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LOWER CARBONIFEROUS (LATE VISÉAN) PLATFORM DEVELOPMENT AND CYCLICITY IN SOUTHERN IRELAND: FORAMINIFERAL BIOFACIES AND LITHOFACIES EVIDENCE

STEPHEN J. GALLAGHER* & IAN D. SOMERVILLE**

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Abstract. The stratigraphy of several well exposed late Viséan carbonate successions in southern Ireland have been correlated using high resolution foraminiferal/algal biostratigraphy and detailed biofacies analysis. This study has revealed that during the lower late Viséan (early Asbian) time platform mudbank and intrabank facies were deposited on a rimmed ramp that dipped southward. By upper late Viséan (late Asbian to Brigantian) time, well bedded carbonates were deposited on a shallow, unrimmed platform expanse that prograded southward through a series of shallowing-upward minor cycles.

Within the late Asbian successions numerous minor cycles (2-15 m thick) occur that contain distinctive lithofacies and three distinct foraminiferal biofacies. The top of these cycles can usually be identified by palaeokarst surfaces with relief of to 0.5 m associated with pedogenic features and fissures indicating initial palaeocave-forming processes. Deposits on these emergent boundary surfaces include thick palaeosols (up to 1 m thick) and eroded boulders of the underlying karst surfaces. The lower transgressive facies of each minor cycle often began with the deposition of shallow-water, subtidal, algal-rich limestone containing diverse foraminiferal biofacies (Biofacies type 2). New foraminiferal taxa may appear in this part of the cycle. Towards the middle part of each cycle deeper water, subtidal, foraminiferal biofacies occur, but with no significant first appearance data. The biofacies at this level in the cycle are often algal-poor limestone rich in bryozoans or crinoids (Biofacies type 1). Biostratigraphically important foraminiferal taxa often first appear or reappear in low diversity assemblages toward the top of most cycles in shallower water grainstone microfacies (Biofacies type 3) rich in dasycladacean algae.

Riassunto. Sezioni di rocce carbonatiche di età tardo viseana, numerose e ben esposte, sono state correlate con biostratigrafia ad alta risoluzione mediante foraminiferi ed alghe ed una dettagliata analisi delle biofacies. Questo studio ha messo in evidenza che durante la prima parte del Viseano superiore (Asbiano inferiore) banchi ricchi in fango carbonatico e facies intrabanco venivano deposti su una rampa bordata da un margine, che immergeva verso sud. Con la parte alta del Viseano superiore (Asbiano superiore e Brigantiano) carbonati ben stratificati venivano deposti su una piattaforma poco profonda e senza margine, che progradava verso sud, mediante una serie di cicli minori di tipo shallowing-upward.

A partire dalle successioni dell'Asbiano superiore compaiono numerosi cicli minori (spessi 2-15 m) che contengono litofacies distinte e tre diverse biofacies a foraminiferi. La sommità di questi cicli può solitamente venir individuata mediante superfici paleocarsiche, con rilievo sino a 0.5 m, associate con elementi pedogenetici e fessure che indicano l'inizio della formazione di cavità. I sedimenti su queste superfici emerse, che funzionano come limite del ciclo, includono paleosuoli spessi sino a 1 m e blocchi erosi dalla sottostante superficie carsificata. La facies basale trasgressiva di ogni ciclo minore spesso inizia con la deposizione di calcari di acque basse, subtidali, ricchi in alghe che contengono diverse biofacies a foraminiferi (Biofacies di tipo 2). Nuovi taxa di foraminiferi possono comparire in questa parte del ciclo. Nella parte centrale di ciascun ciclo si ritrovano biofacies a foraminiferi di acque più profonde, subtidali, ma senza significative nuove comparse. Le biofacies di questa parte del ciclo sono spesso calcari poveri in alghe, ma ricchi in briozoi o crinoidi (Biofacies di tipo 1). Foraminiferi biostratigraficamente significativi spesso appaiono o ricompaiono nelle associazioni a bassa diversità verso la sommità del ciclo, nell'ambito di microfacies di grainstone di acque basse (Biofacies di tipo 3) nuovamente ricche in alghe dasycladacee.

Introduction

A thick sequence of tropical carbonates was deposited on an extensive shallow marine platform during the late Viséan in southern Ireland (Gallagher 1996). Three contrasting limestone units occur within this late Viséan succession: (i) an early Asbian mudbank/bedded sequence, (ii) a late Asbian cyclic, well-bedded unit and (iii) a Brigantian crinoidal/cherty platform unit (Fig. 1; Gallagher 1996). Sedimentation during the late Viséan time was controlled by periodic transgressions and regressions punctuated by emergent periods, caused by glacio-eustacy (Wright & Vanstone 2001). The late Asbian to Brigantian

*School of Earth Sciences, University of Melbourne, Victoria 3010, Australia. E-mail: sjgall@unimelb.edu.au
**Department of Geology, University College Dublin, Belfield, Dublin 4, Ireland.

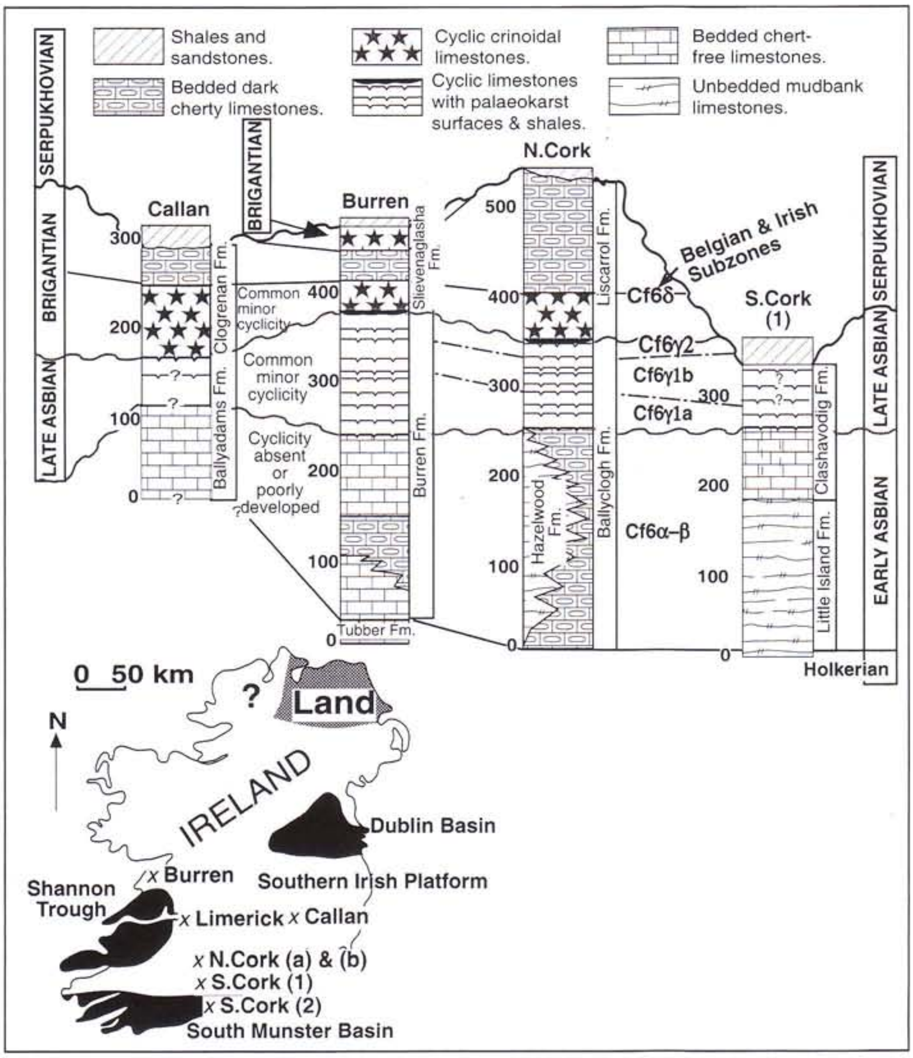

Fig. 1 - A stratigraphic correlation of the late Viséan platform carbonates included in this study (the vertical scales in the columns are in metres) (adapted from Gallagher (1996) and Gallagher & Somerville (1997). Biozones are those of Conil et al. (1991) for Cf6γ and Gallagher (1997) and Jones & Somerville (1996) for subzones Cf6γ1 and Cf6γ2. Note: Cf6γ1a and Cf6γ1b are informal subzonal divisions introduced in this work for this local correlation. The inset map shows the approximate position of the measured sections and the location of the platforms and deeper water basins.

