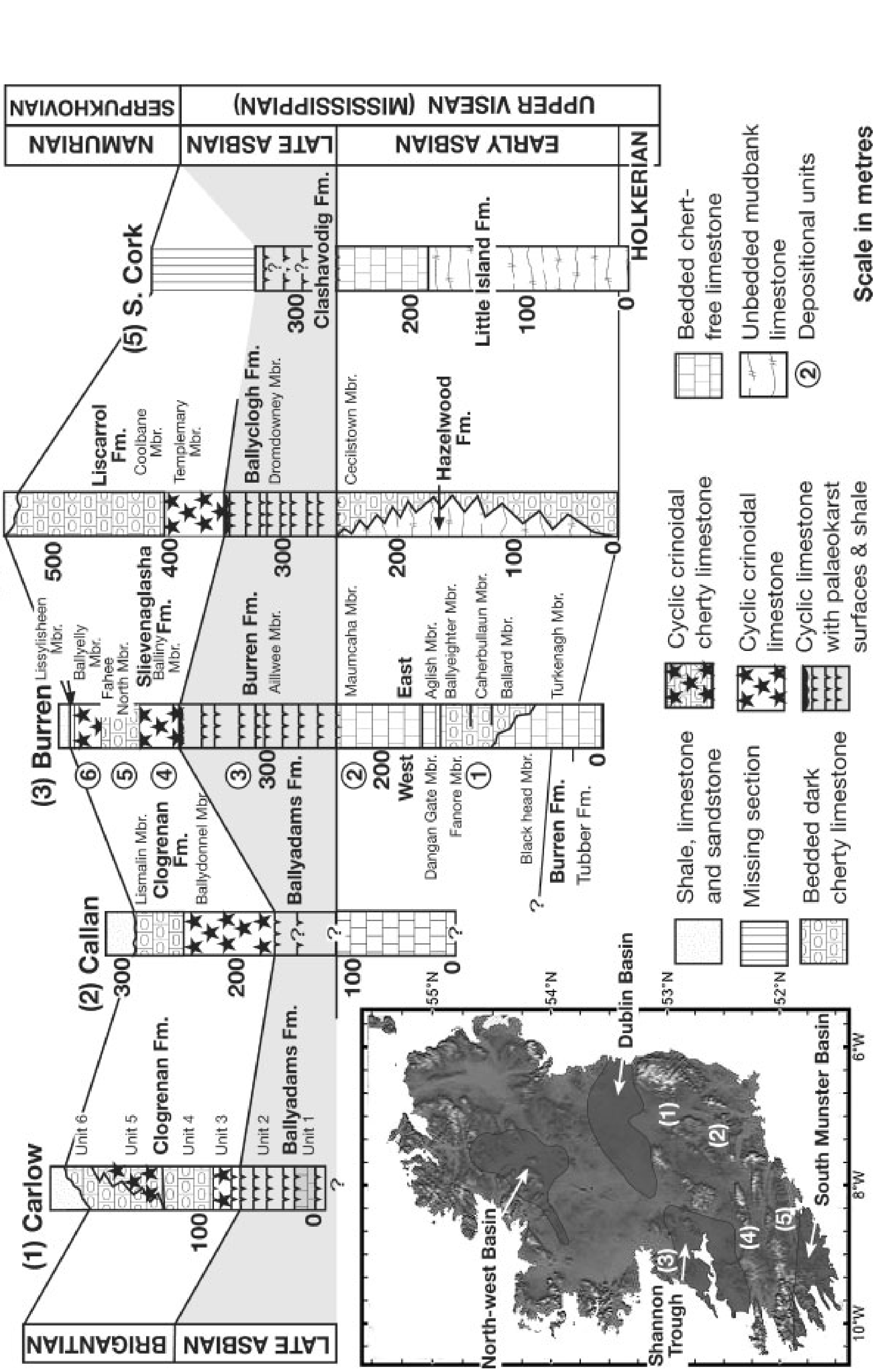

Figure 15. A stratigraphic correlation of the Upper Viséan Burren succession with other platform carbonates in southern and western Ireland. The inset map shows the position of the intraplatform troughs and basins.

spp. in a limestone of Cf7 (Namurian = Serpukhovian) age in Poland. Archaediscids at *tenuis* stage are important in early Namurian (Serpukhovian) times in Great Britain (Fewtrell *et al.* 1981). The data suggest that the upper 1–2 m of the Slievenaglasha Formation in the Burren may have a late Brigantian (Cf6δ) subzonal age.

