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# Shell beds from the Low Head Member (Polonez Cove Formation, early Oligocene) at King George Island, west Antarctica: new insights on facies analysis, taphonomy and environmental significance

FERNANDA QUAGLIO[1], LUCAS VERÍSSIMO WARREN[2], LUIZ EDUARDO ANELLI[1], PAULO ROBERTO DOS SANTOS[1], ANTONIO CARLOS ROCHA-CAMPOS[1], ANDRZEJ GAŹDZICKI[3], PEDRO CARLOS STRIKIS[1], RENATO PIRANI GHILARDI[4], ANDRESSA BARRAVIERA TIOSSI[4] and MARCELLO GUIMARÃES SIMÕES[5]

[1]*Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562, Cidade Universitária, CEP 05508-080, São Paulo, Brazil*
[2]*Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Avenida 24-A, 1515, CEP 13506-900, Rio Claro, SP, Brazil*
[3]*Instytut Paleobiologii PAN, Twarda 51/55, 00-818 Warszawa, Poland*
[4]*Departamento de Ciências Biológicas, Faculdade de Ciências de Bauru, Universidade Estadual Paulista, Avenida Engenheiro Luiz Edmundo Carrijo Coube, CEP 17033-360, Bauru, São Paulo, Brazil*
[5]*Departamento de Zoologia, Instituto de Biociências, Universidade Estadual Paulista, Distrito de Rubião Júnior, CEP 18618-000, Botucatu, São Paulo, Brazil*
*quaglio@usp.br*

**Abstract:** Shell bed levels in the Low Head Member of the early Oligocene Polonez Cove Formation at King George Island, West Antarctica, are re-interpreted based on sedimentological and taphonomic data. The highly fossiliferous Polonez Cove Formation is characterized by basal coastal marine sandstones, overlain by conglomerates and breccias deposited in fan-delta systems. The shell beds are mainly composed of pectinid bivalve shells of *Leoclunipecten gazdzickii* and occur in the basal portion of the Low Head Member. Three main episodes of bioclastic deposition are recorded. Although these shell beds were previously interpreted as shelly tempestites, we present an alternative explanation: the low fragmentation rates and low size sorting of the bioclasts resulted from winnowing due to tidal currents (background or diurnal condition) in the original bivalve habitat. The final deposition (episodic condition) was associated with subaqueous gravity driven flows. This new interpretation fits with the scenario of a prograding fan-delta front, which transported shell accumulations for short distances near the depositional site, possibly between fair-weather and storm wave bases. This work raises the notion that not every shell bed with similar sedimentological and taphonomic features (such as geometry, basal contact, degree of packing and shell orientation in the matrix) is made in the same way.

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**Key words:** Antarctic coquina, *Leoclunipecten*, pecten conglomerate, pectinids, sedimentology, shell-bed genesis

## Introduction

Shell beds of 'modern style' (Kidwell 1990, Kidwell & Brenchley 1996) are bivalve-supported concentrations, usually generated under high energy events. These are thick and internally complex, typically with a sharp, erosional basal contact and discontinuous grading (Aigner 1985, Fürsich & Oschmann 1993, Li & Droser 1999). In Antarctica, shell beds of this type (locally named '*Pecten* conglomerates'; Adie 1964, Gaździcki & Pugaczewska 1984) are currently known from the Oligocene Polonez Cove Formation at King George Island (Figs 1 & 2) and from the Pliocene Cockburn Island Formation in the homonymous island (Gaździcki & Studencka 1997). The presence of shell beds in these deposits was previously used to correlate both units as Pliocene (Adie 1964, Barton 1965). Both deposits are essentially made up by pectinid shells, with the Polonez Cove Formation containing *Leoclunipecten gazdzickii* Beu & Taviani, whereas the Cockburn Island Formation is mainly composed of *Austrochlamys anderssoni* (Hennig) (Beu & Taviani 2013). However, isotope dating and palaeontological data from the Low Head area indicated a latest early Oligocene age (late Rupelian) for the shell-rich strata of the Polonez Cove Formation (Gaździcka & Gaździcki 1985, Birkenmajer & Gaździcki 1986, Birkenmajer *et al*. 1991, Dingle & Lavelle 1998).

The Polonez Cove Formation was first reported and named by Birkenmajer (1980), described in detail by Porębski & Gradziński (1987) and re-studied by

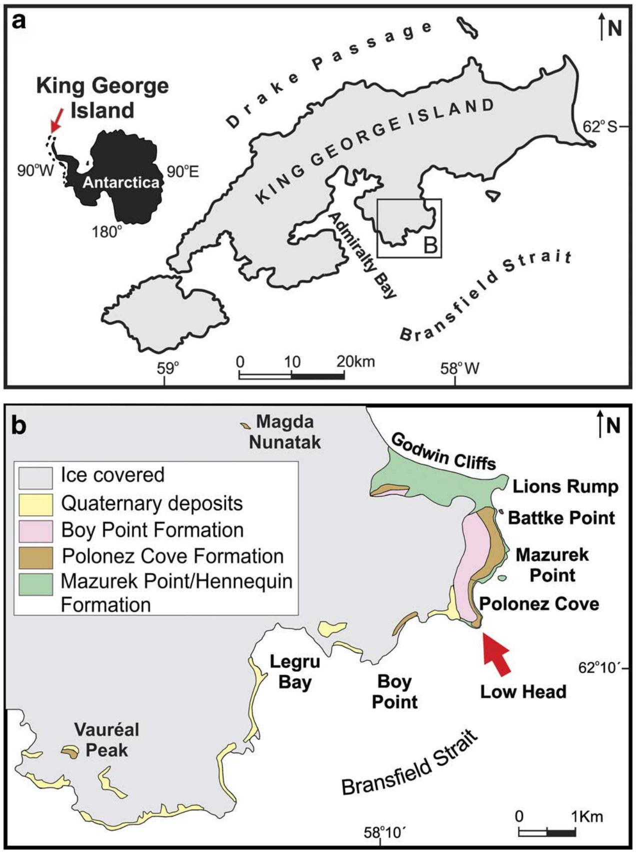


**Fig. 1.** Location maps of shell beds from the Low Head Member, Polonez Cove Formation. **a.** Location of King George Island, Antarctica. **b.** Exposures of the Polonez Cove Formation and other related units, arrow points to the study area and collected material (modified from Birkenmajer 2001 and Troedson & Smellie 2002).