succession is preserved as a series of shallowing-upward minor cycles (cyclothems) (Fig. 1). The thickly-bedded limestones are interpreted to have been deposited at or below fair-weather wave-base, at depths between 5 and 20 m (Gallagher 1996). Thinly-bedded cherty limestone microfacies probably were deposited below fair-weather wave-base, but above storm wave-base, at depths greater than 20 m. The biota of the carbonate sediment are characterized by calcareous algae and foraminifera and/or bryozoans and echinoderms (Gallagher 1996). The purpose of this contribution is to describe how changes in lithofacies are mimicked by changes in the biofacies, particularly foraminiferal assemblages. While the lithofacies and environmental control of the foraminiferal faunas have been outlined previously (Gallagher 1997, 1998), the variation of significant foraminifera within late Asbian minor cycles has not been documented in detail. In addition, the evolution of the higher order variation in the foraminiferal biofacies, from the early Asbian to the late Asbian will be described and interpreted.

This work will also interpret the litho- and biostratigraphic analyses of Gallagher (1996) and Gallagher & Somerville (1997) in a chronostratigraphic context. These data will then be used to correlate the platform sequences with greater precision and form the basis for a platform model for the late Viséan of Ireland.

Stratigraphic Framework

Lithostratigraphy.

The late Viséan platform successions in parts of southern and western Ireland can be subdivided into three principal facies units which are considered to be chronostratigraphic (Gallagher 1996; Fig. 1). These informal lithostratigraphical units are as follows:

(a) ?Holkerian to early Asbian platform facies with massive mudbanks and bedded, non-cyclic, algal and bryozoan carbonates (lower Ballyadams, Tubber, lower Burren, lower Ballyclogh, Hazelwood, lower Clashavodig and Little Island Formations, Fig. 1);

(b) late Asbian platform facies, with cyclic, algal-rich carbonates punctuated by periodic subaerial exposure surfaces (Ballyadams, upper Burren, upper Ballyclogh and Clashavodig Formations, Fig. 1);

(c) early Brigantian cyclic, crinoidal-rich platform limestones with rare subaerial exposure surfaces, succeeded by early-late Brigantian non-cyclic, cherty limestones overlain by cyclic, cherty crinoidal limestone (Clogrenan, Slievenaglasha and Liscarrol Formations, Fig. 1).

The boundary between (a) and (b) is normally represented by a palaeokarst horizon and palaeosol. A major palaeokarst and palaeosol also separate (b) and (c). Serpukhovian siliciclastic rocks disconformably overlie these early Carboniferous units. Large erosional contacts occur at the early/late Asbian, late Asbian/Brigantian and Brigantian/Serpukhovian stage boundaries. The minor cyclicity or cyclothems observed within some of the units have distinctive litho- and biofacies (see below).

Biostratigraphy

The zonation of the sequences was achieved using foraminifera, calcareous algae and pseudo-algae (Gallagher 1992, 1996: Gallagher & Somerville 1997). Where possible, corals and brachiopods were used to supplement the microbiostratigraphy. The macrofaunal biostratigraphy follows George et al. (1976), Mitchell (1989) and Conil et al. (1991). The microfossil biostratigraphic zonation scheme is summarized in Gallagher (1996) and Jones & Somerville (1996). The British and Irish Asbian and Brigantian stages used in this work are considered to be age equivalents of the Belgian Cf6α to Cf6δ foraminiferal subzones of Conil et al. (1991), therefore both stages and zones are used in Fig. 1 to 4. The early Asbian age (Cf6α−β subzones) for the basal part of the studied sections is based on the appearance of the following foraminifers: archaediscids at *angulatus* stage, *Neoarchaediscus, Pseudoendothyra* and *Vissariotaxis compressa* (Brazhnikova).

The base of the late Asbian stage (Cf6γ subzone) is defined on the appearance of the foraminifers: bilayered palaeotextulariids including: *Palaeotextularia* ex gr. *longiseptata* (Lipina) and *Cribrostomum lecomptei* (Conil & Lys), the calcareous pseudo-alga *Ungdarella*, the solitary rugose coral *Dibunophyllum bipartitum* (McCoy) and the brachiopod *Davidsonina septosa* (Davidson). Further subdivision of the late Asbian into the Cf6γ1 and Cf6γ2 subzones can be achieved using the first appearance of *Asteroarchaediscus, Bradyina rotula* (Eichwald) and *Saccamminopsis* at the base of Cf6γ2. The Cf6γ1 subzone is here informally subdivided into two additional biostratigraphic units Cf6γ1a and Cf6γ1b.

The base of Cf6γ1a is simply the base of the Cf6γ1 subzone. The first occurrence of *Cribrospira* and *Bibradya* in all the sections studied defines the base of Cf6γ1b. This informal division of the Cf6γ1 subzone is here used to correlate sections within the late Asbian (Fig. 1 to 4). The base of the Brigantian stage (Cf6δ subzone) is marked by horizons of *Saccamminopsis*, the first occurrence of abundant stellate archaediscids and the colonial rugose coral *Palastraea regia*.

Methods

Three principal sections were studied in North Cork, the Burren and South Cork representing the stratigraphic interval from the early Asbian to the late Asbian (Figs. 1 to 4) (Details of the localities can be found in Gallagher 1992; Gallagher & Somerville 1997). In the North Cork area two separate sections were studied (Ballyclogh Stream, identified as N. Cork (a) and Ballyclogh Quarry, North Cork (b) in Fig. 2 to 4). Over 800 standard thin sections (75 mm x 25 mm) were examined, prepared from samples collected at an average sampling interval of 2 m throughout the sequences. For each sample the lithofacies, bioclast type and abundance, and foraminiferal data were recorded (Fig. 2).

The bioclast abundance was estimated semi-quantitatively (see Tab. 1). The distribution of twelve palaeoenvironmentally significant foraminiferal genera (Gallagher 1997; 1998) and one problematicum (*Draffania*) in each section is illustrated on Fig. 3. These taxa were identified by multivariate analysis (Cluster Analysis and Correspondence Analysis) from a data base compiled from observations of samples of late Viséan limestone in Ireland (Gallagher 1997; 1998). The palaeoenvironmental distribution of these thirteen taxa (adapted from Gallagher 1998) form the basis for recognizing three distinct biofacies (Fig. 5).

The taxa selected range from trochospiral and encrusting forms in low-energy, bryozoan packstone to wackestone microfacies, to complex streptospiral robust tests in higher energy, algal grainstone microfacies. The total bioclast diversity illustrated in Fig. 4, is simply the total number of identifiable foraminifera/algal genera in each sample plus other identifiable bioclast types present (such as bryozoans, brachiopods, crinoids and ostracods) in each sample, based on observation from standard thin sections.

This is not meant to be an absolute measure of faunal diversity, the illustration of this data on Fig. 4 allows trends to be determined within cycles and up section which have palaeoenvironmental significance. It should also be noted, however, that some samples in thin section show diagenetic alteration (such as stylolitization and compaction of foraminiferal tests) making determinations difficult, but in the majority of samples the taxa were well preserved.

The lithofacies and microfossil distributional data are integrated in this study in order to discuss the cyclic biofacies variation that is illustrated using "ideal" cycles from one of the sections (Fig. 6). The stratigraphic data are then placed in its chronostratigraphic context (Fig. 7) and then placed in an idealized platform model (Fig. 8).

