EXPLODED *PLAGIOSTOMA* SHELLS: MACROFOSSIL CONFIRMATION OF DISPLACIVE CEMENTS IN LIMESTONES AND CONCRETIONS OF THE BLUE LIAS FORMATION (LOWER JURASSIC) AROUND LYME REGIS, DORSET, U.K.

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Nearly 70 years ago Peter Kent drew attention to 'crazy' *Plagiostoma* shells in the Blue Lias Formation (Lower Jurassic), which were cracked and the pieces separated by limestone growth. Such 'exploded' shells result from displacive cement growth, which arises when microspar growth continues after total occlusion of pores, thus effectively increasing pore volume. Growth of displacive cements in the Blue Lias has been demonstrated using SEM, but the commonest suggestive evidence from limestones is acid insoluble residue values <20%. 'Exploded' shells can be distinguished from those damaged by compaction because the pieces maintain their relative orientations and the shell profile remains a smooth curve. Compaction damage reorientates shell pieces or displaces them across small faults. Cracks opened perpendicular to their sides. Thus, crack orientation relative to the hinge line can be used to detect any preferred stretching direction. Point counts were used to quantify the amount of stretching. Proportion of cracks on photographs ranges from 6–25%. Kent also recorded 'crazy' *Plagiostoma* shells from the top of the Planorbis Zone in Nottinghamshire. They are common and well developed at this horizon in Devon, but also occur at other horizons.

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INTRODUCTION

Plagiostoma gigantea Sowerby, 1812, is one of the commonest bivalves in the Blue Lias Formation near Lyme Regis, Dorset, U.K. Occasionally, examples occur in the limestone beds that are cracked and which appear to have been pulled apart. They resemble the surface of some muffins that early in cooking form a hard crust, but as the heat penetrates the mixture the dough continues to rise, thus cracking the brittle surface crust. We believe that these 'exploded' *Plagiostoma* shells are macroscopic (and therefore obvious) evidence for the growth of displacive cements in the limestone beds that contain them. Displacive cements arise when diagenetic minerals do not just passively fill the pore spaces, but continue to grow when the pores are completely occluded, thus forcing the host sediment to expand. Arzani (2006) used electron microscopy (EM) to demonstrate the presence of displacive cements in the limestones of the Blue Lias Formation. He showed (e.g., Arzani, 2006, fig. 8a, p. 100) that calcite microspar crystals in the centres of the limestone beds were surrounded by 'clay cages': that is rims of clay minerals compacted by the growth of the microspar crystals. Arzani (2006, p. 100) also cited the presence of ostracod carapaces that had been pushed apart by the calcite crystal growth. In other words microscopic scale analogues of the 'exploded' *Plagiostoma* shells we describe here.

Neither our observations nor interpretations are entirely new. Kent (1957) drew attention to what he called 'crazy *Plagiostoma*' shells. It is worth quoting Kent's comment in full because he recognized the key features that distinguish 'exploded' *Plagiostoma* shells from those damaged by other means, particularly crushing. He wrote:

> "Positive evidence of dilation of the original sediment associated with limestone deposition is provided by the occurrence of *Plagiostoma gigantea* specimens which have become "crazy" (i.e. like the superficial appearance of a septarian nodule) through separation of the pieces of the fractured shell by normal limestone while retaining their original relative orientation; this has been observed in the highest part of the *planorbis* zone in Nottinghamshire, and is known elsewhere." (Kent, 1957, p. 429).

It is clear from the above that Kent recognized that the 'exploded' *Plagiostoma* shells resulted from growth of displacive cement, that 'exploded' shells could be distinguished from crushed shells by the fact that the shells were not distorted merely 'pulled' apart, and that 'exploded' shells were more common at certain stratigraphic horizons. Interestingly, they are common near the top of the Planorbis Zone in Devon as well as Nottinghamshire.

Arzani (2006) used EM to demonstrate his 'clay cages', but the most common evidence that suggests the possibility of displacive cement growth comes from very low acid insoluble residue (AIR) values. For example, Hallam (1960, fig. 2, p. 11) gives five values below 10% and another 14 below 20% from Blue Lias limestones. Similarly, Arzani (2004, p. 263) gives three values for the centres of Blue Lias limestone nodules between 15.5% and 18.2% and Paul *et al*. (2008, p. 265) give three values for limestones and concretions of between 13.5% and 18.5%. All these values imply that, after diagenetic cement growth, the limestones and concretions contain >80% and in rare cases >90% carbonate. Such values are too high to result from passive fill of pore spaces even in freshly deposited clay. In the past AIR values have been taken to indicate original porosities, so-called 'minus-cement porosities' (see review in Raiswell and Fisher, 2000). Yet it seems impossible that original porosities >80% could survive at burial depths at which even early diagenesis started (several 10s of metres below the sea floor). Of course, very low AIR values can result from the original sediment containing some carbonate when first deposited. Nevertheless, in the absence of obvious evidence of original carbonate, very low AIR values are the commonest evidence suggestive that displacive cements may be present. The 'exploded' *Plagiostoma* shells described below are additional macroscopic evidence of displacive cements. If one wishes to study displacive cements, any limestone with very low AIR values and 'exploded' fossils would be a good place to take samples.