Troedson & Smellie (2002). The shell bed levels, as part of the Low Head Member, were described by Gaździcki (1984). These previous studies interpreted the shell beds as reworked by storms or tempestites. However, some of the sedimentological and taphonomic signatures were overlooked, leaving some key data out of the interpretation of the shell-bed genesis. A new facies interpretation of the unit is presented herein, based on novel data collected in the type section of the formation. The new information offers clues about the sedimentological and taphonomic history of the spectacular pectinid beds of the Low Head Member, Polonez Cove Formation, which may have been deposited in conditions other than storms.

## Geological setting

The Polonez Cove Formation crops out almost continuously in the Low Head area (Figs 1 & 2; Porębski & Gradziński 1987, Troedson & Smellie 2002). The succession varies from 22–130 m in thickness and comprises coastal marine sandstones, followed by conglomerates and breccias probably deposited in fan-delta systems (Porębski & Gradziński 1987, Birkenmajer 2001, Troedson & Smellie 2002). The deposition was ice-influenced initially during an extensive glaciation phase (as evidenced by the presence of bottom moraine diamictites, erratic and ice-rafted boulders, lodgement tills and glacial striations at the base of the Polonez Cove Formation) and later during deglaciation events marked by a regional scale marine transgression (Birkenmajer 2001). Both phases were strongly influenced by contemporaneous volcanic and tectonic activity related to the opening of the Bransfield Rift (Birkenmajer 1992, 2001). The unit is not intensely affected by tectonic activity and is limited at both the base and top by erosive discordances with the volcanic Mazurek Point/Hennequin and Boy Point formations (Troedson & Smellie 2002). It comprises Krakowiak Glacier, Bayview, Low Head, Siklawa, Oberek Cliff and Chlamys Ledge members (Porębski & Gradziński 1987, Birkenmajer 2001, Troedson & Smellie 2002; Table I, Fig. 3).

Overall, the Polonez Cove Formation is highly fossiliferous, with the highest abundance in its Low Head Member. Taxonomic groups reported from the Polonez Cove Formation include calcareous nannofossils, bryozoans, ostracods, corals, bivalves, gastropods, brachiopods, foraminifers, worm ichnofossils, plant fragments and stromatolites (Gaździcki & Pugaczewska 1984, Birkenmajer *et al.* 1991, Troedson & Smellie 2002, Gaździcki 2007, Quaglio *et al.* 2008, Bitner *et al.* 2009). Fossil specimens are mostly fragmented and sparsely distributed along the unit, except for the base of the Low Head Member at its type area (Troedson & Smellie 2002) which contains relatively extensive and thick shell beds – the subject of this work (Figs 1 & 2).

The Low Head Member is described as a succession of basaltic breccias, fossiliferous conglomerates, sandstones and diamictites deposited in the nearshore to shallow offshore of a high-energy coast (Porębski & Gradziński 1987) in a fan-delta system (Troedson & Smellie 2002). The occurrence of rare graded beds interbedded with thin pelitic layers was previously interpreted as temporary changes in environmental energy, suggesting deposition as proximal shelly tempestites (Gaździcki 1984). In addition, the presence of gutter casts at the base of some levels of the Polonez Cove Formation associated with bivalve shell beds was previously reported as evidence of deposition by storms (Porębski & Gradziński 1987).

Potassium-argon (K-Ar) dating from andesitic lavas at Lions Rump yielded 34.4 Ma as the maximum age of the Mazurek Point/Hennequin Formation (Smellie *et al.* 1984). Various isotope and geochronology studies indicate late early Oligocene as the age of the Polonez Cove Formation. Strontium (Sr) isotope analysis of brachiopod and bivalve shells collected from the base of the Polonez Cove Formation (Krakowiak Glacier Member) at Magda

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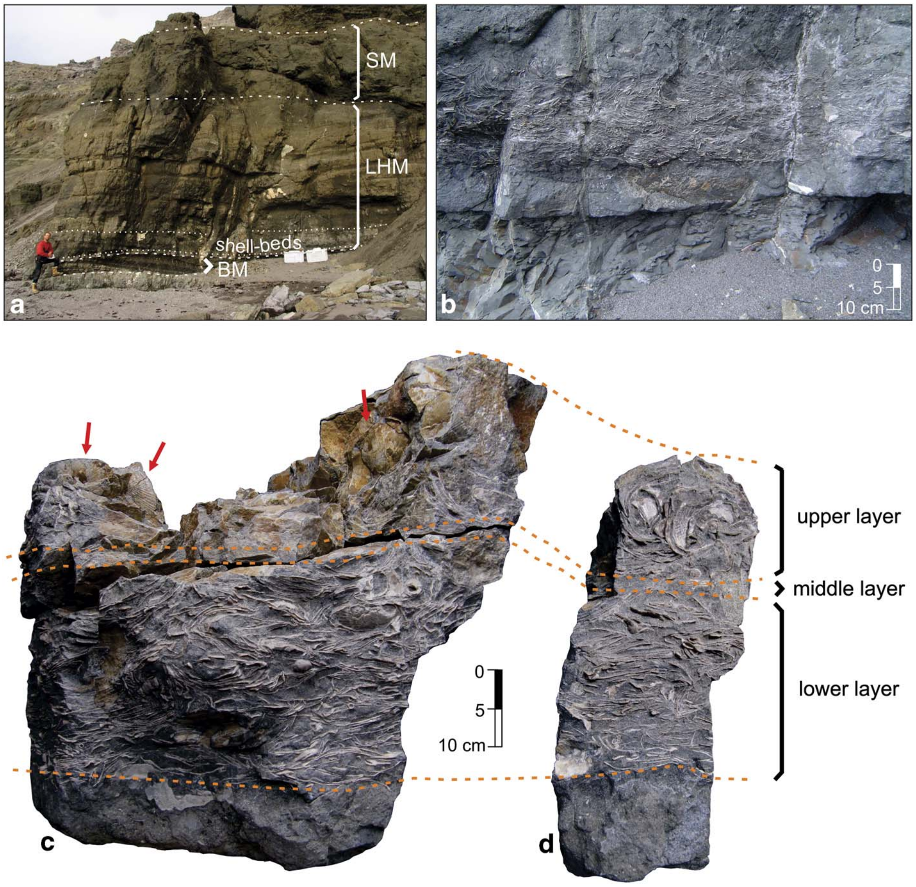


