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Palaeoenvironmental interpretation of the Tramore Limestone Formation (Llandeilo, Ordovician) based on bryozoan colony form

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ABSTRACT: The Tramore Limestone Formation (Llandeilo, Ordovician), exposed in southeast Ireland, contains well-preserved colonies of the trepostome bryozoan *Diplotrypa petropolitana*. Two palaeoenvironmental settings - a deep water carbonate basinal facies and a shallow water carbonate shelf facies - are represented. Shape, size and attitude to bedding of *Diplotrypa* colonies were measured in the field. These data were compared with results gathered from experiments carried out to test the behaviour in a wave tank of representative models of bryozoan colonies. Results have demonstrated a clear environmental partitioning of colonies, and suggest that dome-shaped colonies are more dominant in deep water facies than bell-shaped colonies, which occur more abundantly in the shallow water facies. Morphological analysis of bryozoan colonies can be a useful tool for palaeoenvironmental interpretation.

1 INTRODUCTION

Bryozoan colony form may be utilised to determine the environmental and palaeoenvironmental conditions under which bryozoans grew. The classic study of this approach was by Stach (1932). Recent studies by Kelly & Horowitz (1987), Smith (1995), and Hageman *et al.* (1998) have refined and improved our understanding of the influences of environmental parameters on colony morphology, so much so that we can now make reasonable estimations of the bryozoan colony morphological types expected to grow in any environment, and expected to be found preserved in different facies.

Within the Tramore Limestone Formation (Llandeilo, Ordovician), exposed in southeast Ireland, are well-preserved colonies of the trepostome bryozoan *Diplotrypa petropolitana*. In 1999 and 2000 colonies were collected for taxonomic study from several sites along the Waterford coast west of the town of Tramore. On preliminary examination it appeared that these colonies exhibited palaeoenvironmental trends in relation to the size of colonies, to their state of preservation, and in their orientation relative to the substrate. Material was collected from two palaeoenvironmental settings (as indicated by independent sedimentological evidence) - a deep water carbonate basinal facies exposed at Stage Cove in the western part of the study area, and a shallow water carbonate shelf facies exposed in the eastern part of the study area southeast of Tramore at Lady Doneraile's Cove and at Lady Elizabeth's Cove (Fig. 1).

This paper sets out to do several things: (1) It discusses the geological setting from where the bryozoans were collected. (2) It will outline these apparent colony form trends. (3) The morphology of the bryozoan colonies from the two areas will be examined to see what can be discerned from them concerning the nature of the different environments in which they grew. (4) Laboratory-based experiments will be described which attempted to determine the hydrological characteristics of colonies of different morphologies, in order to shed light on the sedimentological and hydrological regimes that might have been present during the Llandeilo in southeast Ireland; (5) The paper will attempt to suggest and explain the controlling influences that caused these morphological trends.

2 GEOLOGICAL SETTING

The Lower Palaeozoic rocks of southern County Waterford consist of shallow and deep water carbonates and shales overlain by volcanic material (Tietzsch-Tyler & Sleeman 1994a, b, Sleeman & McConnell 1995a, b). The nature and age of sedimentation and volcanism have been a matter of debate for some time.