Coincidentally, Kent (1957) was commenting on Hallam (1957), who first suggested that the limestone-shale rhythms in the Blue Lias Formation were primary depositional features. Kent (1957) argued that the limestones were diagenetic, with the evidence of 'exploded' *Plagiostoma* shells demonstrating the growth of diagenetic cement in the limestone beds. The controversy is still current, but largely results from the confusion of two related questions: 'What is the origin of the rhythms?' and 'What is the origin of the limestone beds?' The rhythms are clearly primary as is demonstrated by the trace fossils (Hallam, 1957; Moghadam and Paul, 2000; Martin, 2004; Paul and Underwood, 2010). Pale-filled trace fossils penetrating dark host sediment and dark-filled trace fossils penetrating pale host sediment indicate unequivocally that there was a primary difference in the sediment type at the time when the trace fossil burrows were being filled with sediment. It is now 30 years since House (1986) first suggested the idea that Blue Lias rhythms were orbital forced (see also Weedon, 1986; Ruhl *et al.*, 2010; Smith, 1989: Weedon *et al.*, 2017), although see Sheppard *et al.*, (2006) for an alternative view. Equally clearly, the limestone beds were not deposited as well-cemented limestone; the trace fossils are burrows not borings. Thus, the limestone beds are diagenetic. In a sense both Hallam (1957) and Kent (1957) were correct in their arguments, but were considering two different aspects of the origin of the Blue Lias Formation.

Damaged shells result from a variety of causes, not least crushing during sediment compaction. Crushed *Plagiostoma* shells are also common in the Blue Lias Formation exposed around Lyme Regis, Dorset, so the two causes of damage need to be distinguished. *Plagiostoma* shells are particularly useful as most are very much darker than the host carbonate rock and so the patterns of cracks show up particularly well. Cracks are much more difficult to detect in latex casts from external moulds of *Plagiostoma* shells (e.g., LYMPH 2016/127). Equally, much of the shell surface is a smooth curve, which renders distortions due to crushing more obvious. This paper aims to document the differences between crushed and 'exploded' shells, to quantify the amount of expansion, assess any anisotropy, and to document the stratigraphic levels within the Blue Lias Formation at which 'exploded' *Plagiostoma* shells have been recorded. The material described herein was collected loose, mostly in Devon, west of Lyme Regis, Dorset, England (Fig. 1) and is preserved in the Lyme Regis, Philpot Museum (registration numbers LYMPH 2016/121-127).

TECHNIQUES

Collected specimens were cleaned with an air pen to expose as much of the shell as possible. The shells were then inspected to check for any possible crushing or other cause of fragmentation. Suitable specimens were photographed using commercial software (Zerene Stacker) to ensure photographs were completely in focus. To check for any preferred stretching direction, the orientations of sections of cracks between triple junctions were measured with reference to an arbitrary datum, the hinge line (Fig. 2). Generally, photographs were orientated with the hinge line east–west. Where cracks were curved between triple junctions, the orientation of a straight line between the triple junctions was used (Fig. 2). Usually there are several examples of conspicuous growth lines or the margins of the shell where equivalent points on either side of a crack can be recognized. These examples were used to check that stretching direction was perpendicular to the sides of the crack (Fig. 3). Wherever this condition is met, the orientation of the cracks reveals stretching direction. Thus, a rose diagram of crack orientation can be used to test for any preferred stretching direction. Crack orientation was grouped into 45° segments, starting at 1, 11, 21, 31 and 41°, to identify the maximum departure from the expected random distribution. Then a chi-squared test was used to detect any significant departure from random (Table 1). In practice preferred crack orientation is usually immediately obvious (see Discussion below).

Point counts were used to estimate the amount of stretching. To accommodate specimens where preservation was less than perfect, for example where pieces of shell were missing, a modified point counting technique was used. An overall grid of eleven equally-spaced vertical and eleven equally-spaced horizontal lines was superimposed over the photograph of the