**Fig. 2.** Lower shell bed (sb1) of the Low Head Member, Polonez Cove Formation, at Low Head area, King George Island, West Antarctica (from S3 column). **a.** General view of the outcrop (BM = Bayview Member, LHM = Low Head Member, SM = Siklawa Member). **b.** Detail of the shell bed. **c.** & **d.** Samples from the main shell bed level of the Low Head Member (profile I of Gaździcki & Pugaczewska 1984) showing three shell bed layers, including oblique valves from the top of the upper layer, some of them articulated (indicated by arrows). (Samples housed at the Laboratory of the Institute of Geosciences, University of São Paulo, Brazil.)

Nunatak yielded ages of 29.8 Ma. Similar ages were indicated by bivalve shells from beds (Low Head Member) at Low Head area (29.4 Ma) and at Magda Nunatak locality (28.5 Ma) (Dingle & Lavelle 1998).

## Material and methods

During the twenty-third Brazilian Antarctic expedition in the summer of 2005, four geologic sections were measured near the type section of the Polonez Cove Formation at Low Head locality. Facies analysis concepts, following Miall (2000), are used for the facies description and identification of important stratigraphic surfaces.

Boulder-sized samples were collected from the lower shell bed level (sb1 of Fig. 4) of the Polonez Cove Formation to be analysed in the laboratory. The upper shell bed level (sb2 of Fig. 4) was not sampled due to difficulties with accessibility. The samples collected are housed at the Laboratory of Systematic Palaeontology of the Institute of Geosciences, University of São Paulo, Brazil and at the Department of Biological Sciences, São Paulo State University, Brazil. Additional samples were previously collected by A. Gaździcki in the summers of 1978–79 and 1980–81 during the third and fifth Polish Antarctic expeditions and are housed in the Institute of Palaeobiology PAS, Warsaw, Poland.

Six samples from the basal portion of coquinas were sectioned and polished for visualization of the bioclastic fabric and associated sedimentary structures, according to the nomenclature of Fürsich & Oschmann (1993). Images of each sample were treated in drawing software to enhance black and white contrast between valves and matrix background (i.e. matrix and cement). Bitmaps of each image were traced so that each shell fragment or group of fragments was considered as an object.

Four other samples were dismantled to remove shells from the matrix, enabling the shell measurements and recognition of valve types (right or left). Shell sizes (height and length) were measured along the dorsal-ventral and anterior-posterior axes of the valves. The descriptive procedure followed Kidwell *et al*. (1986) and included the 3D arrangement of shells in the matrix: cross-section orientation to the bedding (parallel, concordant, oblique and convex-up or -down) and plan section or azimuthal orientation. The azimuths were measured in relation to the hydrodynamic stable position of the valves, which is the ventral-dorsal axis that indicates the direction and flow.

**Table I.** Names and lithological characteristics of members of the Polonez Cove Formation.

| Member | Lithology | Interpretation | Reference |
|---|---|---|---|
| Chlamys Ledge | Conglomerate and gravelly sandstones with subordinate pelites. | Turbidite, debris flow and traction current deposition under shallow marine environments with glacial influence. | Troedson & Smellie 2002<br>Bitner *et al*. 2009 |
| *Oberek Cliff | Basaltic lava flooding, lava breccias and subordinated sandstones and conglomerates. | Deposition under shallow glacial marine environment, influenced by volcanic activity. | Birkenmajer 1982, 2001<br>Porębski & Gradziński 1987<br>Troedson & Smellie 2002<br>This work |
| *Siklawa | Planar beds of sandstones, siltstones and claystones, intercalated with gravelly sandstones. | Turbidite current deposition in the offshore transition zone. | Birkenmajer 1982, 2001<br>Porębski & Gradziński 1987<br>Troedson & Smellie 2002<br>This work |
| *Low Head | Fossiliferous basaltic conglomerates containing bivalve coquinas and sandstones. | Ice-sheet retreat influenced by volcanic activity. | Birkenmajer 1982, 2001<br>Gaździcki 1984<br>Porębski & Gradziński 1987<br>Troedson & Smellie 2002<br>This work |
| *Bayview | Planar bedded, medium to fine sandstones and mudstones, with very rare marine fossils. | Deposition mainly by suspension and traction currents under normal marine conditions. | Troedson & Smellie 2002<br>This work |
| Krakowiak Glacier | Conglomerate and diamictite facies, with faceted and striated clasts. | Previous presence of ice sheets that would have transported lithic fragments westerly from the Transantarctic and Ellsworth mountains. | Birkenmajer 1982, 2001<br>Porębski & Gradziński 1987<br>Troedson & Smellie 2002 |

*Members found in the study area.