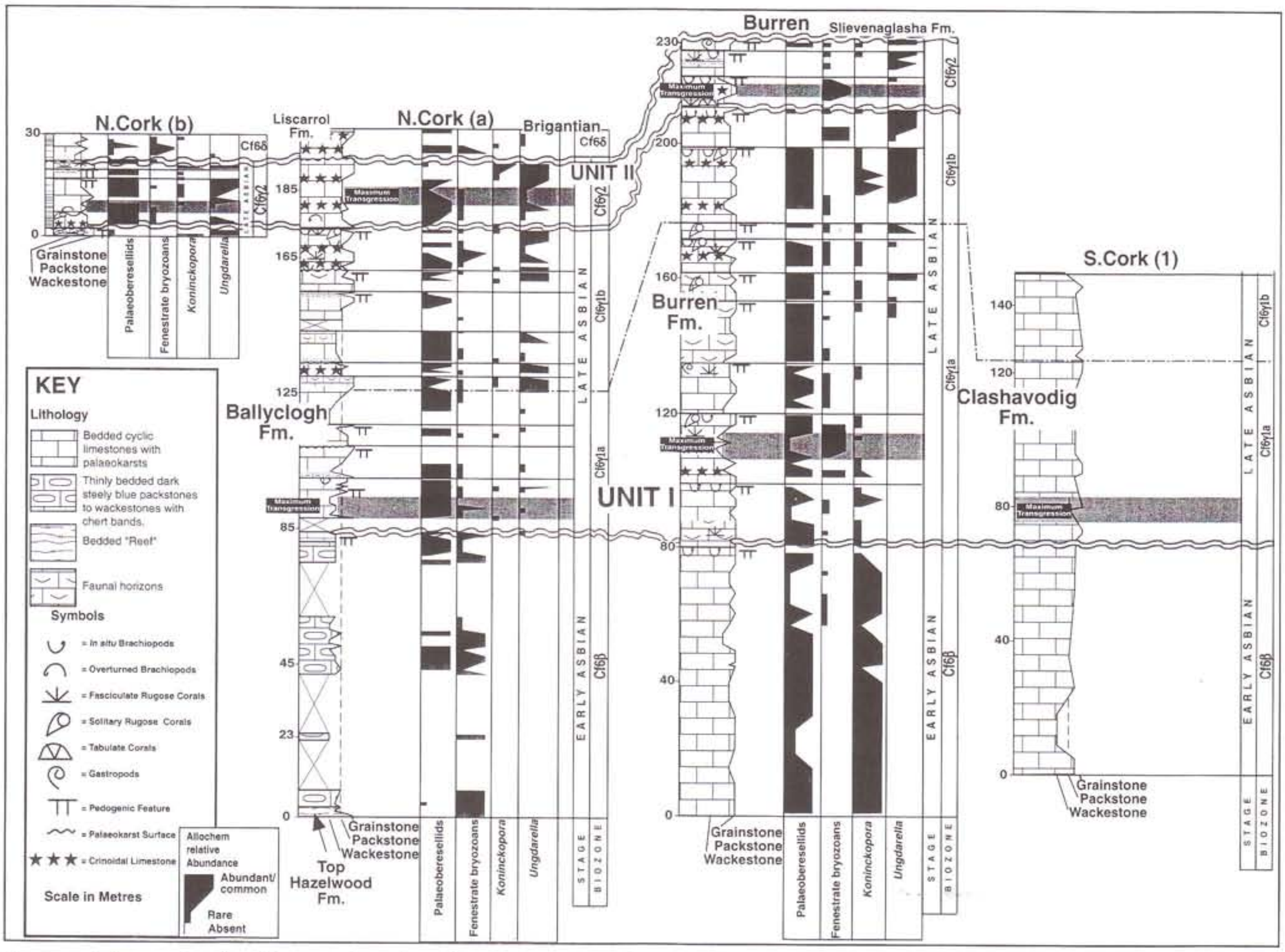

Fig. 2 - The stratigraphy of four sections through the upper part of the early Asbian to the lower part of the Brigantian from the Burren, North Cork and South Cork areas. (N.B. In the North Cork area, Ballyclogh Stream section is identified as N. Cork (a) and Ballyclogh Quarry as North Cork (b)). Each column shows the carbonate microfacies (cf. Dunham 1962) and variation in abundance of algae and fenestrate bryozoa (see Table 1). No macrofacies data or range in algal abundance was obtained from the Clashavodig Formation (South Cork). The samples for the South Cork succession were supplied by Heseldene (pers. comm.). The dark horizontal bands correspond to the maximum transgressions in Units I and II in the late Viséan.

Summary of the facies variation within late Asbian cycles

Palaeokarst Surfaces and Palaeosols (cycle boundary criteria)

Palaeokarsts (with pedotubules) and clay palaeosols cap minor cycles within the late Asbian succession and occur at the early/late Asbian and Asbian/Brigantian boundaries. These features represent periods of emergence when karstification and soil formation took place (Walkden 1987; Wright 1996). The maturity of the soil development on these surfaces is partly related to the duration of emergence, tectonic and climatic factors (Vanstone 1996).

The major erosional surfaces identified in this study preserve well-developed karst features with irregular scalloped surfaces with up to 0.5 m relief and thick palaeosols (up 1m in thickness). The surfaces of these palaeokarsts may preserve evidence of rootlet bioturbation in the form of alveolar textures and pedotubules (Gallagher 1996). Boulders (<0.3 m) may occur in these soils, which are considered to have been eroded from the underlying strata. Fissures several metres deep and up to 0.5 metre wide also occur. These may represent initial palaeocave development.

Minor cycle boundaries in the Irish late Viséan preserve flat to slightly undulose palaeokarst features with or without clay palaeosols. These surfaces usually preserve pedogenic textures such as calcretes and pedotubules.

In the late Asbian sequences, palaeokarst development increases in complexity up through the section and palaeosols become thicker. This pattern is similar to that observed by Wright (1996) who described the phenomenon of highstand thickening of palaeosols. Vanstone (1996) suggests that immature palaeokarsts in the late Viséan of Wales and England were probably only exposed for periods in the order of a few tens of thousands of years.

Carbonate facies and biota

The distribution and relative abundance of key allochemical components for the successions studied in the late Asbian minor cycles are illustrated in Fig. 2. One calcareous algae *Koninckopora* was observed and two calcareous pseudo-algae were documented: palaeoberesellids and *Ungdarella*. Palaeoberesellids are regarded as possible dasycladacean algae typifying depths of around 10 m in late Viséan microfacies (Skompski 1987; Adams et al. 1992, Horbury & Adams 1996). Termier et al. (1977) and Vachard (1991) regard palaeoberesellids as pseudoalgal moravamminids. The affinity of *Ungdarella* is problematical, although it is thought to have been a rhodophyte (Wray 1977; Skompski 1986) or a pseudo-algal aoujgaliid by Termier et al. (1977) and Vachard (1991). It may have occupied a similar palaeoecological niche to the palaeoberesellids, although it seems to occur in higher energy facies in the late Viséan of Ireland (Gallagher 1992). *Koninckopora* is regarded to have been a possible dasycladacean alga (Wray 1977; Skompski 1986) that may have inhabited water depths shallower than 5 m (Gallagher 1992; 1998) although Vachard (pers comm.) suggests optimal depths between 10 and 20 m for this taxon. The relative abundance of bryozoans is inversely related to the abundance of *Ungdarella* and *Koninckopora*.

The upper section of the early Asbian sequence is characterized by contrasting sections in the Burren and Cork areas (Fig. 2). In the Burren area, packstone to grainstone microfacies occur with abundant *Koninckopora* and palaeoberesellids. In North Cork rocks of this same age are typified by packstone to wackestone microfacies, lacking calcareous algae, and dominated by the presence of abundant fenestrate bryozoans. In South Cork well-bedded packstone to grainstone microfacies with some wackestone occur in this same time interval (the allochemical abundance in the thin sections of this section were not noted). None of the sections are cyclic nor do they exhibit paleokarst features or macrofaunal horizons (except at the top of the early Asbian sequence in the Burren). In addition, the early Asbian cherty facies of the North Cork area are laterally equivalent to mudbank facies (Gallagher & Somerville 1997; Fig. 1, 7).