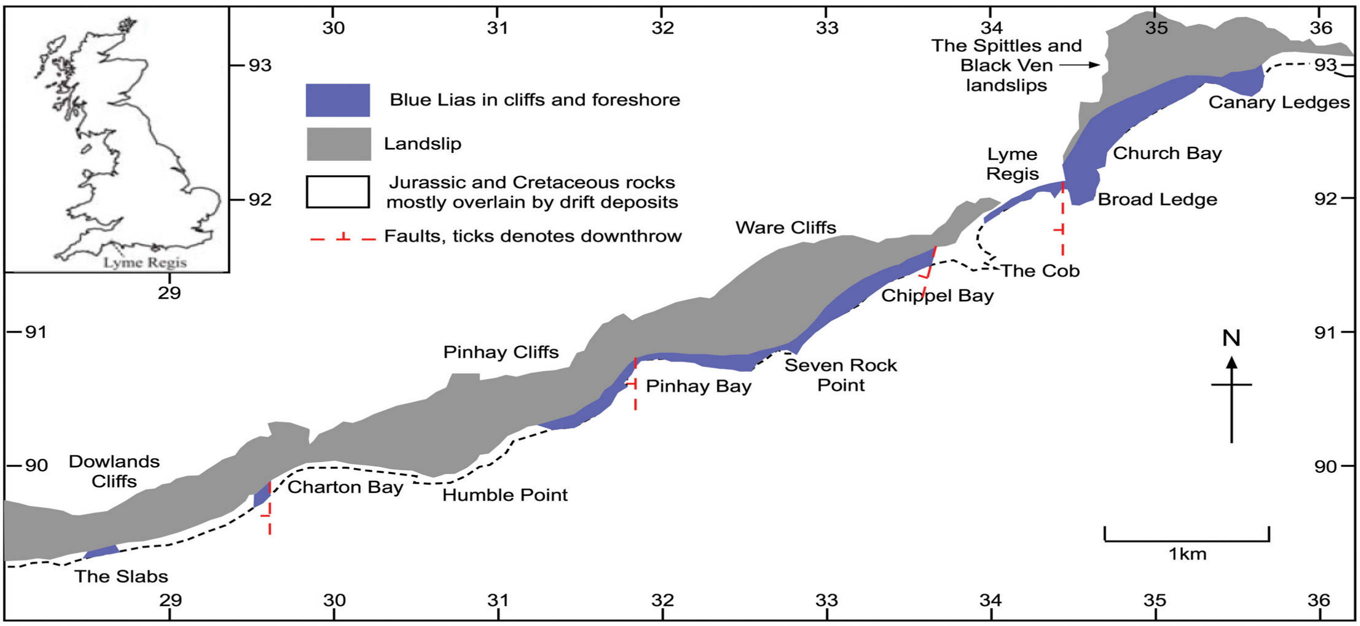

Figure 1. *Map showing the exposures of the Blue Lias Formation in the vicinity of Lyme Regis, Dorset, UK. Numbers around the margin represent 1 km divisions of the British National Grid in 100 km square SY. (Modified from Gallois and Paul, 2010, fig. 1)*

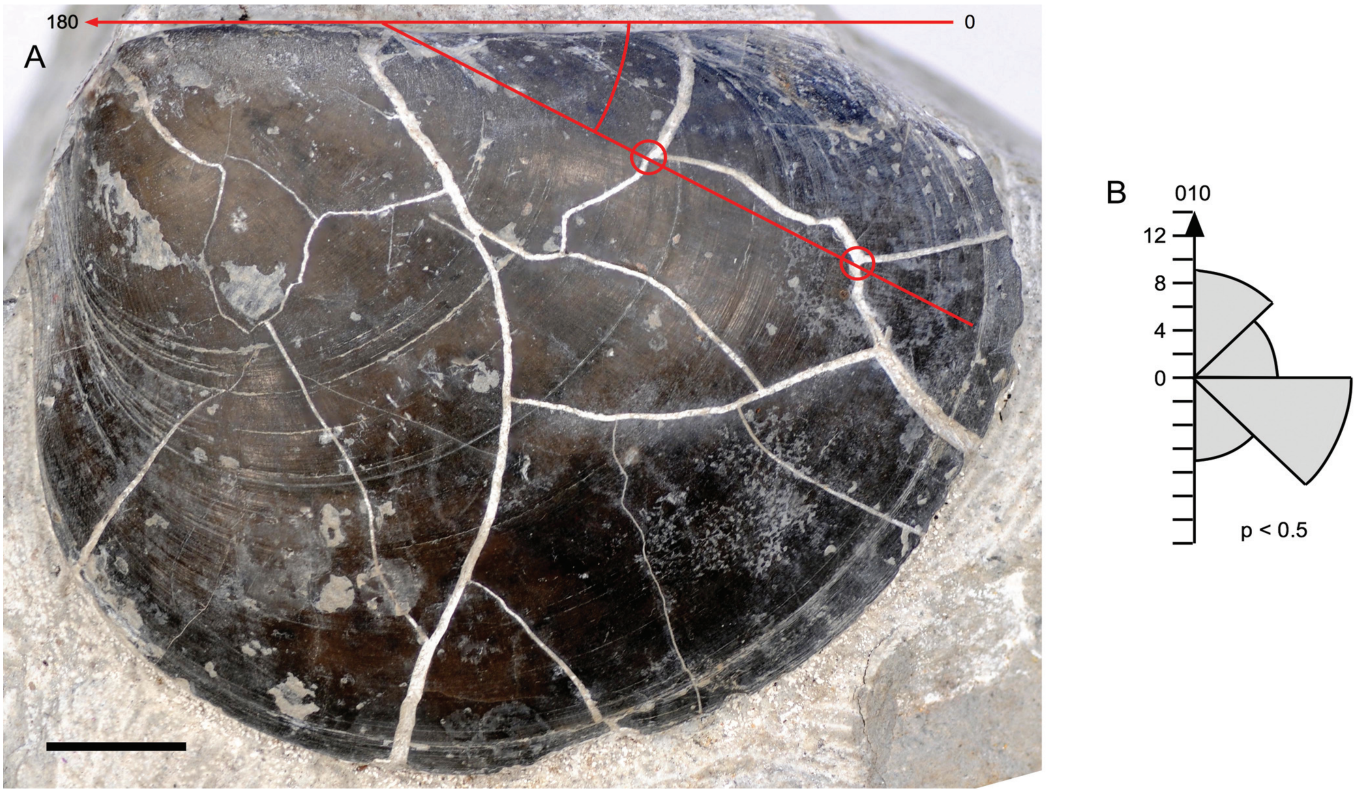

Figure 2. *(**A**) Measurement of the orientation of cracks in an 'exploded'* Plagiostoma *shell (LYMPH 2016/121). Two triple junctions are identified (red circles) and the angle between a line parallel to the hinge line and a straight line connecting the two triple junctions is recorded. Specimen found loose near Seven Rock Point, Devon, from unknown horizon in the Blue Lias Formation. (**B**) Rose diagram showing the maximum deviation from random in the frequency distribution of crack angles. In this example p < 0.5 (= 50 %) and the null hypothesis of random crack orientation cannot be rejected. Scale bar = 10 mm.*