In summary, more precise age determinations have been achieved based on the new micropalaeontological data. In the Black Head Section the Tubber Formation contains Cf5 Zone taxa of Holkerian age. Similar taxa also occur in the lower part of the Burren Formation (Black Head Member). Diagnostic Cf6 Zone taxa such as *Neoarchaediscus* and *Vissariotaxis* are very sparse to absent in this section. Archaediscids at angulatus stage in the middle of the Black Head Member suggest a possible early Asbian (Cf6α–β subzonal) age. However, in the Ballard Bridge section a diagnostic Asbian age is recorded at the very top of the Tubber Formation with the presence of *Archaediscus* at *angulatus* stage and *Neoarchaediscus*. Taxa of the Cf6 subzone of late Asbian age including *Cribrostomum lecomptei* and *Koskinobigenerina* are recorded near the base of the Aillwee Member of the Burren Formation (T1 and T2). Uppermost Asbian taxa are recorded in T8 including *Bradyina rotula*, *Howchinia bradyana*, *Asteroarchaediscus* and *Koninckopora* sp. B. Some of these taxa also occur in the Slievenaglasha Formation (of Cf6δ subzone, early Brigantian age), except that *Asteroarchaediscus* is now very common and new algae such as *Coelosporella* and *Fasciella crustosa* are recorded. The Lissylisheen Member at the top of the Slievenaglasha Formation contains evolved archaediscids and howchiniids characteristic of a youngest Brigantian age.

4. BURREN PALAEOGEOGRAPHY AND SOUTHERN IRELAND PLATFORM DEVELOPMENT

The Burren succession forms the westerly part of an upper Viséan platform sequence that can be correlated across southern Ireland (Figure 15). The platform is bound in the south by the Munster Basin and contains three tectonically controlled intra-platform basins: the Dublin Basin, the Shannon Trough and the North-West Basin (Figure 15). The Holkerian and early Asbian lithofacies is most variable and represents a regional south-dipping rimmed platform/ramp (Gallagher and Somerville 2003). Cyclicity is absent in this part of the sequence where cherty and non-cherty limestones are laterally equivalent to mudbank complexes. Cyclic sedimentation became prevalent during late Asbian times, when a progradational non-rimmed carbonate platform developed across much of southern and western Ireland (Gallagher and Somerville 2003). The palaeokarsts that cap the minor cycles of the Aillwee Member in the Burren are similar to those in the Ballyadams, Ballyclogh and Clashavodig formations (Gallagher 1996; Cózar and Somerville 2005a). The fourth-order upper Asbian cyclicity in southern Ireland is typical of carbonate successions elsewhere in Britain (Ramsbottom 1973; Somerville 1979; Walkden 1987) suggesting a possible glacio-eustatic control on their formation (see summary in Wright and Vanstone 2001). The cyclic sedimentation continued into the Brigantian, although few of these cycles shallowed sufficiently to lead to the establishment of subaerial conditions and palaeokarstic development in the Burren. However, Cózar and Somerville (2005a) describe palaeokarst surfaces in the Carlow area at the top of minor cycles in the Brigantian. Platform-wide deepening during the Brigantian caused deeper shelf subtidal chert-rich limestone to be deposited across Ireland. Most of the Brigantian strata in Ireland are unconformably overlain by Serpukhovian deltaic siliciclastics that eroded down to the cherty limestone facies (Figure 15). However, in the Burren succession there is an upper cyclic crinoidal unit (Ballyelly Member) in the Slievenaglasha Formation, equivalent to unit 5 in the Clogrenan Formation in the Carlow region (Cózar and Somerville 2005a). The presence of this upper Brigantian deeper subtidal cyclic facies across Ireland suggests the continuation of the glacio-eustatic control on cycle development. However, the very top of the Slievenaglasha Formation (Lissylisheen Member) suggests a rapid shallowing event associated with reduced subsidence, as indicated by the presence of pedogenic structures and ooids. Also, there appears to be evidence of very low sedimentation rates with little siliciclastic input. This is suggested by the presence of bored, rolled and 'algal' encrusted skeletal fragments, as well as the presence of phosphatic coatings to bioclasts on the top limestone surface and pebbly phosphate in the overlying basal shale (Hodson 1954; Hodson and Lewarne 1961). Nevertheless, the predominantly transgressive nature of the Asbian to Brigantian transition in much of southern and western Ireland is probably related to increased platform subsidence during this time (see Ramsbottom 1979) overprinting minor cycle development.

5. DEPOSITIONAL SEQUENCES AND CONCLUSIONS

The lithofacies, microfacies, biostratigraphy and depositional setting of the upper Viséan (Mississippian) platform carbonates of the Burren are described in detail for the first time. The Burren Formation is assigned to the Holkerian and Asbian stages and the Slievenaglasha Formation to the Brigantian Stage. In the lower part of the Burren Formation in the Black Head Section (NW Burren), the Black Head, Fanore and Dangan Gate members are laterally equivalent to the Turkenagh, Ballard, Caherbullaun, Ballyeighter and Aglish members in the Ballard Bridge Section (SE Burren). The upper part of the Burren Formation includes the Maumcaha and Aillwee members. The Slievenaglasha Formation is divided into the Balliny, Fahee North, Ballyelly and Lissylisheen members. In south County Clare the thin Magowna Formation is interposed between the Slievenaglasha Formation and the overlying Clare Shale Formation, but north of Lisdoonvarna the latter rests directly on the Slievenaglasha Formation.

The upper Viséan (Holkerian to Brigantian) succession in the Burren area can be subdivided in to six depositional intervals (Figures 2 and 15).