The late Asbian succession is characterized by algal packstone to grainstone microfacies with macrofaunal horizons (mainly brachiopod bands and coral biostromes) and can be into two parts: Unit I and Unit II (Figs. 2 to 4). Unit I comprises the majority of the late Asbian succession of Cf6γ1a and Cf6γ1b subzonal age, its base is the first major palaeokarst at the early/late Asbian boundary. The base of Unit II is also a major palaeokarst surface and palaeosol and comprises the last minor cycles in the late Asbian succession of Cf6γ2 subzonal age. Crinoidal material and coral/brachiopods increase in abundance towards the top of Unit 1 and into Unit II (see Fig. 2). Macrofossils are also common in the upper sections of Unit II. Palaeoberesellids are abundant in Unit I although they may be much rarer in Unit II especially in the Burren. *Ungdarella* is rare in the lower half of Unit I, where packstone to wackestone textures are most common, but become abundant up section in grainstone beds towards the top of both sequences. *Koninckopora* occurs in low amounts throughout both sequences principally in grainstones. Bryozoans are rare in Unit I but become more common in Unit II. Algae are rare in the overlying Brigantian succession where crinoidal and bryozoan material are the dominant bioclasts.

A 10 m-thick interval near the base of Unit I (bryozoan and crinoidal packstone to wackestone microfacies) lacks *Koninckopora, Ungdarella* and macrofaunal bands. This package is interpreted to represent the lowest energy, deepest water carbonate facies of the succession, and therefore corresponds to the maximum transgression (flooding) of Unit I (Fig. 2). Algal-poor, bryozoan and crinoidal-rich packstone to grainstone microfacies occur as a thin interval near the base of Unit II and along with the presence of a distinctive suite of foraminifera (e.g. *Valvulinella*, *Tetrataxis*, *Scalebrina*) is similarly considered to be the maximum transgression of Unit II. Similar facies to these are interpreted by Horbury & Adams (1996) to have been deposited at subtidal depths greater than 20m. The increase in *Ungdarella* and macrofaunal content in packstone/grainstone microfacies towards the top of each late Asbian unit suggests an overall shallowing-upward trend.

Each individual minor cycle within the late Asbian sequences preserves shallowing-upward lithofacies that terminated in subaerial exposure (Gallagher 1996). *Koninckopora* and *Ungdarella*-rich packstone to grainstone microfacies with macrofaunal horizons are present at the top of cycles, and in some instances at the base of cycles where bryozoans are absent (Fig. 2, 3). Bryozoan or crinoidal packstone (to wackestone) occur towards the base of minor cycles, associated with low algal abundance and an absence of macrofauna.

The occasional preservation of algal limestone at the base of each cycle followed by bryozoan facies in the centre of each cycle represents small-scale transgressive 'flooding' events. The macrofaunal bands and algal grainy facies at the top of cycles are interpreted to be regressive events (Fig. 2, 3).

The stacked cycles that comprise the upper part of each late Asbian unit become more algal- and macrofaunal-rich up section (Fig. 2) and thus represents increasingly shallower water facies.

Foraminiferal distribution

FAD's and LAD's

Although the first appearance datum (FAD) of archaediscids at *angulatus* stage defines the base of the early Asbian in the successions, there are no other significant

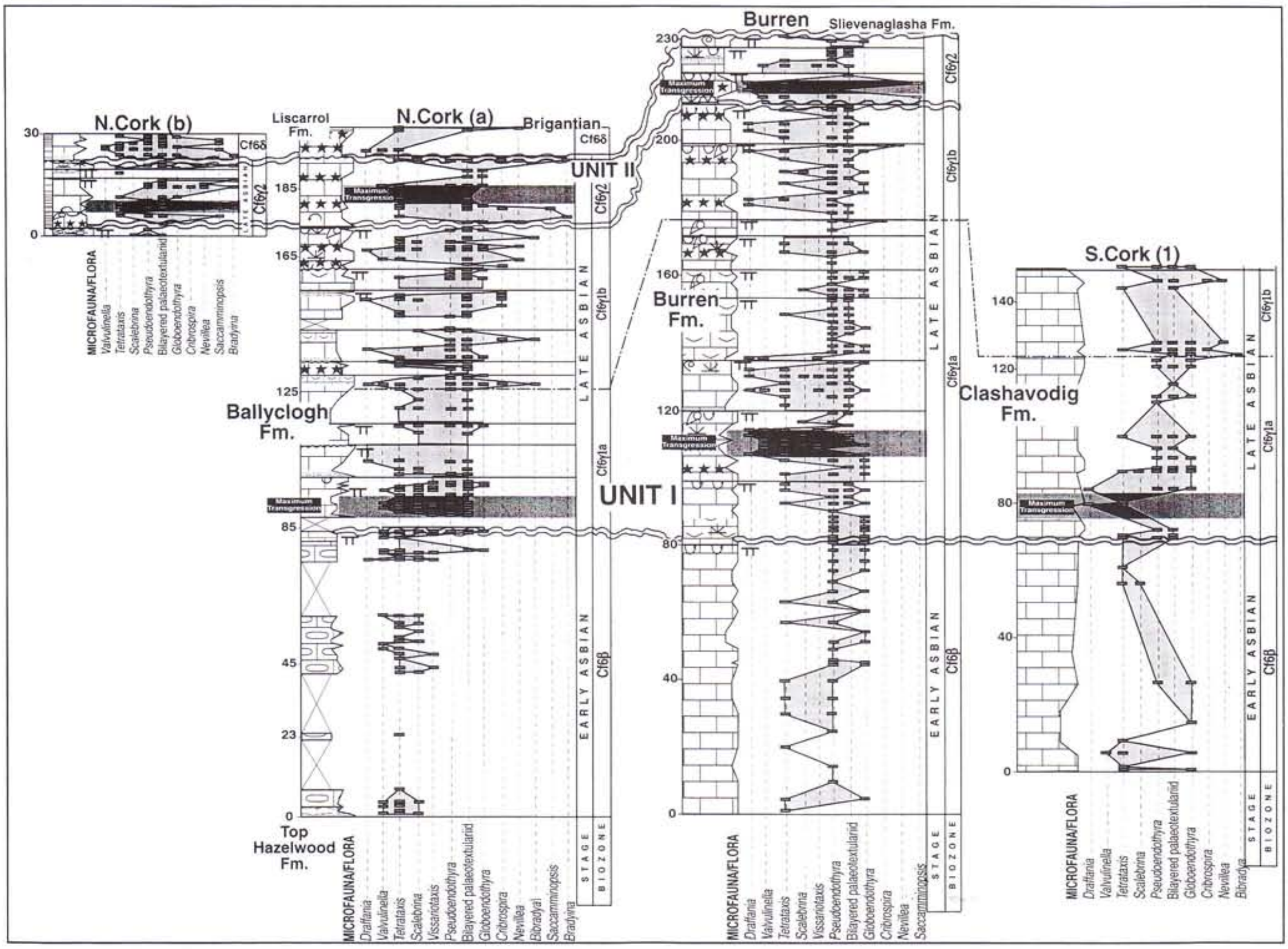

Fig. 3 - The significant foraminiferal taxa recorded from the four stratigraphic sections (Burren, North Cork (a) and (b), and South Cork) through the upper part of the early Asbian to the lower part of the Brigantian. All vertical scales are in metres. Biozones are those of Conil et al. (1991) and Jones & Somerville (1996). See Fig. 2 for key to lithology and symbols in the logs.

FAD's within the early Asbian. The first significant arrival of age-diagnostic taxa occurs in the lower part of the late Asbian Unit I (Fig. 3) where bilayered palaeotextulariids such as *Cribrostomum* and *Palaeotextularia* ex gr. *longiseptata* first appear (the base of Cf6γ1a on Fig. 3). Other FAD's include the alga *Ungdarella* (in the North Cork (a) section), and the foraminifera: *Plectostaffella* and *Koskinobigenerina*, but none of these biostratigraphically significant taxa first appear in the maximum transgressive phase of this unit. The next significant biomarker is the first appearance of *Bibradya* and *Cribrospira* defining the base of the Cf6γ1b subzone in the upper part of Unit I (Fig. 3). *Saccamminopsis*, *Howchinia bradyana* (Howchin), *Bradyina rotula* (Eichwald) and *Koninckopora* sp. B first occur at the base of Unit II. The deposition of the overlying Brigantian succession was associated with the first appearance of *Loeblichia paraammonoides* and the radiation of the Asteroarchaediscidae, *Howchinia bradyana* and abundant *Fasciella* (Gallagher & Somerville 1997). Several taxa disappear (Last appearance datum; LAD) at the top of Unit II (Asbian/Brigantian boundary). These include: *Cribrospira, Bibradya* and the algae *Koninckopora* sp. B. Other species of *Koninckopora* disappear near the base of the Brigantian sequence in Ireland (Gallagher & Somerville 1997).