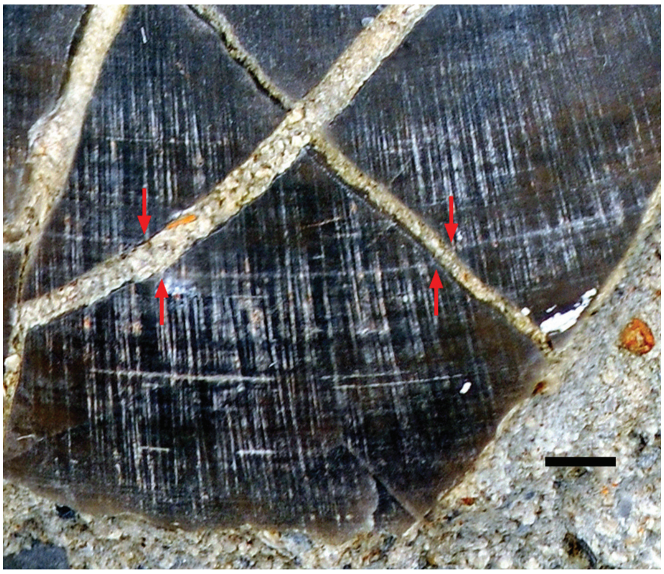

Figure 3. *Offset of growth lines (arrows) by cracks in an 'exploded'* Plagiostoma *shell (LYMPH 2016/122). Blue Lias Formation, Bed H54, Pinhay Bay, Devon. Scale bar = 2 mm.*

shell (Fig. 4). Counting was rejected for any rectangle in this grid that was not completely filled with shell material and cracks. Rectangles at the edges of the shell or where it was suspected that shell chips were missing were rejected. A second grid of 25 points was created to fit within the larger grid rectangles. Points in this grid lying over a crack were counted within all suitable larger grid rectangles. Then the total of points lying over cracks was expressed as a percentage of the total number of points counted (Table 2). Results are presented in Tables 1 and 2.

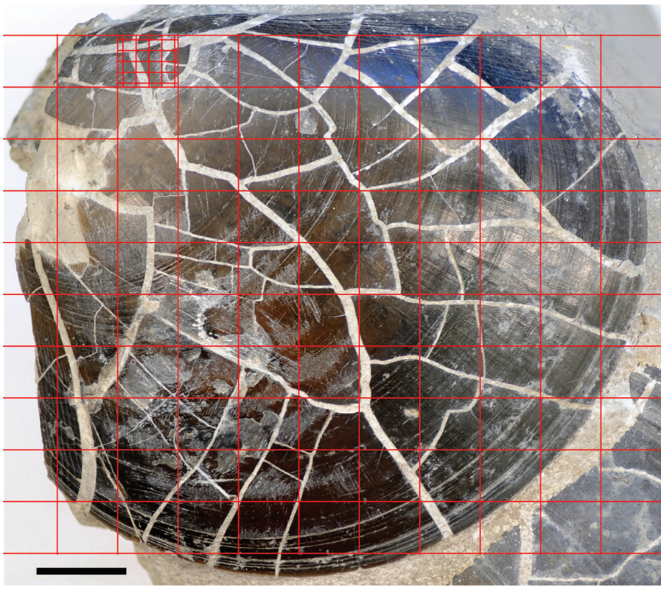

Figure 4. *Diagram to show system of point counting to estimate amount of expansion in an 'exploded'* Plagiostoma *shell (LYMPH 2016/123.1). Intersections of the finer grid were counted for every rectangle within the coarser grid in which the entire rectangle overlies shell material. So, for example, none of the left column of large rectangles was used for point counting and only three (the 3rd, 4th and 5th up from the bottom) in the second column. Blue Lias Formation, Bed H54, Pinhay Bay, Devon. Scale bar = 10 mm.*

Specimen	Orient	Observed	Chi sq	P	Orient	Observed	Chi sq	P	Orient	Observed	Chi sq	P
2016/121	1-45	6			11-55	9			21-65	11		
	46-90	10			56-100	7			66-110	9		
	91-135	12			101-145	13			111-155	9		
	136-180	8	2.31	c.5	146-10	7	2.77	<.5	156-20	7	0.94	c.8
2016/121	31-75	11			41-85	9						
	76-120	10			86-130	11						
	121-165	9			131-175	10						
	166-30	6	1.63	<.7	176-40	6	1.63	<.7				
N = 36												
2016/123.1	1-45	41			11-55	33			21-65	29		
	46-90	26			56-100	32			66-110	31		
	91-135	30			101-145	27			111-155	23		
	136-180	22	6.75	<.1	146-10	27	1.03	c.8	156-20	36	2.92	<.5
2016/123.1	31-75	31			41-85	28						
	76-120	31			86-130	27						
	121-165	20			131-175	25						
	166-30	37	5.07	<.2	176-40	39	3.99	<.3				
N = 119												
2016/125	1-45	17			11-55	24			21-65	27		
	46-90	44			56-100	40			66-110	37		
	91-135	52			101-145	54			111-155	48		
	136-180	41	19.61	<.001	146-10	36	13.44	<.01	156-20	42	7.28	<.1
2016/125	31-75	35			41-85	39						
	76-120	27			86-130	18						
	121-165	37			131-175	41						
	166-30	55	12.33	<.01	176-40	56	21.06	<.001				
N = 154												