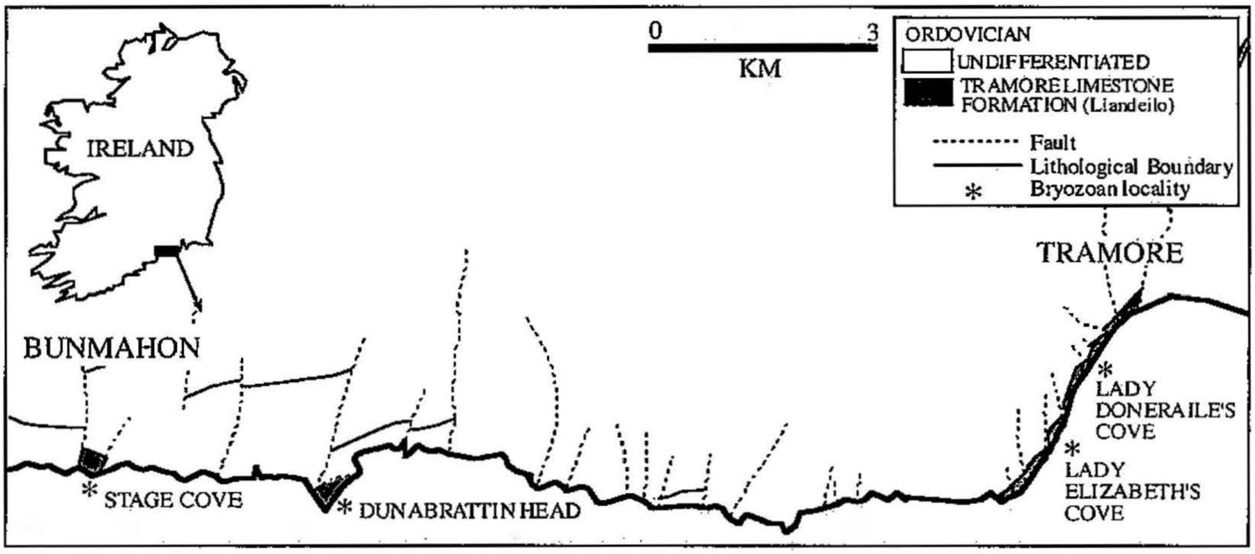

Figure 1. Geological map of south-east Ireland showing the distribution of the Tramore Limestone Formation and the localities mentioned in the text from where bryozoans were collected. Modified from Tietzsch-Tyler & Sleeman 1994a and Sleeman & McConnell 1995a.

Cambrian, Arenig, or Llanvirn sediments are overlain unconformibly by dark shales of the Llanvirn Tramore Shale Formation (to the east) and the Dunabrattin Shale Formation (to the west). These are in turn overlain by the Tramore Limestone Formation, which consists of interbedded shales and carbonates. It is best exposed southwest of the town of Tramore (Ball 1978), Dunabrattin Head (Stillman 1978) and Stage Cove, Knockmahon (Stillman 1978) (Fig. 1), from where specimens of *Diplotrypa petropolitana* have been collected. During the Caradoc volcanism produced a succession of rhyolites, breccias and tuffs (Stillman 1978) which have been assigned to the Campile Formation. It has been postulated that this succession represents a submarine volcanic island arc formed at the margins of the Avalonian continental plate margin above subducting Iapetus Ocean.

The Tramore Limestone Formation crops out in southeast County Waterford, Ireland from Tramore Bay in the east to Ballydowne Bay in the west. Exposures of the Tramore Limestone Formation are excellent along the 30-60 m high coastal sea cliffs but are only accessible by the occasional entrenched gulley, and the inland outcrops are obscured by glacial drift.

The formation consists of grey calcareous mudstones, siltstones, and sandstones with interbedded blue-grey argillaceous nodular limestone beds containing a rich shelly fauna (Murphy 1958, Mitchell *et al.* 1972, Tietzsch-Tyler & Sleeman 1994b, Sleeman & McConnell 1995b, Buttler & Wyse Jackson 1997). The more carbonate-rich beds represent buildups of shelly faunas in shallow water adjacent to the volcanic arc to the southeast (Tietzsch-Tyler & Sleeman 1994a). In response to contemporaneous faults downthrown to the northwest, the Tramore Limestone Formation grades from a shallower shelf facies in the east to a deeper basinal facies in the west. The transition from shelf to basinal facies occurs between Black Rock and Dunabrattin Head (Sleeman & McConnell 1995a). The shelf facies is more fossiliferous and carbonate-rich than the muddier basinal facies (Phillips *et al.* 1976, Carlisle 1979, Boland 1983).

The shelf facies reaches a maximum 65 m thick and comprises calcareous sandstones, siltstones, and mudstones, and limestones which have yielded a rich and diverse fauna. These light to dark grey indurated nodular limestones dip steeply 78° northwest. This shelf facies is best exposed to the east towards Tramore.

The basinal facies, which reaches a maximum thickness of 450 m, is dominated by calcareous shales with more widely spaced, more argillaceous, and less continuous limestones than the shelf facies, and contains immature brachiopods and trilobites. It is well exposed at Boat Strand at Dunabrattin Head and at Stage Cove.

Bryozoans have been reported as most abundant at Tramore from Lady Doneraile's Cove and Lady Elizabeth's Cove to Great Newtown Head, and at Dunabrittin Head, Stage Cove, and Ballydowane Bay (Fig. 1), where they commonly occur in the more carbonate-rich nodular limestones. The shalier beds often contain fragmentary bryozoan, brachiopod, and trilobite remains.