The first transgressive facies at the base of late Asbian Units I and II were associated with an influx of biostratigraphically important microfossils at the base of biozones. On a smaller scale, a similar pattern is observed within the minor cycles, where diagnostic taxa first appear or reappear in the shallower water transgressive and regressive facies at their base and top, but rarely within the deeper water facies of the mid cycle (Gallagher 1992; Gallagher & Somerville 1997). The basal part of the Brigantian succession in Fig. 2 to 4 is associated with faunal LAD's. This change in biota is accompanied by a switch from algal-dominated bioclasts in late Asbian carbonates to more crinoidal and bryozoan-rich facies in the Brigantian (cf. Gallagher 1996). The sea-level variations responsible for the facies changes that mark major erosional surfaces in the late Viséan platform carbonates of the Cork and Burren areas, also brought in new taxa that define biostratigraphic boundaries (Gallagher & Somerville 1997).

Code	Allochems per (50mm X 10mm) thin section
Absent	= 0 specimens.
Rare	= 1-30 fronds of bryozoans, 1-30 pseudo-thalli of palaeoberesellids and *Ungdarella*, 1-6 fragments of *Koninckopora.*
Common to Abundant	>30 fronds of bryozoans, >30 pseudo-thalli of palaeoberesellids and *Ungdarella*, > 6 fragments of *Koninckopora.*

Tab. 1 - The semi-quantitative basis of the allochemical abundance data in Fig. 2.

Biofacies variations in the Asbian succession

The distribution of several foraminiferal taxa, microproblematica and pseudo-algae in the early to late Asbian sequences (Gallagher 1997; 1998) has enabled three palaeoenvironmentally significant biofacies to be distinguished (Tab. 1; Fig. 5). In addition, the number of genera of calcareous algae, pseudo-algae, foraminifera and problematica (together with the number of identifiable bioclasts, see Section 3, Methods) are plotted in Fig. 4 as diversity values. *Draffania* is a problematicum that typified low energy, deeper water, subtidal, bryozoan-rich facies that mostly lacks calcareous algae in the studied biofacies (Fig. 5). The foraminifera *Valvulinella* and *Tetrataxis* are interpreted to have thrived at water depths below 20 m in algal-poor facies. The taxa forming Biofacies type 1 (Fig. 5) are usually not present towards the top of shallowing-upward cycles (Fig. 4). *Scalebrina* survived in high- to low-energy, subtidal palaeoenvironments above and below fair-weather wave-base (Gallagher 1992). *Vissariotaxis* thrived in palaeoberesellid pseudo-algal meadow paleoenvironments below fair-weather wave-base, at water depths of 10 m or greater (Gallagher 1992). This forms Biofacies type 2 which includes the foraminifera *Pseudoendothyra*, *Globoendothyra* and bilayered palaeotextulariids which were most abundant in this shallow water, subtidal facies. This biofacies is also generally charac-

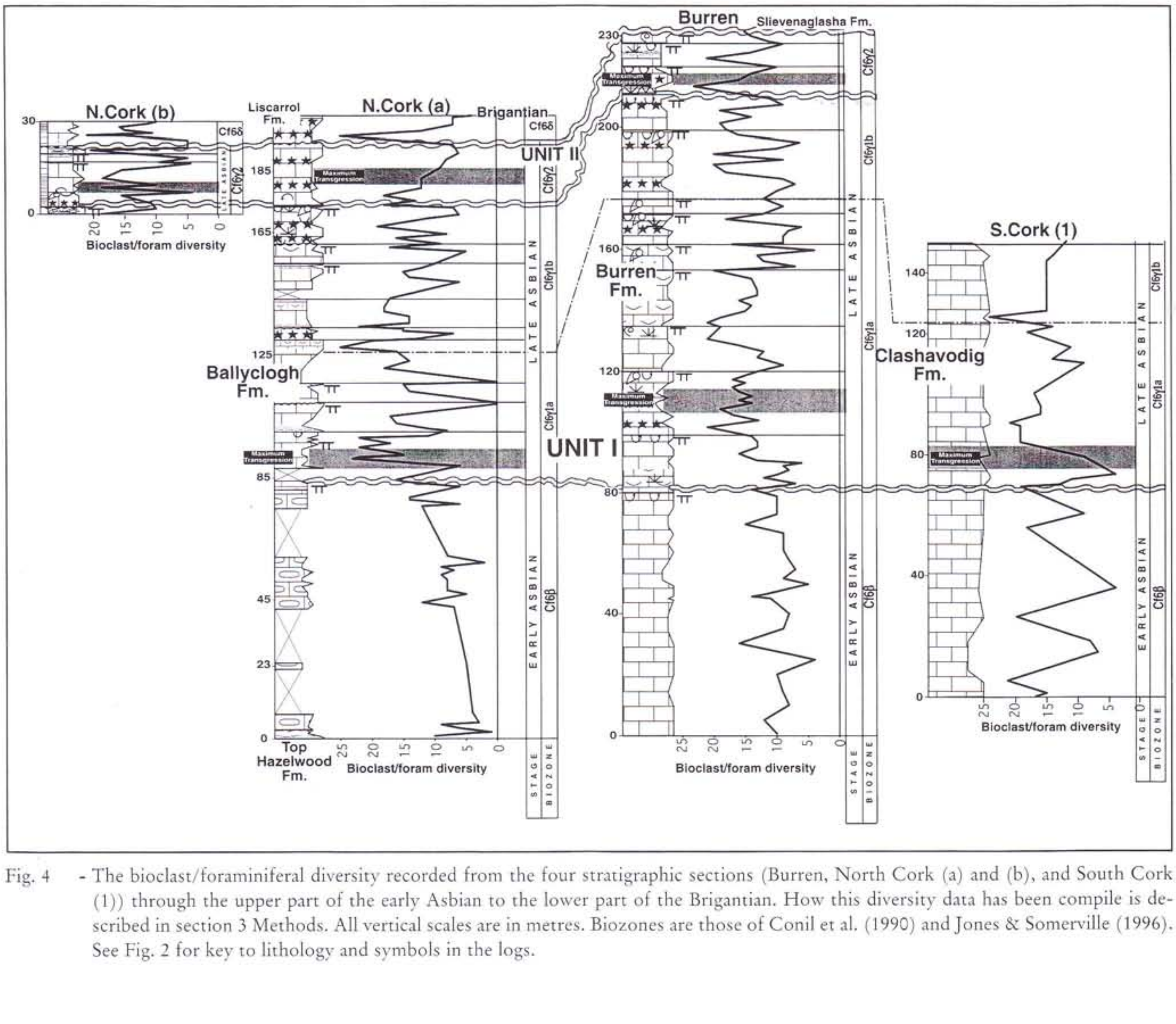

Fig. 4 - The bioclast/foraminiferal diversity recorded from the four stratigraphic sections (Burren, North Cork (a) and (b), and South Cork (1)) through the upper part of the early Asbian to the lower part of the Brigantian. How this diversity data has been compile is described in section 3 Methods. All vertical scales are in metres. Biozones are those of Conil et al. (1990) and Jones & Somerville (1996). See Fig. 2 for key to lithology and symbols in the logs.