Although preserved in high numbers, the specimens are very thin and easily breakable. Hence, it was not possible to measure all specimens for all parameters, thus the number of shells analysed for each measured parameter is variable. Furthermore, the middle layer is very thin and its pectinid specimens are densely packed and brittle. Therefore, it was difficult to extract individual shells and consequently the low sample number (eight shells) hinders the statistical analysis of this layer. However, the lower and the upper layers yielded more than a hundred measurable specimens for the statistical analysis. All measurements are listed in the supplemental material (which can be found at http://dx.doi.org/10.1017/S0954102013000783).

In order to check if the difference of each identified layer is significant regarding the taphonomic parameters, statistical analyses were performed in Bio Estat 5.3 and PAST using chi-squared, contingency, as well as *t*-test and *G* test, according to the type of data to be analysed.

## Results

### *Sedimentology of the Polonez Cove Formation at the Low Head area*

In the studied area, only rocks comprising Bayview, Low Head, Siklawa and Oberek Cliff members were found (Tables I & II, Fig. 4). The base of the succession, represented by the Bayview Member (Table II, Fig. 4), is characterized by massive sandstones (Sm) with rare exotic clasts and centimetre-scale intercalation of tabular beds of mudstones (M) and fine Sm. The wedge-shaped basal contact of the Bayview and Low Head members shows high sinuosity with wavelength of 2.5 m and amplitude of 40 cm, forming a horizontally irregular erosive surface of metric scale.

At the base of the Low Head Member, Sm facies are followed by matrix-supported massive conglomerates (Cm) and bioclast-supported conglomerates (Cb), both occurring as amalgamated decimetre-thick lenticular beds and containing exotic clasts (Table II, Fig. 4). The framework of the Cb facies is composed of marine macrofossils making up well sorted, bivalve-dominated shell beds with poorly sorted sandy matrix and occasionally pebble-sized clasts. This facies is often separated by erosive surfaces and interbedded with unfossiliferous coarse and gravelly sandstones of the facies Sp (sandstone with parallel-stratification), Sr (sandstone with climbing ripples), Sm and Sl (sandstone with low-angle cross-stratification). No evidence of combined flow and reworking or re-sedimentation by wave orbitals and traction currents was found.

In the studied sections, the Siklawa Member comprises a series of fine Sp interbedded with Sm (Table II, Fig. 4). Tabular beds of coarse sandstones fining upward grading to fine Sr occur occasionally. Metric beds of basaltic polymict breccias composed of Cm facies of the Oberek Cliff Member onlap these deposits at an erosive boundary (Table II, Fig. 4).

### *Taphonomy*

At outcrop scale, the shell beds (Cb facies) are 5–40 cm thick internally complex concentrations showing several metres of lateral extension and forming beds or flat lenses, with sharp and erosive basal contact (Fig. 2). They occur in

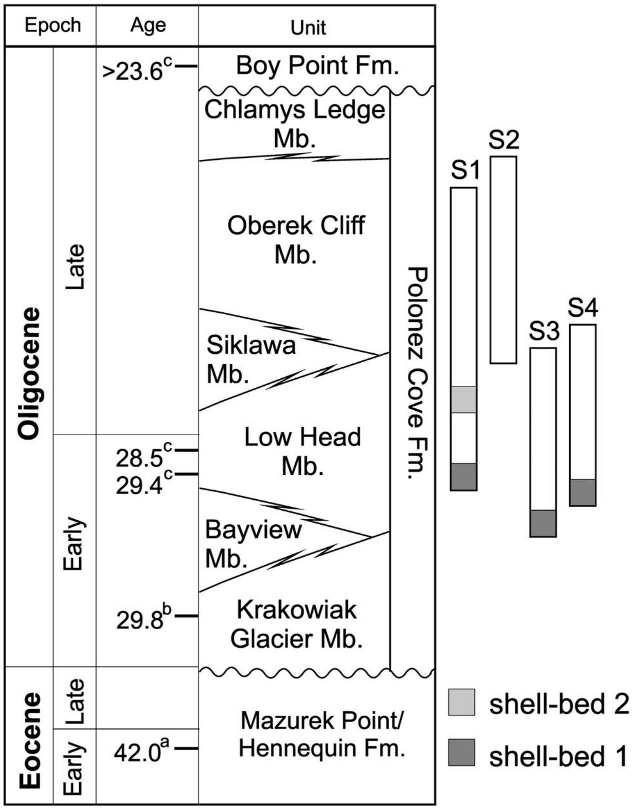


**Fig. 3.** Lithostratigraphic subdivision of the Polonez Cove Formation with indication of stratigraphic sections (S1–S4) and shell bed levels. Relation of thickness and chronology is not proportional. (Chart based on Birkenmajer 2001 and Troedson & Smellie 2002, ages based on: a. Birkenmajer *et al*. 1989 K-Ar dating of andesitic lavas from Turret Point, b. Smellie *et al*. 1984 K-Ar dating of andesitic lavas from Lions Rump area, c. Dingle & Lavelle 1998 Sr isotopic dating of bivalve and brachiopod shells from Low Head, Polonez Cove, Lions Rump and Magda Nunatak.)

two stratigraphic levels (sb1 and sb2, Figs 3 & 4) and at least three distinct layers are amalgamated in the thicker portions of the lower level (Fig. 2c).

In total, 340 shells were measured (see supplemental table http://dx.doi.org/10.1017/S0954102013000783) from three layers of the lower shell bed level (sb1 of S3, Figs 3 & 4). The material is mainly composed of complete valves of the thin-shelled pectinid *L. gazdzickii*, with very rare valve fragments. Externally the shells are unabraided and only four of them are incrusted with bryozoans. Shell size varies from 2.4–8.7 cm in height and 2.1–7.9 cm in length, with most valves varying from 4.6–6.5 cm (55.3% of height and 54.0% of length measurements), with an average height of 6.5 cm, a minimum of 5.3 cm and a maximum of 7.5 cm, except for one valve from the lower layer with a height of 8.7 cm. Other, less common, associated bioclasts included gastropods, other bivalve mollusc shells, as well as bryozoan, echinoid and other unidentified invertebrate remains.