Table 1. *Tests for preferred crack orientation in 'exploded'* Plagiostoma *shells. Orient = Orientation, Chi sq =* X^2*, P = probability of observing the* X^2 *value from a sample of randomly orientated cracks with 3 degrees of freedom (expressed as decimal fractions). Values <0.05 are statistically significant at the 95 % level.*

Specimen	Total count	Shell	Crack	% of total	% of shell
LYMPH 2016/121	1875	1758	117	6.24	6.66
LYMPH 2016/126	1575	1166	409	25.97	35.08
LYMPH 2016/123.1	1775	1538	237	13.35	15.41
LYMPH 2016/125	1600	1438	162	10.13	11.27

Table 2. *Point counts to detect proportion of cracks in photographs of some 'exploded'* Plagiostoma *shells.*

'Exploded' versus crushed shells

The following criteria enable recognition of crushed shells:

1) Crushing of shells usually results in the distortion of the original smooth profile of the shell;
2) Cracks in the shell often show relative displacement, like miniature faults, with pieces of the shell on either side offset 'vertically' rather than pulled apart 'horizontally' (Fig. 5A, B);
3) The shell pieces often change orientation across a crack, so that the cracks coincide with an angle in the shell profile (Fig. 5A, C);
4) Cracks may show a preferred distribution over the shell if only part of the shell has been crushed (Fig. 5A); and
5) Where crushing has flattened the shell, cracks are widest at the shell margins.

In contrast, criteria for the recognizing 'exploded' shells include:

1) Lack of distortion of the regular, curved shell profile (Fig. 6);
2) Cracks lack any relative fault-like displacement across them, but merely show evidence that shell pieces have been 'pulled' apart (Fig. 6);
3) Intersections of growth lines or shell margins with cracks of different orientations show that shell pieces have been 'pulled' apart in different directions (usually perpendicular to the crack margins, e.g., Fig. 3);
4) Cracks show no preferred distribution over the shell (Figs 2, 4); and
5) Cracks may show a preferred orientation with respect to the hinge line. If so, this may be used to investigate anisotropy in the amount of displacive cement growth in different directions within the rock (Fig. 7).

In both crushed and exploded shells cracks do not penetrate the host rock, but merely separate the pieces of the shell (Fig. 8). The cracks do not result from post-lithification damage due, for example, to fracturing or faulting of the host rock itself. The two categories (crushed and 'exploded') are not mutually exclusive. Some 'exploded' examples also show minor distortion due to local crushing (e.g., Fig. 9).

Results

The distribution of crack orientation is sometimes random, but at least one example (Fig. 7) shows a clear preferred orientation (see Table 1 and discussion below). Point counts vary from about 6 to 26% crack and 94–74% shell (Table 2). If the shell counts represent 100 % of the original, undamaged shell, the crack counts suggest an expansion in two dimensions of up to about 35% maximum (Table 2). 'Exploded' *Plagiostoma* are most common in Lang's Bed H54 (Lang, 1924), but have also been recorded from beds H58, H64, H90, 9, 11 and possibly H70 although that specimen may not have been a *Plagiostoma*. According to Simms (in Simms *et al.*, 2004, p. 64) the Planorbis Zone ranges from Lang's beds H25 to H56 (Lang, 1924). Thus, in Devon, the horizon where 'exploded' *Plagiostoma* shells are most common (Bed H54) is the same as Kent (1957) reported for Nottinghamshire.