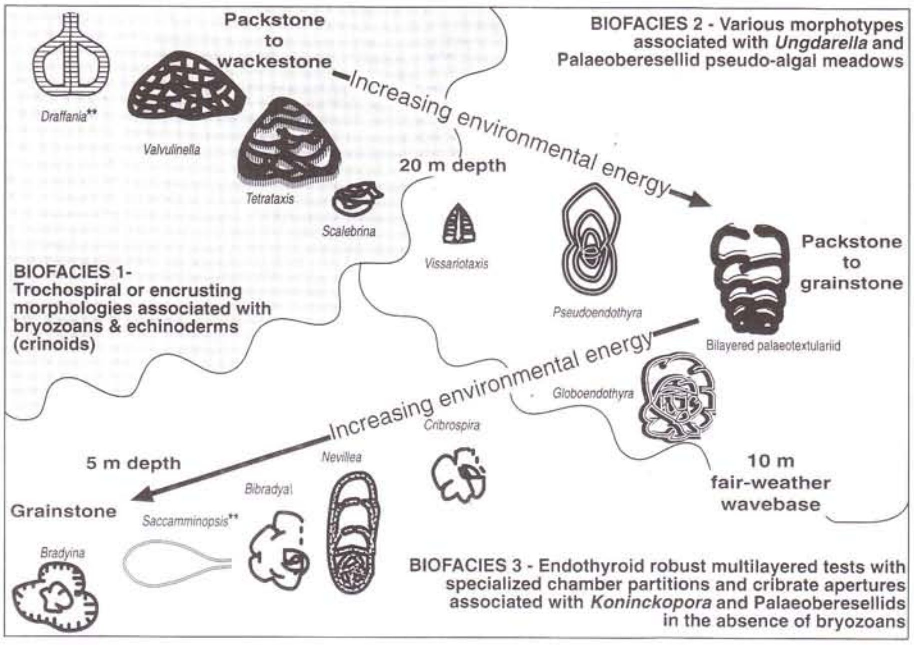

Fig. 5 - A schematic cartoon to show the relationship of palaeoenvironmentally significant foraminiferal/problematica/algal/pseudo-algal assemblages (Biofacies 1-3) to lithofacies, water depth and energy levels. (N.B. *Draffania* is a Problematicum and *Saccamminopsis* is not recognized as a foraminifer by all workers).

terized by its lack of crinoids and bryozoans (Gallagher 1997). *Cribrospira, Nevillea, Bibradya, Saccamminopsis* and *Bradyina* are characteristic of Biofacies type 3, that thrived in high-energy, shallow water, open-marine algal meadows at water depths between 5 to 10 m (Gallagher 1997; 1998). Thus, the taxa selected to illustrate biofacies variations within cycles inhabited contrasting ends of an environmental continuum (or gradient) from low-energy, deeper water, subtidal, bryozoan wackestone to packstone microfacies, to high-energy, shallower water, algal grainstone microfacies (Fig. 5). The distribution of these taxa and microfossil diversity varies from the early to late Asbian time, and within late Asbian minor cycles (see below).

Early Asbian biofacies. The early Asbian intervals in the Burren and North Cork areas contain low diversity assemblages (Fig. 4). The bryozoan cherty packstone to wackestone microfacies of the North Cork area contains common deep water, subtidal, foraminiferal assemblages (*Valvulinella, Tetrataxis* and *Scalebrina*). In contrast, the shallower water, subtidal foraminiferal assemblages (*Globoendothyra* and *Pseudoendothyra*) dominate algal packstone to grainstone microfacies of the Burren (Fig. 3). In South Cork algal/foraminiferal diversity fluctuates markedly (Fig. 4). This probably related to a poorly developed minor cyclicity, as reported by Hesledene (pers. comm.) or influence of predominant deeper water conditions.

Late Asbian biofacies. The transgressive phase of Unit I during late Asbian time is associated with a diversification of shallow water species types including the bilayered palaeotextulariids (Biofacies type 2). The maximum transgressive part of Unit I is characterized by a high diversity (>15 taxa), deep water, subtidal foraminiferal biofacies (Biofacies type 1) with *Draffania, Valvulinella, Tetrataxis* and *Scalebrina* in packstone to wackestone microfacies, with the addition of *Vissariotaxis, Pseudoendothyra* and bilayered palaeotextulariids (from Biofacies type 2, Fig. 5). The minor cycles of Unit I exhibit great variations in species diversity and biofacies (to be discussed below). Towards the top of Unit I, shallow water, subtidal, higher energy taxa (*Cribrospira, Bibradya* and *Nevillea*) characterize high diversity (>15 taxa) foraminiferal assemblages in grainstone microfacies (Biofacies type 3). The transgressive phase of the overlying Unit II brings in a slightly different shallower water, high energy assemblage including *Saccamminopsis* and *Bradyina*. This was followed by a switch to deeper water foraminiferal biofacies of the maximum transgression (*Tetrataxis* and *Draffania*) and then back to shallower water foraminiferal biofacies (*Cribrospira, Bradyina* and *Saccamminopsis*) in the upper part of the cycle.

Minor cycle biofacies variations. Within each minor cycle the distribution of the thirteen selected taxa (Fig. 3) and total faunal diversity (Fig. 4) varies markedly. The deeper water palaeoenvironmental indicators *Draffania* and *Valvulinella* are absent in samples from the top and base of many minor cycles in Ireland. These taxa typify mid cycle facies horizons associated with bryozoan-rich facies. *Tetrataxis* is absent from many cycle tops although this taxon may occur in the samples from cycle bases. *Pseudoendothyra* and bilayered palaeotextulariids are present in most palaeoberesellid-rich samples and are often the only representatives of the thirteen selected taxa present in the uppermost and lowermost samples in minor cycles. The shallower water, subtidal foraminifers such as *Cribrospira* and *Bibradya* are typical of grainstone microfacies occurring in the upper half of minor cycles. The diversity is relatively low near cycle bases and generally increases up through a cycle, but is often most marked in the middle of a cycle (Fig. 4).

The biofacies changes within cycles reflect initial shallow water, palaeoberesellid-rich deposition followed by a deeper water, subtidal transgressive phase (mid cycle) then by upward shallowing into algal-rich packstone/grainstone microfacies with abundant *Koninckopora, Ungdarella* and palaeoberesellids, ultimately leading to subaerial exposure at the cycle top.

Two typical minor cycles profiles are shown on Fig. 6, illustrating the variation in distribution of Biofacies 1-3 within the North Cork succession. While the cycles have packstone/grainstone microfacies, each began with an initial shallow marine trangressive phase with *Koninckopora, Ungdarella* and palaeoberesellid limestone with high diversity Biofacies 2-3 assemblages. This was followed by the deepest facies as algal-poor and bryozoan-rich facies with Biofacies 1-2 assemblages. Algal facies returned in the shallower subtidal low diversity Biofacies 2-3 assemblage.

Late Viséan chronostratigraphy and stratigraphy of southern Ireland

Strogen (1988), Somerville & Strogen (1992) and Somerville et al. (1992) described shallow marine platform carbonates from the late Viséan of the Limerick Syncline. The lower Asbian strata include the cross-bedded oolitic and crinoidal grainstone of the Herbertstown Limestone Formation with subaerial to submarine volcanics (Knockseefin Volcanic Formation) occurring in the upper part. The overlying late Asbian shallow marine rubbly packstone to wackestone microfacies of the Dromkeen Limestone Formation have occasional shelly horizons. Significantly, all key bioevents occurring in the late Asbian sequences outlined in this study also appear in the Dromkeen Limestone Formation (Fig. 6), with the appearance of diagnostic taxa indicative of biozones Cf6γ1a, Cf6γ1b and Cf6γ2 within the subzone Cf6γ of Somerville et al. (1992). On the basis of these faunal/floral and lithofacies data the Asbian sequences of the Burren, North Cork and South Cork areas can be correlated to the stratigraphy of the Limerick