The thickness and degree of packing and cementing are variable along the densely fossiliferous layers of the Low Head Member. Dense shell packing predominates at the base of each level, whereas dispersed and loosely packed valves are much more common toward the top of each shell-rich interval.

The lower layer is 20–30 cm thick and shows densely packed bioclasts in a poorly selected sandy matrix (Figs 2c–d & 5). The bioclasts comprise mostly pectinid valves, some of them disrupted (Fig. 5). More rarely, additional bioclasts include other molluscs (such as one decimetre-sized hiatellid bivalve and very few centimetre- to decimetre-sized gastropods), millimetre- to centimetre-sized echinoid remains and other unidentified invertebrate fragments. Rare granules and pebbles of volcanic origin that reach 4 cm in diameter (Fig. 5) are also recorded in this layer. Pectinid shells are on average 5.3 cm in height, ranging from 4.6–5.5 cm (Fig. 6a). Most of them are disarticulated (93.4%, $n = 198$) and left valves predominate (53.7%, $n = 86$; Fig. 6b). The valves are in a convex-down posture (66.3%, $n = 114$; Fig. 6c), parallel to the bedding (64.6%, $n = 128$; Fig. 6d) and oriented to south and west (52.6%, $n = 82$; Fig. 6e).

The middle layer is very thin, often less than 4 cm thick, and includes nested and imbricated valves (Fig. 2c & d). It is composed mainly of disarticulated (87.5%, $n = 7$), convex-down pectinid shells (75.0%, $n = 6$), ranging in size from 56 mm to 66 mm in height. The shells in this layer are firmly cemented to the rock matrix by carbonates. The middle layer is set apart from the lower layer by a very thin (5–10 mm), unfossiliferous muddy bed of irregular surface.

The upper layer is 5–30 cm thick and is characterized by bioclasts composed almost exclusively of pectinid shells with strong size sorting, most of them ranging from 4.6–5.5 cm (50%, $n = 44$) and 5.1 cm of average height (Figs 2c–d & 6a). The shells are more dispersed to loosely packed than in the lower and middle layers. Disarticulated (90%, $n = 108$), right valves (51.8%, $n = 56$; Fig. 6b) in convex-down attitude (62.8%, $n = 49$; Fig. 6c) predominate. The valves are also mostly perpendicular to the bedding (47.4%, $n = 56$; Fig. 6d) and show south-east as the main azimuthal direction (35.4%, $n = 34$; Fig. 6e). At the top of thicker accumulations, the upper layer bears rare oblique articulated pairs (Fig. 2c). Below this level, the valves are only disarticulated and commonly nested. When nested, the shells are 10–20 mm apart by the matrix. Very few specimens are incrusted by bryozoans (0.03%, $n = 4$); when it occurs, the percentage of covered area is low (often below 10% coverage) and only externally at the ventral margin.

Some of the studied taphonomic parameters are not distinct in the lower and upper layers (such as size, valve types and convexity), whereas others (such as orientation and azimuth) are statistically distinct in both layers (Fig. 6). The size frequencies of the specimens in both layers show similar height distributions (Fig. 6a), with no statistically significant difference between layers (*t*-test: difference

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**Table II.** Facies description and interpretation of the sedimentary processes of the Polonez Cove Formation at Low Head area.

| Code | Facies | Description | Interpretation |
|---|---|---|---|
| Cb | Bioclast-supported conglomerate | Decimetre to metric lenticular beds of bioclast-supported massive conglomerates, matrix of medium to coarse poorly sorted sands, with exotic clasts, bioclasts of mainly disarticulated pectinid valves. | Subaqueous gravity driven flows that transported pectinid valves for short distances. |
| Cm | Matrix-supported conglomerate, massive | Discontinuous lenticular beds of matrix-supported massive conglomerates of grey colour, normally graded, matrix of medium to coarse poorly sorted sands. | Subaqueous gravity driven flows. |
| Sp | Sandstone, with parallel-stratification | Medium to fine sandstones arranged in decimetre beds with parallel-stratification, with exotic clasts locally, features of soft sediment deformation evidenced by load structures like pillow and flame. | Traction of bottom currents in planar beds at upper flowing regime. |
| Sl | Sandstone, with low-angle cross-stratification | Medium to fine sandstones arranged in decimetre beds with low-angle cross-stratification, with exotic clasts locally, features of soft sediment deformation evidenced by load structures like pillow and flame. | Migration of bed forms over low-angle beds at upper flowing regime. |
| Sr | Sandstone, with climbing ripples | Medium to fine sandstones, arranged in planar decimetre beds with climbing ripples. | Subaqueous migrating dunes of irregular crests mainly under unidirectional currents in lower flow regime. |
| Sm | Sandstone, massive | Medium to fine sandstones arranged in centimetre to decimetre planar beds of great lateral extension, with exotic clasts, locally normally graded. | Massive feature due to obliteration of previous structures by fluidization after sedimentary overload. |
| M | Mudstone | Beds of decimetre thickness of grey to brown massive mudstone, rare dispersed granules. | Suspension deposits in low energy waters lacking action of bottom currents. The presence of granules is attributed to grain fall processes associated with icebergs or ice flow melt. |

between means = -0.3030). Although both layers yielded more convex-down shells, the lower one is proportionally much richer in convex-up valves than the upper layer (Fig. 6c). The number of left valves in the lower layer is slightly greater than right valves, while the upper layer shows the opposite: more right valves than left valves (Fig. 6b). However, this difference is not statistically significant ($\chi^2 = 0.288$, df = 1), which means that both layers have the same proportion of left and right valves. The lower layer contains very different parallel, oblique and perpendicular valve numbers (Fig. 6d). The upper layer shows the opposite distribution, with more perpendicular valves, followed by oblique and finally by parallel-oriented shells (Fig. 6d). The difference is clearly observed in the histograms and is statistically significant ($\chi^2 = 24.763$, df = 2). The azimuth measurements in each layer are also different. Shells from the lower layer are mostly oriented south and west, while specimens from the upper layer show south-east as the main direction (Fig. 6e). This difference in main direction between the lower and upper layers is statistically significant (*G* test = 47.7213, df = 7).