(1) *A Holkerian to lower Asbian Tubber and lower Burren formations bedded carbonate succession*. The *Koninckopora*-rich skeletal peloidal limestone facies at the top of the Tubber Formation and in the lower Burren Formation in the Black Head Section were deposited mostly in above-normal-wave-base subtidal, open marine conditions. The bryozoan-rich limestone facies of the equivalent strata in the Ballard Bridge Section were deposited below normal wave-base in open marine, quieter water conditions.

(2) *Lower Asbian Maumcaha Member massive shallow-water carbonate facies*. The light grey massive *Koninckopora*-rich limestone of the Maumcaha Member was deposited in a subtidal, above normal wave-base environment. This unit represents the shallowest water facies of the rimmed carbonate platform/ramp in Ireland during early Asbian time (cf. Gallagher and Somerville 2003).

(3) *Upper Asbian Aillwee Member cyclic carbonates*. The poorly bedded dark grey limestones of the Aillwee Member form topographically distinctive terraces. Most of the terraces represent a minor cycle capped by a shell horizon and palaeokarst with or without a palaeosol (clay wayboard). The foraminiferan and *Kamaenella*-rich packstone to grainstone facies of these cycles were deposited in predominantly shallow subtidal conditions. Shallowing upwards near the top of each cycle is suggested by the presence of the dasycladacean alga *Koninckopora* and the probable red alga *Ungdarella* prior to karst development. The Aillwee Member is similar to other cyclic upper Asbian units across southern Ireland (Figure 15) and elsewhere in Britain and Europe, suggesting a glacio-eustatic control on minor fourth-order cycle formation.

(4) *Lower Brigantian Balliny Member cyclic crinoidal facies*. By early Brigantian time, the *Kamaenella* spp. and ungdarellid-dominated shallow subtidal facies of the late Asbian were replaced by laterally extensive subtidal crinoid and bryozoan meadows. Metre-scale shallowing-upward cycles of deeper subtidal crinoidal/bryozoan packstone to grainstone and fine-grained shallower subtidal ‘lagoonal’ peloidal grainstone or wackestone with coral thickets are typical. Unlike the upper Asbian succession these Brigantian cycles do not show palaeokarst features and reached shallow subtidal depths prior to the next transgressive event. This change in sedimentation style is typical of other Brigantian successions in Ireland, suggesting a regional transgressive deepening episode and pronounced subsidence overprinting cycle development. However, karst development continued above the Asbian/Brigantian boundary in the Carlow region (Figure 15; Cózar and Somerville 2005a) suggesting local platform variability, such as differences in subsidence rates, producing increases and decreases in net accommodation space.

(5) *Brigantian Fahee North Member cherty dark limestone facies*. The continuance of Brigantian transgressive conditions deposited bioturbated crinoidal, bryozoan and *Fasciella*-rich packstone to wackestone with chert horizons, in deeper shelf subtidal conditions below normal wave-base. This bedded, dark cherty limestone facies is laterally extensive in southern Ireland (Figure 15) and represents the maximum transgressive conditions, probably accompanied by an increase in subsidence rate.

(6) *Brigantian Ballyelly Member cherty crinoidal limestone facies and Lissylisheen Member*. Cyclic alternations of subtidal cherty crinoidal packstone and grainstone alternate with cherty wackestone facies. This facies shows continued deepening from the base to the upper part of the Brigantian. However, the uppermost unit (the Lissylisheen Member) shows a rare upper Brigantian microfauna, and evidence for rapid shallowing. Equivalents of this

unit crop out in the Carlow area (Figure 15; Cózar and Somerville 2005a). This unit is mostly absent elsewhere in Ireland since it was truncated by Serpukhovian deltaic siliciclastics. The widespread evidence of cyclicity and deeper marine conditions during Brigantian time in Ireland suggests platform subsidence has overprinted the glacio-eustatic effects on the cyclicity, establishing more stable sedimentation patterns.

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APPENDIX

The grid references of the locations and sections referred to in the text and on Figure 1. The IGR (Irish Grid Reference) is given.

Location	Nature of locality	Grid reference
1	Ailladie-Maumcaha/T1 boundary	M0900 0313
2	Near Poulsallagh–Asbian coral locality	M0863 0263
3	Asbian/Brigantian boundary	M3038 0075
4	Terraces in scarp exposure	M3375 0250
5	Upper Slievenaglasha Formation	R2000 9938
6	Section from T8 to Asbian/Brigantian boundary	R0588 9788
7	Brigantian coral locality	M3075 0150
8	Upper Slievenaglasha Formation	R0569 0150
9	Roadside Quarry, Upper Slievenaglasha Formation	R1540 9950
10	St. Brendan's Well/Gowlaun River section, contact of Slievenaglasha Formation and Magowna Formation	R1450 9850
Section	**Name of Section**	
1	Black Head Section (base)	M1532 1215
2	Ballard Bridge Section (base)	R3291 9177
3	northeast Aillwee Section (base)	M2481 0658
4	Slievenaglasha Section (base) and Clooncloose Section (base)	R3126 9835 R2835 9506

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