3 FAUNA AND CORRELATION OF THE TRAMORE LIMESTONE FORMATION

The earliest record of fossils from the Tramore area were those noted by Frederick M'Coy in a monograph on Irish Lower Palaeozoic fossils published in 1846 (M'Coy 1846). He illustrated a coral *Favosites petropolitana* var. *lycopodites* Emmons, which is now known as the trepostome bryozoan *Diplotrypa petropolitana*, the subject of the present study.

In the 1860s the officers of the Geological Survey of Ireland collected extensively from limestones (the Tramore Limestone Formation) and black shales in the area. Baily (1865) listed many taxa including 6 graptolite species (from the shales), 22 brachiopods, 25 trilobites, some gastropods, cephalopods, corals, echinoderms, and four bryozoans including *Stenopora fibrosa* var. *lycoperdon* [*Diplotrypa petropolitana*]. *D. petropolitana* has a complex nomenclatural history which requires evaluation by the ICZN. Until our application (Wyse Jackson, Buttler & Key 2001) is considered and the ICNZ publishes its opinion on the nomenclatural status of the taxon, we prefer to leave it in open nomenclature.

At the end of the last century Reed (1899) noted many species and described several trilobite species from the formation. Little work was carried out until Carlisle (1979) who mapped the area as part of a Ph.D. study. Although she collected many brachiopod taxa, these still remain to be fully described (Parkes & Harper 1996). Assessment of the complete fauna has given an unequivocal Llandeilo age for the Tramore Limestone Formation, and has allowed for correlation with the Courtown Limestone Formation 75 km to the east. Initially correlation was on the basis of the common occurrence of the rare trilobite *Eirelithus* (Crimes & Crossley 1968), but subsequently on the basis of additional faunal elements (Mitchell et al. 1972, Carlisle 1979). Twelve brachiopod genera including *Dalmanella, Glyptorthis, Hesperorthis, Howellites, Leptestiina, Palaeostrophomena, Philhedrella, Platystrophia, Porambonites, Salopia* and *Sowerbyella* and four trilobite genera are common to both formations with the stratigraphically restricted brachiopod *Glyptorthis crispa* (M'Coy) and trilobite *Eirelithus* being particularly important for their correlation.

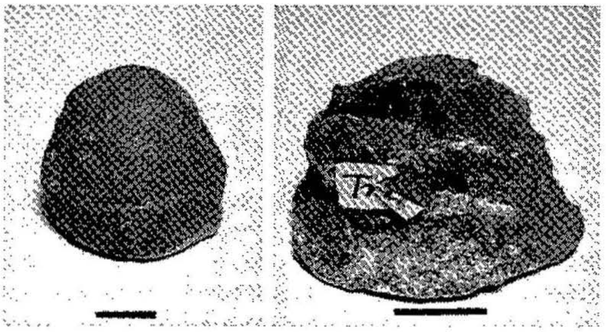

Figure 2. *Diplotrypa petropolitana* colonies form the TLF showing the two end members of colony form. The dome-shaped colony (h/w = 1.0) on the left is from Stage Cove [TCD.49189]; the bell-shaped colony (h/w = 0.55) on the right is from Lady Elizabeth's Cove [TCD.49192]. Scale bars = 1cm.

4 MATERIAL

This paper is based on material collected by the authors during fieldwork in June 1999 and February 2000, and on specimens contained in various museum collections: Trinity College, Dublin [prefix TCD.], Geological Survey of Ireland, Dublin, The Natural History Museum, London, and the National Museum and Galleries of Wales, Cardiff.

5 METHODS

5.1 *Field analysis*

Detailed examination of colonies *in situ* at the two sites (Stage Cove and Lady Elizabeth's Cove) near Tramore was carried out. We measured colony height, basal diameter and noted orientation relative to bedding (i.e. upright or overturned) as well as the spatial distribution of colonies (i.e. colonies clustered into lenses or dispersed). We were also able to access the nature of preservation of colonies at both sites. In addition photographs were taken for later colony shape and size analysis.

5.2 *Laboratory analysis*

Eighty nine specimens of the trepostome *Diplotrypa petropolitana* held in various museums were examined for this study. Colony height and basal diameter were measured to the nearest mm. From these measurements, size (height x basal diameter = mm^2) and shape (Height/basal diameter = dimensionless) were calculated.

Eight replicates of 12 different models both of actual colonies, and of dome-shaped and bell-shaped hypothetical colonies of various sizes were cast in resin. The resin had a density of 1.06 g/cm^3 which was chosen to be similar to the density of living bryozoan colonies. These models were used in wave tank experiments to access the effect of colony shape on settling, and on movement under different wave conditions. This was done in order to understand the features observed in the field.