## Discussion

### *General sedimentological context*

The facies association described in the study area (Table II, Fig. 4) indicates mainly shallow marine environment with subordinated glacial conditions. The volcanic influence is only observed at the top of the succession (S2) as indicated by the basal lava breccias of the Oberek Cliff Member. These interpretations partially corroborate the geological description made by Troedson & Smellie (2002).

The facies association of the Bayview Member (M and Sm), in the lower portion of the succession is indicative of deposition by suspension and bottom currents associated with high density hyperpycnal flows, possibly representing a prodeltaic or distal fan-delta system prograding in a marine basin (Table II, Fig. 4). The presence of erratic clasts is suggestive of ice rafted deposition, which reinforces the glacial influence on the unit (Troedson & Smellie 2002). At the top, this stratigraphic level is marked by an erosive discontinuous surface, interpreted as a result of subaerial exposure due to a glacial eustatic rebound (Troedson & Smellie 2002). This interpretation could be valid on a regional scale only if the erosive surface occurs in most localities where the contact of Bayview and Low Head members is observed. Considering only the sections studied in this work, the characteristics of the basal contact suggest a local erosive discordance. The lenticular sandstone bed occurring just above the discordance was probably deposited by gravity driven flows confined in subaqueous channels or fan-delta front fill deposits of the previously excavated gullies. The abundance of channel deposits in the Low Head Member reinforces this interpretation.

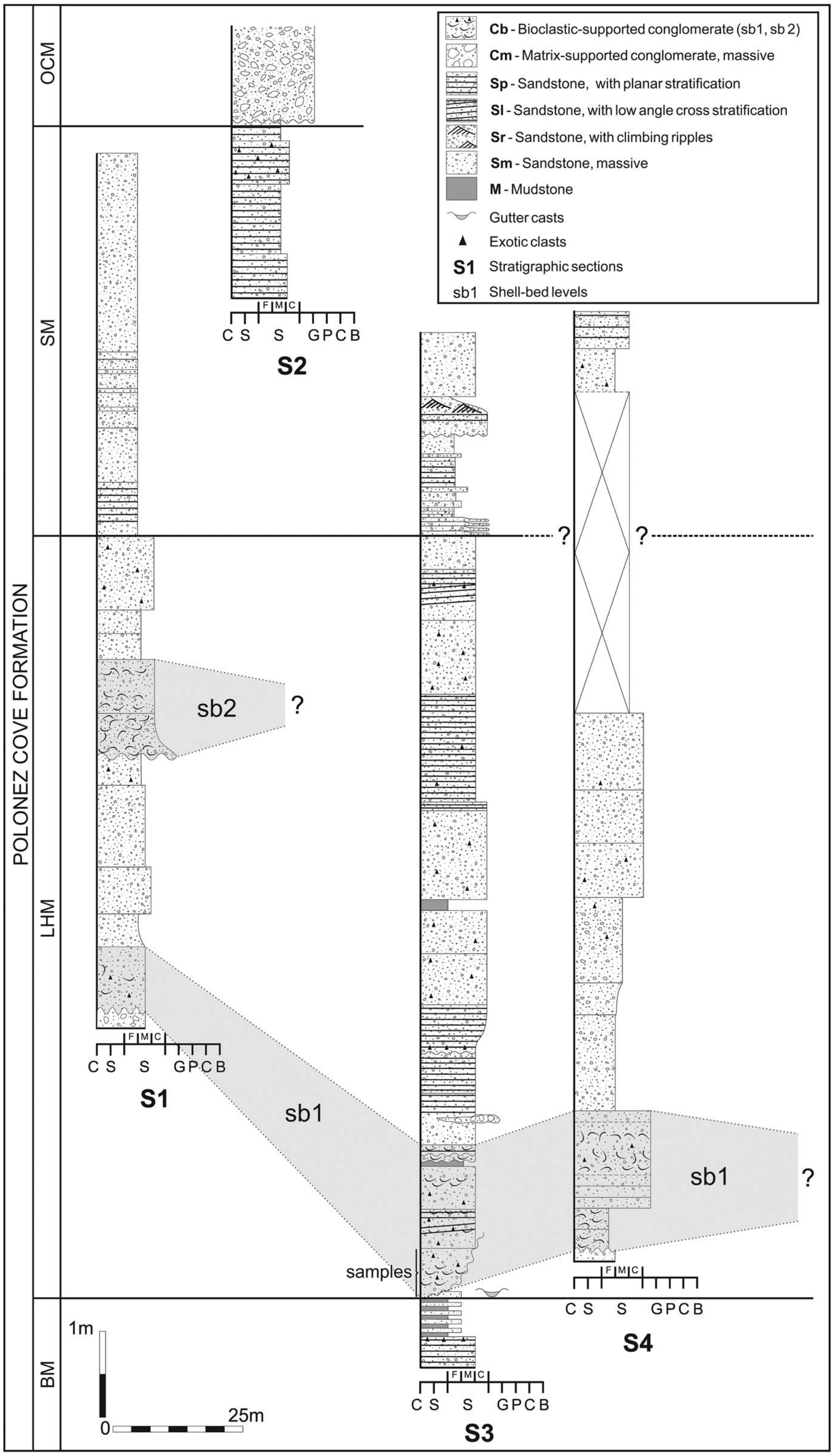


**Fig. 4.** Stratigraphic sections of the Polonez Cove Formation measured at Low Head area, King George Island. BM = Bayview Member, LHM = Low Head Member, SM = Siklawa Member, OCM = Oberek Cliff Member. Samples are from the lower shell bed level (sb1) from section 3 (S3).