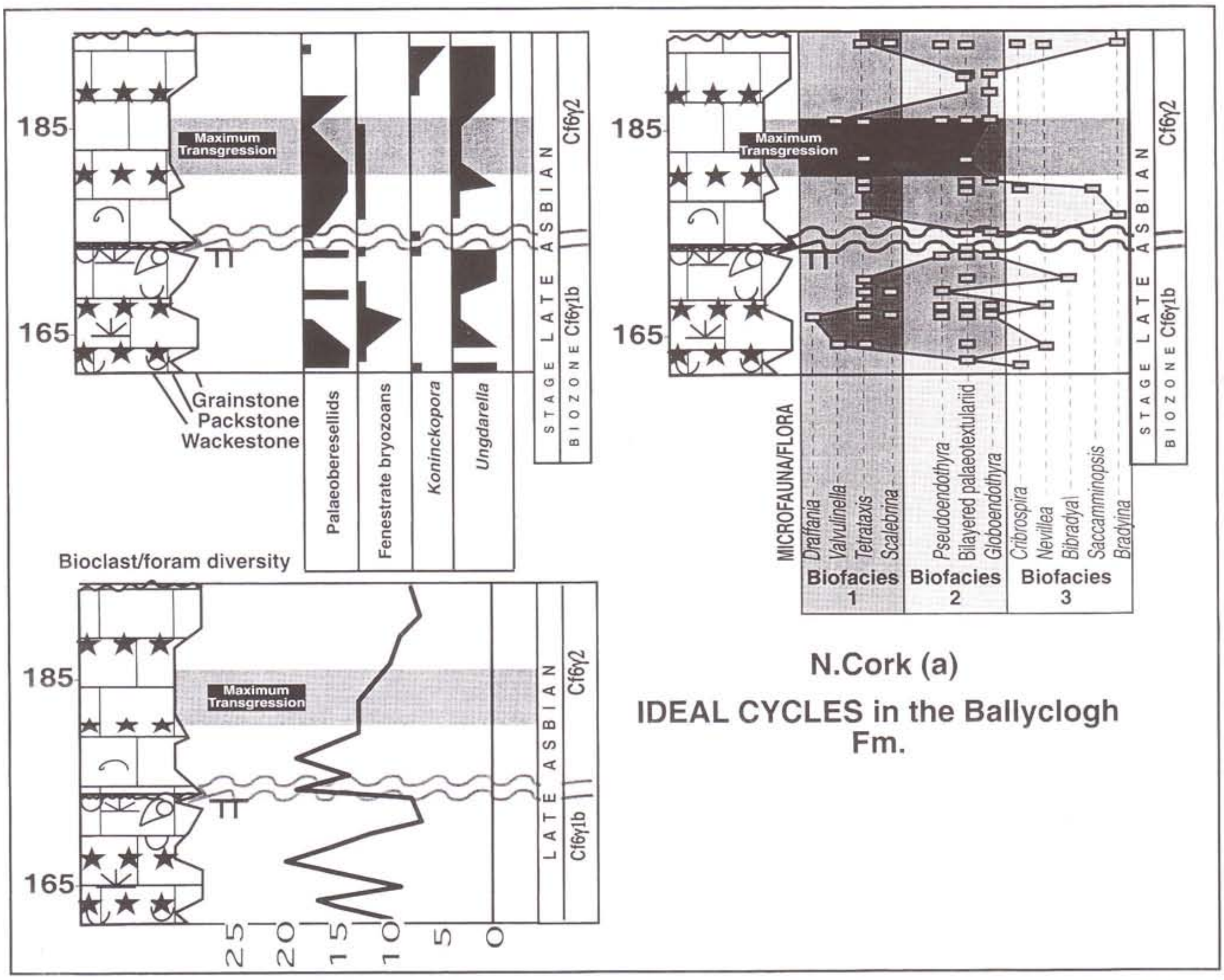

Fig. 6 - An illustration of two "ideal" cycles selected from the North Cork Ballyclogh Formation (from log level 165-185m in the section of N. Cork (a) on Fig. 2-4). The occurrence of assemblages from the three biofacies (Fig. 5) are shown. See Fig. 2 for key to lithology and symbols in the logs.

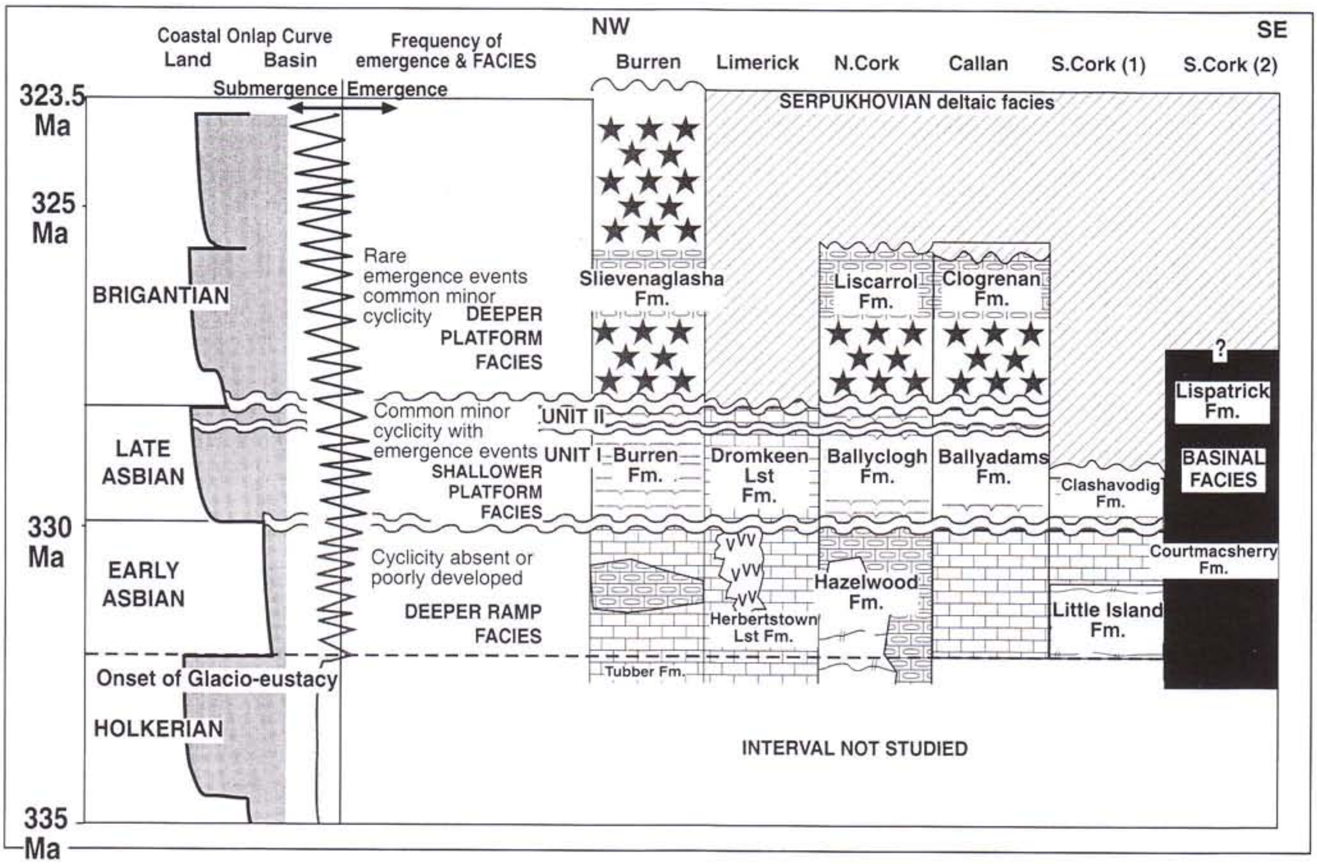

Fig. 7 - Comparison of sequences showing lithofacies and cyclicity from various regions in southern Ireland. Data from Burren (Gallagher 1992,1996; Gallagher & Somerville 1997); Limerick (Strogen 1988; Somerville & Strogen 1992; Somerville et al. 1992); Callan and N. Cork (Gallagher 1992,1996); S.Cork 1 (Hazeldene, pers. comm.) and South Cork 2 – South Munster Basin (Sevastapulo 1981; Sleeman 1987; Naylor et al. 1988). The time scale (in millions of years) correlation of the Coastal Onlap Curve is from Wright & Vanstone (2001). See Fig. 1 for key to lithology and symbols.