The wave tank measured 45 cm long x 30 cm wide x 30 cm deep. Water depth: 20 cm. Substrate thickness: 1 cm. Substrate type: very well sorted fine sand.

When doing experimental wave tank work, one must be careful of edge effects (Kaneko 1985). As each model on average only occupied 0.34% of the tank's water volume this effect should have been minimal.

Several experiments were carried out: (1) Settling pattern of colonies. Models were dropped into the water from three initial orientations: right side up, upside down, and sideways. They were simply allowed to fall through the water column and their final attitude in the sediment recorded (upright or overturned). (2) Effect of water agitation on colonies placed on substrate in living position. For each type of colony model, the eight models were placed upright on the sediment surface in the wave tank. They were then subjected to 3 different wave velocities (Low = 2 cm/sec; Medium = 6 cm/sec; High = 8 cm/sec) and in each case their final attitude to the substrate recorded. These velocities were created by dipping a paddle of dimensions 21.5 cm x 13.5 cm to depths of 6, 12, and 18 cm respectively and moving it backwards and forwards across the tank three times.

6 RESULTS

6.1 *Field observations of the nature of bryozoan colonies at each site*

1. Colonies in Stage Cove appeared to be smaller than those at Lady Elizabeth's Cove.
2. Colonies at Stage Cove appeared to be more dome-shaped than bell-shaped.
3. Colonies at Lady Elizabeth's Cove appeared to be more bell-shaped than dome-shaped.
4. At Stage Cove 58% [73] of colonies observed were upright while 42% [53] were overturned.
5. At Lady Elizabeth's Cove 83% [112] of colonies were upright while 17% [23] were overturned.

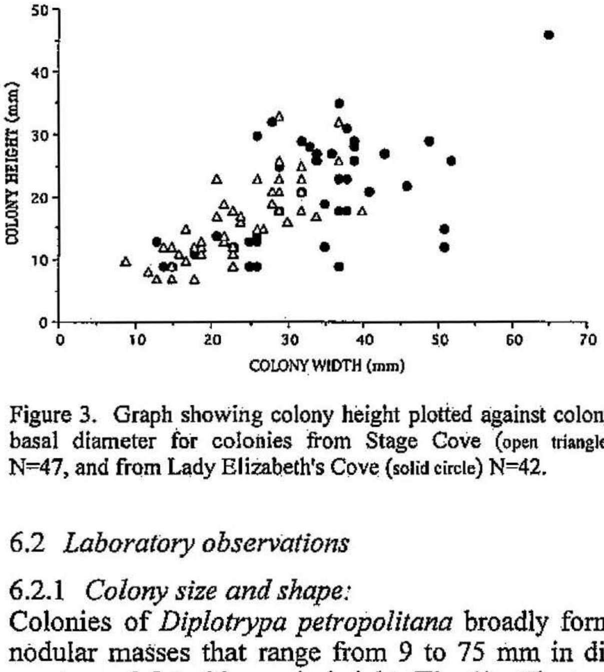

Figure 3. Graph showing colony height plotted against colony basal diameter for colonies from Stage Cove (open triangle) N=47, and from Lady Elizabeth's Cove (solid circle) N=42.

6.2 *Laboratory observations*

6.2.1 *Colony size and shape:*

Colonies of *Diplotrypa petropolitana* broadly form nodular masses that range from 9 to 75 mm in diameter and 5 to 32 mm in height (Fig. 2). The majority of colonies have flat or concave bases. Several colony morphologies have been identified in this study. Conical colonies narrow towards their pointed apices at angles of roughly 45°. Domes are similar to cones but have rounded apices, and may be depressed. Mound-shaped colonies have straight or sub-parallel sides or may show marked increase or decrease in colony width. Some mounds show marked asymmetrical development which suggests that these colonies may have grown on slopes of up to 20°. Nodular and irregular-shaped colonies are present, but rare.