At the base of the Low Head Member, the Cb facies shows a low grain size variation in both matrix and framework. This is probably a result of diurnal subaqueous processes, such as tidal or wave currents, that continuously rework bivalve accumulations on coastal sites prior to final burial. These processes are related to the input of an originally non-sorted gravitational flow that reworked and transported a previously sorted pectinid-rich accumulation.

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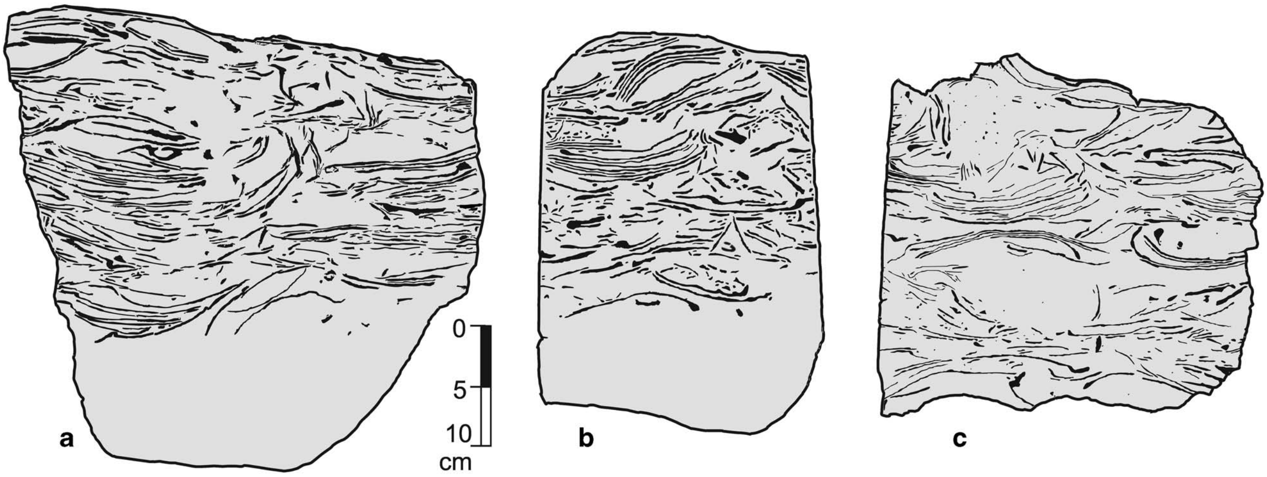


**Fig. 5.** Bitmap-traced images of polished cross-sectioned samples of the lower layer (sb1, S3), Low Head Member, Polonez Cove Formation, showing the shell specimens (black) and clasts (dark grey). Samples A and B are from the base of the lower layer. (Sample A housed at the Laboratory of the Institute of Geosciences, University of São Paulo, Brazil. Samples B and C are kept in the collections of the Institute of Palaeobiology, Polish Academy of Sciences, Warsaw, Poland. Sample C is featured in Gaździcki 1984, fig. 5.)

The facies of Sp, Sr, Sm and Sl (which commonly interbed with the Cb facies) are deposited by dense bottom flows associated with the median to distal portion of fan-deltas. The presence of lenticular beds with erosive bases and the co-occurrence of very coarse sediments with finer grains fit well in a scenario of episodic sedimentation. Previous works interpreted the shell bed levels as deposited or reworked by storms (Gaździcki 1984, Porębski & Gradziński 1987, Troedson & Smellie 2002). Although a fan-delta system would not exclude storm reworking as one of the depositional agents for the bivalve-rich intervals, no evidence of combined flow and reworking or re-sedimentation by wave orbitals and traction currents was found. Furthermore, the presence of channelized beds and facies deposited by high density flows indicate that the Cb facies was not subjected to diurnal currents and/or wave orbitals. Hence, there is no clear evidence for the deposition by storm currents and waves. On the other hand, the channelized deposits lack interbedded pelitic facies, which suggests that these channels were not deposited in offshore conditions (below the storm wave base). Thus, the shell beds were probably deposited by subaqueous gravity driven flows, related to prograding distal fan-delta fronts, between fair-weather and storm wave bases in the offshore-shoreface transition.

Troedson & Smellie (2002) reported the presence of pelitic facies in the Siklawa Member. In our studied sections, the Siklawa Member is represented by deposits of the Sp and Sm facies, and occasionally by fine sandstones with current ripples of the Sr facies. The fining upwards successions of the facies Sm and Sp associated with lower flow regime structures (Sr facies) suggest deposition by bottom currents. These hyperpycnal flows are typically associated to distal portions of fan-deltas in which the flow progrades and decelerates towards the basin. This facies association indicates deposition in deeper waters than the Low Head Member facies, in a lower slope fan-delta system, below the storm wave base setting.

Toward the top, the metre-scale beds of basaltic polymict breccias of the Oberek Cliff Member erosively onlapping those successions are interpreted here as deposited by subaqueous debris flows in upper shoreface waters (Table II, Fig. 4). Several basaltic clasts, as well as pillow lavas and columnar disjunctions, towards to the top of the unit support the evidence of intense volcanic activity during sedimentation (Porębski & Gradziński 1987). The thickness and granulation differences along the beds may represent variations of the sedimentary input ratio or even lateral variations within the same fan-delta lobe.