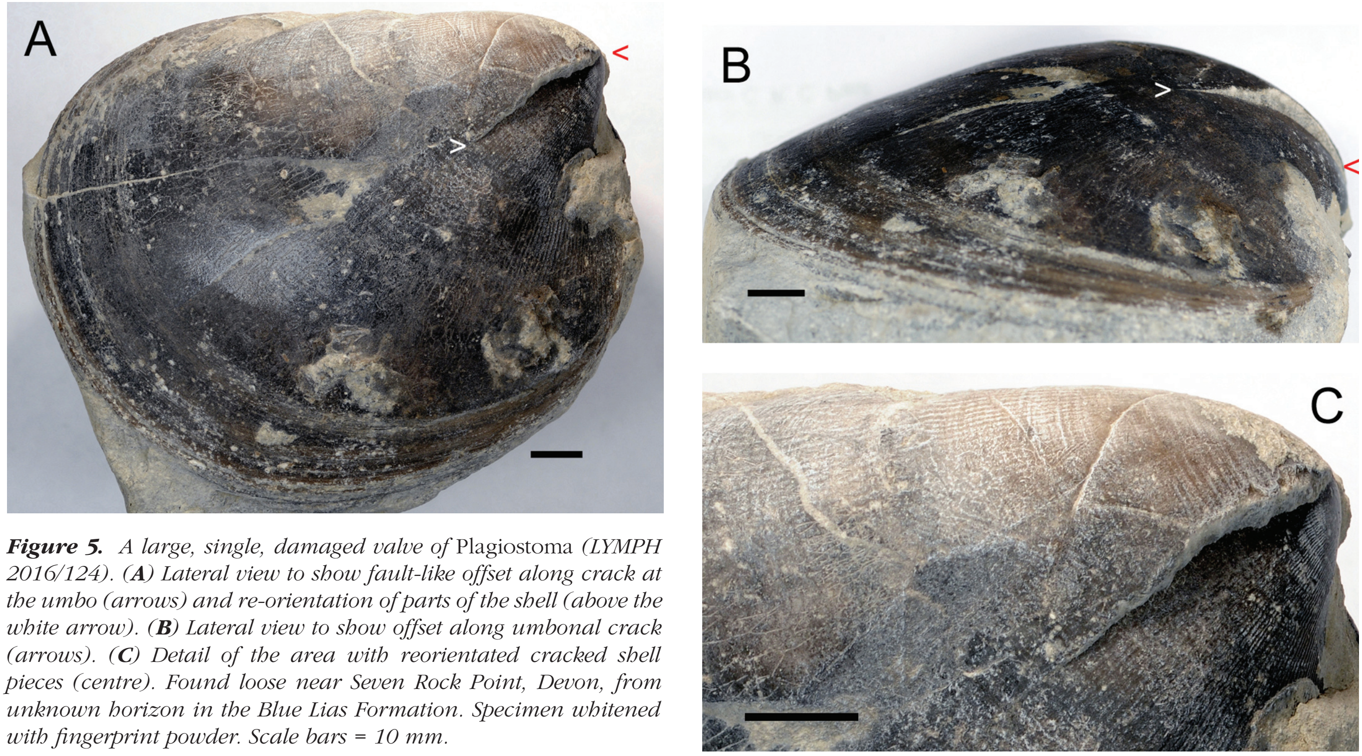

Figure 5. *A large, single, damaged valve of* Plagiostoma *(LYMPH 2016/124). (**A**) Lateral view to show fault-like offset along crack at the umbo (arrows) and re-orientation of parts of the shell (above the white arrow). (**B**) Lateral view to show offset along umbonal crack (arrows). (**C**) Detail of the area with reorientated cracked shell pieces (centre). Found loose near Seven Rock Point, Devon, from unknown horizon in the Blue Lias Formation. Specimen whitened with fingerprint powder. Scale bars = 10 mm.*

Figure 6. *Smooth profile of an 'exploded'* Plagiostoma *shell (LYMPH 2016/121). Found loose near Seven Rock Point, Devon, from unknown horizon in the Blue Lias Formation. Scale bar = 10 mm.*