Eighty nine colonies of *Diplotrypa petropolitana* were analyzed for shape, with 53% coming from Stage Cove and 47% from Lady Elizabeth's Cove. These comprised 61% relatively complete hand samples and 39% photographs of colonies in outcrop showing cross-sectional views. The *Diplotrypa petropolitana* colonies from Stage Cove were significantly smaller in both height and width than those from Lady Elizabeth's Cove (Table 1; t-tests, $p < 0.01$). A simple shape parameter was calculated from the height/basal diameter ratio that removed the effect of size (Table 1). 93 % of all of the colonies had values less than 1 (Fig. 3). Based on this shape parameter, *Diplotrypa petropolitana* colonies from Stage Cove were more dome shaped (mean height/width ratio = 0.67) whereas those from Lady Elizabeth's Cove were more bell shaped (mean height/width ratio = 0.62), but this difference was insignificant (t-test, $p = 0.24$).

In the resin models domes were slightly larger (mean size = 614 mm^2) than bells (mean size = 612 mm^2) (t-test, $p > 0.07$). Domes were significantly more cube-shaped (mean height/basal diameter ratio = 0.73), whereas bells were more pancake-shaped (Mean height/basal diameter ratio = 0.48) (t-test, $p = 0.028$) (Table 2).

6.2.2 *Settling experiments*

There was no significant correlation ($p > 0.05$) between height, basal diameter or size, and initial orientations in the settling experiments. Most colonies (91%) tended to settle upside down regardless of shape. Bells were less likely to become orientated right side up than domes, but this was barely insignificant ($R2 = 0.251$, $p = 0.097$). The correlation improves with quadratic regression ($p < 0.05$) indicating that bells were less likely to become orientated right side up than pancakes and domes.

6.2.3 *Wave experiments*

Specimens with right side up final orientation often moved along the substrate but did not flip over during exposure to wave currents. The specimens (particularly the bell-shaped variety) tended to end up with a fringe of sediment covering their lateral margins after settling in medium energy and under high energy were often buried. As the current velocity increased, the percentage of models that overturned increased from 9% (low velocity) to 30% (medium velocity) to 58% (high velocity). There was no correlation ($p > 0.05$) between size, height, or basal diameter and orientation in low or high energy regimes. There was an inverse correlation between shape and orientation in medium and high energy

Table 1. Field observations.

	Stage Cove (Basinal facies)	Lady Elizabeth's Cove (Shelf facies)
	n, mean, sd	n, mean, sd
Colony size*	47, 379 mm^2, 247 mm^2	42, 707 mm^2, 486 mm^2
Colony shape†	47, 0.67, 0.18	42, 0.62, 0.22
Colonies upright	58%	83%
Colonies overturned	42%	17%
Spatial distribution	Clustered (lenses)	Dispersed

n = number of colonies; sd = standard deviation; *size = height x basal diameter; †shape = height / basal diameter.

Table 2. Model size and shapes.

Specimen	Height (mm)	Basal diameter (mm)	Size (mm^2)	Shape (height/basal diameter)
DOMES				
Large (M) - TCD.50340	25	28	700	0.89
Skewed (C) - TCD.49181	27	33	891	0.82
Medium (M) - TCD.50341	25	32	800	0.78
Small (M) - TCD.50342	20	28	580	0.69
Small (C) - TCD.49189	23	23	529	1.00
Flat (C) - TCD.49165	7	29	203	0.24
Averages: x (sd)	21 (7)	29 (3)	614 (238)	0.73 (0.26)
BELLS				
Extra large (M) - TCD.50343	21	45	945	0.47
Large (M) - TCD.50344	21	40	840	0.53
Medium (M) - TCD.50345	21	39	819	0.54
Small (C) - TCD.28155	10	18	180	0.56
Flat (M) - TCD.50346	13	36	468	0.36
Small flat (M) - TCD.50347	12	32	384	0.38
Averages: x (sd)	17 (6)	35 (9)	612 (324)	0.48 (0.10)

Table 3. Results of colony settling experiments using models listed in Table 2.

	Right side up initial Orientation		Upside down initial Orientation		Sideways initial Orientation		Average %	
Final Orientation	Right side up	Upside down	Right side up	Upside down	Right side up	Upside down	Right side up	Upside down
Domes (n=48)	12 [25%]	36 [75%]	2 [4%]	46 [96%]	7 [15%]	41 [85%]	15	85
Bells (n=48)	5 [10%]	43 [90%]	0 [0%]	48 [100%]	0 [0%]	48 [100%]	3	97

Table 4. Results of wave action experiments using models listed in Table 2.