Syncline. Sevastopulo (1981), Sleeman (1987) and Naylor et al. (1988) describe the stratigraphy of the late Viséan platform carbonates and their clastic equivalents in the South Munster Basin. Here, the mudbanks of the Little Island Formation and bedded shallow marine carbonates of the Clashavodig Formation pass laterally into basinal mudstone of the Courtmacsherry and Lispatrick Formations at the Old Head of Kinsale (Fig. 7).

The late Viséan units in southern Ireland are correlated to the relative coastal onlap curve of Ross & Ross (1988) in Fig. 7. The chronology and relative amplitude of cyclic oscillation within each stage is plotted based on data in Wright & Vanstone (2001). Cyclicity is well developed in early Asbian successions elsewhere in the U.K. (Wright & Vanstone 2001), but is poorly developed or absent in the Irish successions studied. The significance of this difference is discussed in the platform model below. The cyclicity in the late Asbian to Brigantian of southern Ireland is similar to elsewhere in western Europe (Walkden 1987) and is considered to have been caused by glacio-eustatic sea-level change (as summarised in Wright & Vanstone 2001). The major palaeokarst development and change in sedimentation style at the Asbian/Brigantian boundary in Ireland clearly correlates to the sequence boundary at that level illustrated by Ross & Ross (1988) on their relative coastal onlap (Fig. 7). Similarly, the palaeokarst development and change in sedimentation style at the early Asbian/late Asbian boundary in Ireland correlates to the lower sequence boundary illustrated by Ross & Ross (1988) on their relative coastal onlap (Fig. 7). However, the palaeokarst development at the Unit 1/Unit II boundary does not correlate with any sequence boundary on the onlap curve, although it correlates with a change from the shallower basinward part of Ross & Ross's Asbian sequence to the more landward part of the sequence.

Late Viséan platform development

The palaeogeography of Ireland during the late Viséan time is shown in Fig. 1. During this time Ireland was dominated by a wide shallow-marine carbonate platform with land to the north and the deep water basinal facies of the South Munster Basin to the south. Fault controlled intraplatform basins on this platform included the Shannon Trough (Somerville & Strogen 1992; Strogen et

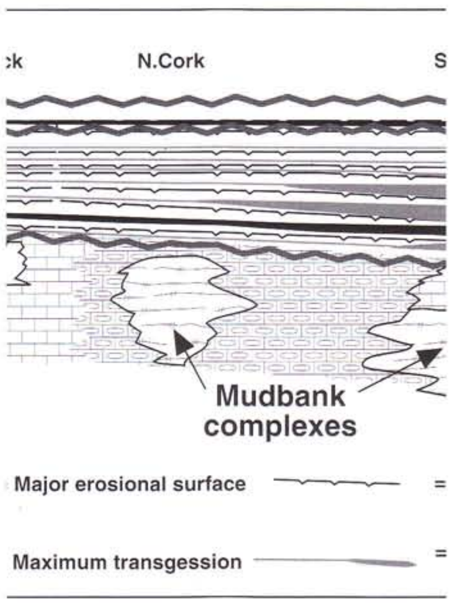

Fig. 8 - A reconstruction of the late Asbian platform and platform margin development in southern Ireland showing the lateral passage from shallow water facies of the Burren into the deeper water basinal rocks of South Munster Basin (S. Cork 2). See Fig. 1 for key to lithology and symbols.

al. 1990) and the Dublin Basin (Pickard et al. 1994; Strogen et al. 1996). A transect from northwest to southeast from the Burren to the South Munster Basin shows evidence for the existence of two principal platform styles from early Asbian to late Asbian times (see below) over an along-strike distance in excess of 200 km. The interpretation that follows is based on this work and from studies by Sevastopulo (1981), Sleeman (1987), Naylor et al. (1988), Strogen (1988), Somerville & Strogen (1992) and Somerville et al. (1992).

Shallow subtidal platform carbonates developed during the early Asbian in the northern part of the transect shown on Fig. 8. These shallow marine facies in the Burren area pass into cherty, deeper water subtidal facies in North and South Cork where mudbank complexes developed (Gallagher 1996). Shoaling occurred above the South Cork mudbank complex. The early Asbian facies pass laterally into basinal mudstone of the Courtmacsherry Formation at the Old Head of Kinsale (Fig. 7). The preserved evidence as recognized by previous workers (Sevastopulo 1981; Sleeman 1987; Naylor et al. 1988; Strogen 1988; Somerville & Strogen 1992; Somerville et al. 1992) suggest a complex rimmed ramp developed in southern Ireland during early Asbian time.

Palaeokarst development at the base of the late Asbian Unit I, terminated ramp deposition. Late Asbian deposition established shallow marine platform carbonates in all areas. No significant mudbank or cherty facies developed in the late Asbian; most facies consist of minor cycles with well bedded packstone to grainstone microfacies (Fig. 8). Facies near the base of the late Asbian succession in Unit I preserve evidence of initial deeper water subtidal deposition (the maximum transgression) and subsequent upward-shoaling, stacked cycle sets, leading ultimately to prolonged subaerial exposure (the major palaeokarst at the top of Unit I). Deeper water subtidal deposition was initiated near the base of Unit II in late Asbian time. Subsequently, regressive shallowing-upward cyclic facies were established and Unit II deposition was terminated by the major palaeokarst at the Asbian/Brigantian boundary. The aggradational shallowing-upward nature of the late Asbian succession, together with the general palaeogeographical data and documented lateral facies changes, suggests that platform development probably prograded southwards during this time (Fig. 8). Therefore, the late Asbian platform geometry of southern Ireland consisted of a shallow unrimmed platform expanse that prograded basinward (Gallagher 1992). A major palaeokarst terminated late Asbian platform development at the base of the Brigantian. After this time further platform facies were established across southern Ireland. The nature of this platform type is unclear due to the relative lack of preserved strata of this age.

Conclusion

The stratigraphy of several late Viséan carbonate successions in southern Ireland have been correlated using high resolution foraminiferal/algal biostratigraphy and detailed lithostratigraphic analysis. This data is integrated with detailed biofacies analyses to arrive at the following conclusions:

(1) The microfacies of early Asbian strata are variable ranging from shallow algal grainstone to cherty wackestone well bedded units to unbedded mudbank

facies. These platform mudbank and intrabank facies were deposited on a rimmed ramp that dipped southward.

(2) By upper late Viséan (late Asbian to Brigantian) time, well bedded carbonates were deposited on a shallow, unrimmed platform expanse that prograded southward through a series of shallowing-upward minor cycles.

(3) The late Asbian strata are cyclic consisting of several minor cycles (2-15m thick) capped by palaeokarst surfaces and palaeosols. Within each cycle the lithofacies and biofacies varies markedly. Three distinctive foraminiferal biofacies occur in different part of the cycles:

(a) Biofacies type 1 assemblages are hosted in predominantly packstone to wackestone microfacies that are interpreted to have deposited in deep subtidal palaeoenvironments (possibly below 20 m depth). The assemblage is associated with bryozoan and crinoids in the absence of calcareous algae. The representatives of this biofacies are *Draffania* (a problematicum); the trochospiral *Valvulinella* and *Tetrataxis* and the encrusting *Scalebrina*. This biofacies typifies the middle of each minor cycle and represents the deepest transgressive phase of each cycle where no significant first appearance datums occur.

(b) Biofacies type 2 typifies algal-rich shallow marine packstone to grainstone microfacies. The representative of this biofacies are some of the most common foraminifera in the late Viséan units studied and include *Vissariotaxis*, *Pseudoendothyra*, bilayered Palaeotextulariids and *Globoendothyra*. This biofacies may occur in the lower transgressive facies of each minor cycle with a diverse foraminiferal biofacies. New foraminiferal taxa may appear in this part of the cycle.

(c) Biofacies type 3 occurs near the top of minor cyles in shallow water dasycladacean-rich grainstone microfacies. The endothyroid foraminifers with cribrate apertures and specialized chamber partitions in this biofacies include: *Cribrospira, Nevillea, Bibradya* and *Bradyina* that may occur in association with the problematicum *Saccamminopsis.* Biostratigraphically important foraminiferal taxa often first appear or reappear in this low diversity biofacies assemblages toward the top of many cycles.

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