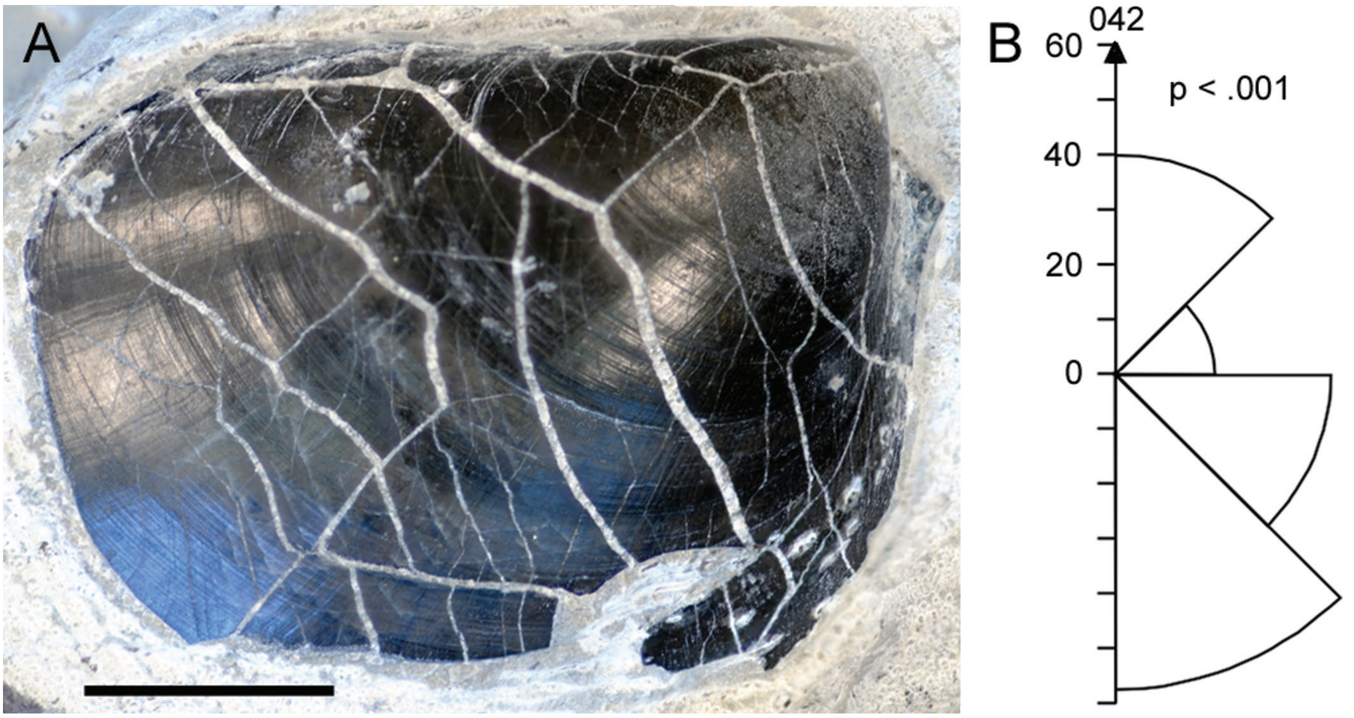

Figure 7. *(**A**) An 'exploded'* Plagiostoma *shell with preferred crack orientation (LYMPH 2016/125). Blue Lias Formation, Bed H54, Pinhay Bay, Devon. Scale bar = 10 mm. (**B**) Rose diagram showing maximum deviation from random in the frequency distribution of crack angles.*

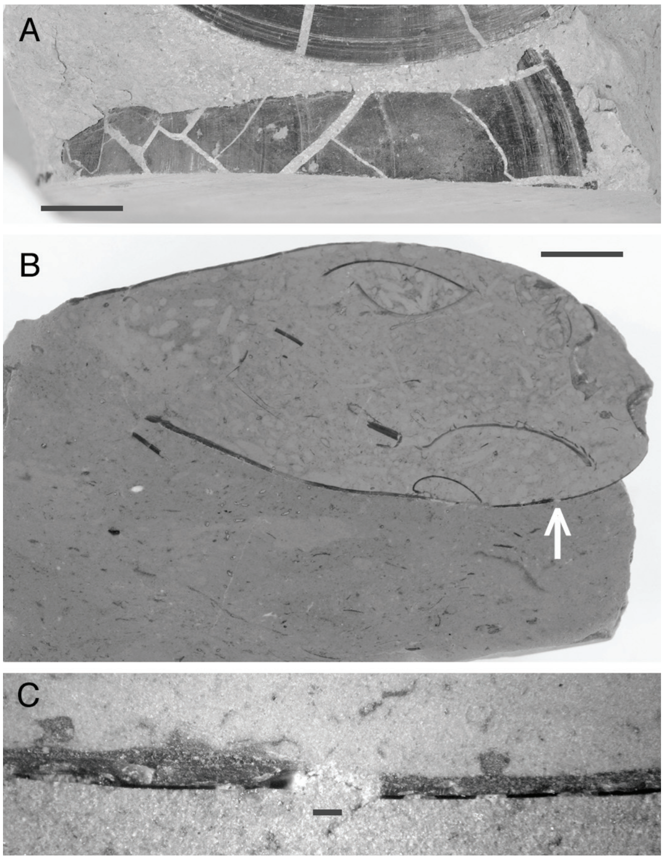

Figure 8. *Sectioned example of an 'exploded'* Plagiostoma *shell to show the cracks in the shell do not extend into the host rock (LYMPH 2016/123.2). (**A**) Surface view with cut surface (below). (**B**) View of section. Note the two valves are slightly offset and the fill between them is paler and more obviously bioturbated than that surrounding the shell (below and left). (**C**) Detail of crack arrowed in (**B**) to show the gap is filled with sediment from outside the shell (below). Blue Lias Formation, Bed H54, Pinhay Bay, Devon. Scale bars = 10 mm (**A**, **B**) and 100 µm (**C**).*

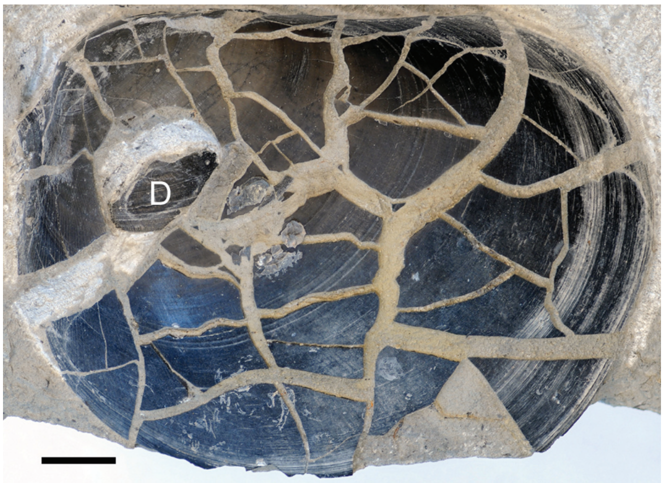

Figure 9. *An example of an 'exploded'* Plagiostoma *shell with a small piece of shell displaced (D) by crushing, probably as the limestone expanded due to displacive cement growth. LYMPH 2016/126. Blue Lias Formation, Bed H54, Pinhay Bay, Devon. Scale bar = 10 mm.*

Discussion

All our measured specimens came from loose blocks, although in several cases it has been possible to determine the original stratigraphic level from which the blocks came. One example (LYMPH 2016/121, Fig. 2) contains some ammonites with geopetal fills so that we can detect which way up the block was originally. This shows that the *Plagiostoma* shell was preserved at the original base of the limestone bed, which was definitely not Lang's Bed H54, but the precise origin remains unknown. For all our other examples we do not know way up. Thus, in attempting to detect a preferred crack orientation there is no way we can relate our specimens either to a compass direction or way up. However, specimens preserved on bedding surfaces, whether top or base, were originally more or less horizontal. Field observations show that *Plagiostoma* valves and pairs of valves are frequently preserved at any orientation to bedding. This is equally true of most fossils preserved in the Blue Lias (e.g., see Paul *et al*., 2008).