	Low Energy		Medium Energy		High Energy	
	Right side up	Upside down	Right side up	Upside down	Right side up	Upside down
Domes (n=48)	45 [94%]	3 [6%]	31 [65%]	17 [35%]	17 [35%]	31 [65%]
Bells (n=48)	42 [88%]	6 [12%]	36 [75%]	12 [25%]	23 [48%]	25 [52%]

regimes. Put simply, the models that were more dome-shaped were more likely to flip over - but this correlation was insignificant ($p > 0.05$). A higher proportion of bell-shaped colonies remained upright at medium and high wave velocities, but again this correlation was not significant (t-test, $p > 0.05$).

7 DISCUSSION

Colonies were not cemented to the substrate and so were liable to being turned and rolled in water currents. Such mechanisms explain the development of irregular and nodular colony forms, and the occasional occurrence of colonial regeneration at different basal angles. Flat-bottomed colonies (such as those developed at Stage Cove) or concave-bottomed colonies (as seen in more specimens at Lady Elizabeth's Cove) probably sat on the sediment surface and were usually held in a normal orientation by their weight.

The differences in size and shape of *Diplotrypa petropolitana* colonies between Stage Cove and Lady Elizabeth's Cove may be due to a combination of several factors. Perhaps the smaller colonies are found in Stage Cove because they grow more slowly due to their deeper water conditions. Perhaps size was partially controlled by the availability of nutrients which would have been more plentiful in the shallow water environments of Lady Elizabeth's Cove, rather than in the deeper water basins to the west. Colony width may have been controlled by the coarseness of the sediment - those colonies from Lady Elizabeth's Cove grew in coarse shallow water skeletal carbonates, while those at Stage Cove grew in deep water argillaceous carbonates. A further alternative view, but one which is less favoured by us, is that the smaller colonies are found in Stage Cove because they were preferentially transported due to their smaller size to the deeper environment from the shallow Lady Elizabeth's Cove environment where they lived.

We suggest that the slight predominance of bell-shaped colonies in the shallow water facies was an adaptation to the higher energy regimes that would have been present. As has been clearly demonstrated in the settling and wave experiments, these bell-shaped colonies were more stable than the dome-shaped counterparts. The fact that, firstly, in the settling experiments the bulk of the bell-shaped colonies settled upside down, and that secondly this is not seen in the exposures at Lady Elizabeth's Cove, suggests that few in fact were entrained by wave action. The majority of colonies were found in life position on horizontal bedding planes, and not in clusters which would have suggested transportation, except in one exceptional horizon where colonies accumulated at the bottom of foreset crossbeds. The characteristics of the carbonates suggest that they were deposited in shallow water conditions.

The deeper water facies at Stage Cove contained a higher proportion of dome-shaped colonies which we have demonstrated are more susceptible to being overturned than their bell-shaped counterparts. This was reflected in the counts of colony orientation made in the field. Examination of the exposures where they are best seen at Stage Cove revealed that the bulk of specimens were preserved in small lense-like accumulations, where colonies had been moved and sorted by current activity. Although the settling experiment showed that more dome-shaped colonies would settle upright when entrained, we suggest that the dominance of overturned specimens at the localities is easily explained by the fact that most of the specimens are small and dome-shaped and most would have moved in moderate current activity. It is likely that all but the smallest colonies would simply have rolled over rather than be lifted into the water column.

We postulate that the source of the wave currents that agitated the colonies in the basinal facies may have been episodic storms which would have produced the tempstites seen at Stage Cove. Similarly shaped colonies in the mid-Ordovician in Pennsylvania also seem affected primarily by storm processes (Cuffey 1997)

Spjeldnaes (1996) has discussed the application of morphological shape of Lower Ordovician bryozoans from Öland, Sweden in determining sediment - water interface conditions. Concave-based colonies which are commonly developed in *Diplotrypa petropolitana* were thought to indicate a slight winnowing or removal of surface sediment which allowed the basal layer to grow downwards. We are in agreement with his findings, and further suggest that flat-based colonies (such as those in the basinal facies at Stage Cove) grew at a time when sedimentation rate was low.

8 CONCLUSIONS

There is clear morphological partitioning in colonies of *Diplotrypa petropolitana* from the Llandeilo of Tramore, Co. Waterford. Those that grew in shallow water shelf facies were larger, more bell-shaped, and more frequently preserved in life position. By way of contrast those preserved in the basinal facies were smaller, more dome-shaped, and were more susceptible to being overturned by current activity. Colony morphology (shape and size) in *Diplotrypa petropolitana* is controlled by the prevailing environmental and sedimentological characteristics of each site, and provide a useful tool for palaeonenvironmental interpretation.

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