Our null hypothesis is that crack orientation is random, which implies that the rock was stretched more or less equally in all directions within the plane of the commissure of the *Plagiostoma* shells. So, we have tested for a preferred orientation of cracks in relation to an arbitrary line parallel to the hinge line (Fig. 2) and then assigned the angles to four 45° segments relative to this line. We have then repeated the test assigning angles to 45° segments but starting at 11, 21, 31 and 41°. This was done because we have no a priori way of knowing in which direction a preferred orientation might lie. For example, if a maximum concentration of cracks was orientated between 35° and 55°, our initial division at 45° would split that concentration in the middle and assign it to two adjacent segments, even though the concentration only spans 20° and could be contained entirely within a single 45° segment. Thus, since the chi-squared test depends on the difference between observed and expected values, such divisions would reduce the value of chi and might well lead to a false conclusion that there was no preferred crack orientation.

Our results (Table 1) show that in two of our specimens (2016/121 and 2016/123.1) the maximum deviation from the expected values lies below a statistically significant level (95% confidence of rejecting the null hypothesis) whatever the starting point. In the latter case, one orientation (starting at 1°) does produce a probability of < 0.1 (i.e., > 90% probability of rejecting the null hypothesis). In contrast, specimen 2016/125 appears to have a definite preferred crack orientation on first inspection (Fig. 7). In this example the least deviation from expected values gives a statistical significance between 93 and 94%. Two other values lie above 99% and the values starting at 1° and 41° lie above 99.9%. Thus, it is reasonable to reject the null hypothesis in this example and conclude that it has a highly significant preferred crack orientation. This is interesting as 2016/125 lies in the same piece of rock as 2016/126, which apparently shows no preferred crack orientation (Fig. 9).

In theory, detecting a preferred crack orientation gives a maximum stretching direction at 90° to that orientation. Summing the thickness of the cracks in the stretching direction should give an estimate of the amount of stretching and hence the shape of the strain ellipse. We have not done this as our measurements are made on a two-dimensional print of a three-dimensional bivalve shell, thus introducing some distortion to the crack orientations. Nor is this a suitable general method for estimating amount of stretching. In the absence of clear evidence of a preferred stretching direction, how does one decide in which direction(s) to measure and how does one allow for stretching in cracks that are not perpendicular to the direction(s) chosen? For these reasons point counts were chosen to estimate amount of stretching.

Point counts produce values of the percentage crack between 6.24% and 25.97% on counts between 1875 and 1575, respectively (Table 2). Three repeated point counts on 2016/125 with the larger grid moved between each count gave values of 9.25, 10.13 and 11.10% crack (mean 10.16%), suggesting that point counts are only accurate to about 2%.

Finally, both tests of crack orientation and amount of stretching are fairly crude first approximations. They were both carried out on flat photographs of curved surfaces, which must introduce some distortion. This was reduced in the case of the point counts by avoiding cracks near the margin of the shell or where other causes of distortion were suspected. Cracks in the posterior hinge area were not visible on these photographs and so could not be measured. Finally, it has been assumed that crack orientation was a straight line between triple junctions on photographs, whereas in some cases this was far from true. Despite these deficiencies, it has been possible to distinguish shells with random crack orientation from at least one with a clear preferred orientation. Equally, it is possible to state with reasonable certainty that all the 'exploded' *Plagiostoma* shells have not been doubled in size, for example. Expressing the crack counts as a percentage of the shell counts suggests that maximum stretching reached about 35% increase in the size of the original shell in two dimensions (Table 2) within the plane of the commisure.

CONCLUSIONS

'Exploded' *Plagiostoma* shells in the Blue Lias Formation near Lyme Regis, Dorset, UK are macroscopic evidence of the growth of displacive cements in the limestones that contain them. 'Exploded' shells may be distinguished from those damaged by crushing because the pieces of shell retain their relative positions and profiles of the shell remain smooth curves. Crushed shells often have offsets, like small faults, across cracks or the shell pieces have been reorientated with respect to each other. Major growth lines that cross cracks can be used to confirm the stretching direction, which in our experience is always perpendicular to the crack margins. Hence, crack orientation relative to the hinge line has been used to detect any preferred stretching direction. This has been detected in one example although others show random crack orientation. Similarly, point counts on photographs have been used to get a first order estimate of the amount of stretching in two dimensions. Crack counts range from about 6 to 26% of the total count. 'Exploded' *Plagiostoma* shells have previously been reported from the top of the Planorbis Zone in Nottinghamshire. They are most common at the same horizon in Devon, but do occur at other horizons.

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