### *Shell-bed genesis*

The material analysed includes three layers of the same stratigraphic shell bed level (sb1, Figs 3 & 4). The upper shell bed level (sb2, Figs 3 & 4) was not sampled. However, both shell bed levels are thought to be generated by the same depositional mechanism, despite different episodes of sedimentation. Each of the three layers (facies Cb) of the sb1 also corresponds to different depositional events. The middle layer was not statistically analysed due to its thinness and preservation characteristics that prevented proper sampling. The hard cementing carbonate content may be assigned to differential or early diagenesis, suggesting that this layer represents a hiatus in the sedimentation or even a local hardground.

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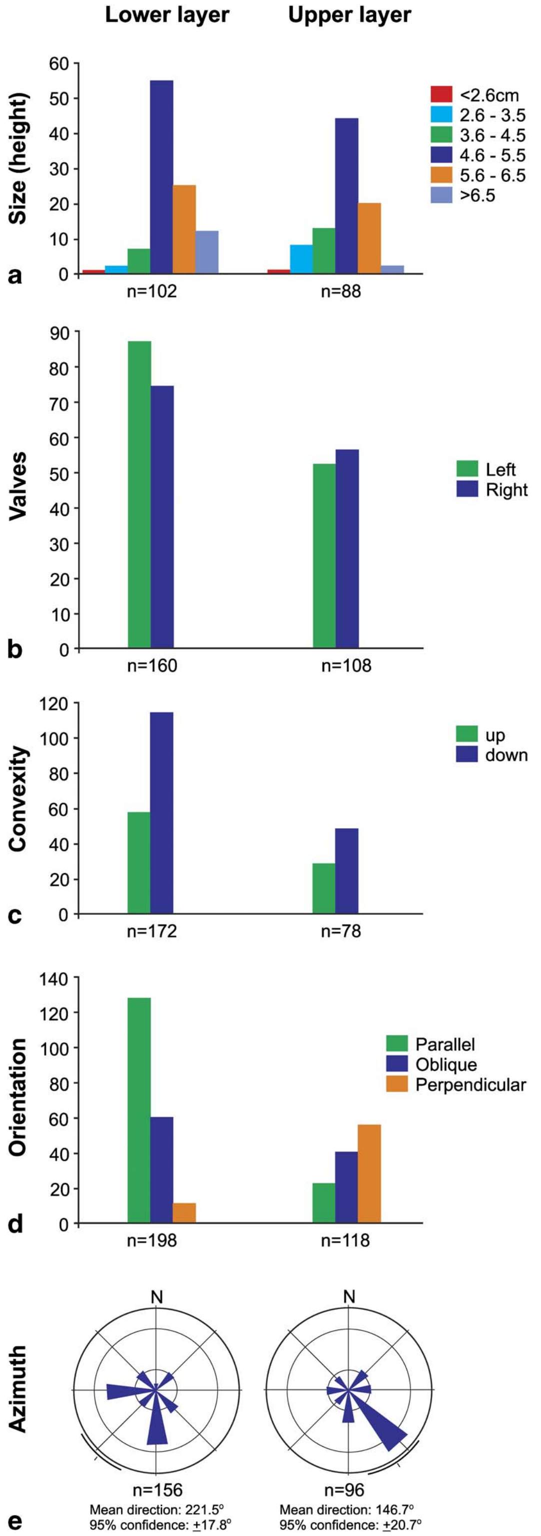


**Fig. 6.** Taphonomic parameters of lower and upper layers of shell bed level from the Low Head Member, Polonez Cove Formation. **a.** Histogram of shell size (height). **b.** Histogram of valve types (left/right). **c.** Histogram of shell convexity. **d.** Histogram of orientation in relation to the bedding. **e.** Rose diagram of pectinid azimuthal orientation.

The statistical analysis of specimens sampled from the upper and lower layers shows differences and similarities for taphonomic parameters related to the genesis of the shell bed layers.

The parameters that are not statistically different between the upper and lower layers (valve size and type, Fig. 6a & b) are related to the bioclast source; in this case, the same for both layers. They did not result from selective transport because of the low frequency of fragmented shells and the inferred sedimentological interpretation of high energy episodic deposition. Both layers show low variation in valve size (see Gaździcki 1984 and Beu & Taviani 2013 for similar results) and statistically equivalent numbers of left and right valves. This indicates that similar numbers of left and right and similar sized valves were present in the bioclast source. The similar numbers of left and right valves suggest that the original bioclast source was the living site of the pectinids. However, the high frequency of similar sized valves (4.6–5.5 cm for both layers) and the low number of articulated valves (12.5% and 7.5%) suggest that the bioclast source was not a living pectinid community. The great number of disarticulated, similar sized valves, as well as a low degree of fragmentation, requires an agent of size sorting prior to the bioclast transport and final burial. The sedimentary process responsible for the *in situ* sorting of the shells is probably associated with winnowing, or similar process, resulting from the action of tidal currents in shallow and protected waters. The shell accumulation in areas near the bivalve living site might have occurred in shoreface conditions possibly under continuing tidal currents or wave orbitals (Fig. 7). Bioclast accumulation in such an environment is generally associated with shallow areas where current activity is only able to transport finer grains, with large clastic and bioclastic grains forming lags. This winnowing process selects bioclasts in variable size classes according to current intensity and bioclast shape, height and density. The absence of significant lateral transport precludes the concentration of highly abraded or fragmented shells. Also, the thin shell material, the delicate external ornamentation, the absence or low degree of incrustation and the absence of abrasion of the pectinid bivalve shells indicate short residence time of the bioclasts in the taphonomic active zone (Davies *et al.* 1989). All taphonomic signatures described in the shell bed levels characterize parautochthonous assemblages - autochthonous shells that were reworked to some degree but not transported out of their life habits (Kidwell *et al.* 1986, p. 229).

The studied samples suggest at least two, probably three, depositional events, resulting in different shell bed layers of the lower shell bed level. The variations in convexity and vertical orientation are statistically different in the upper and lower layers, probably as a consequence of intensity and energy variation of the depositional flow.

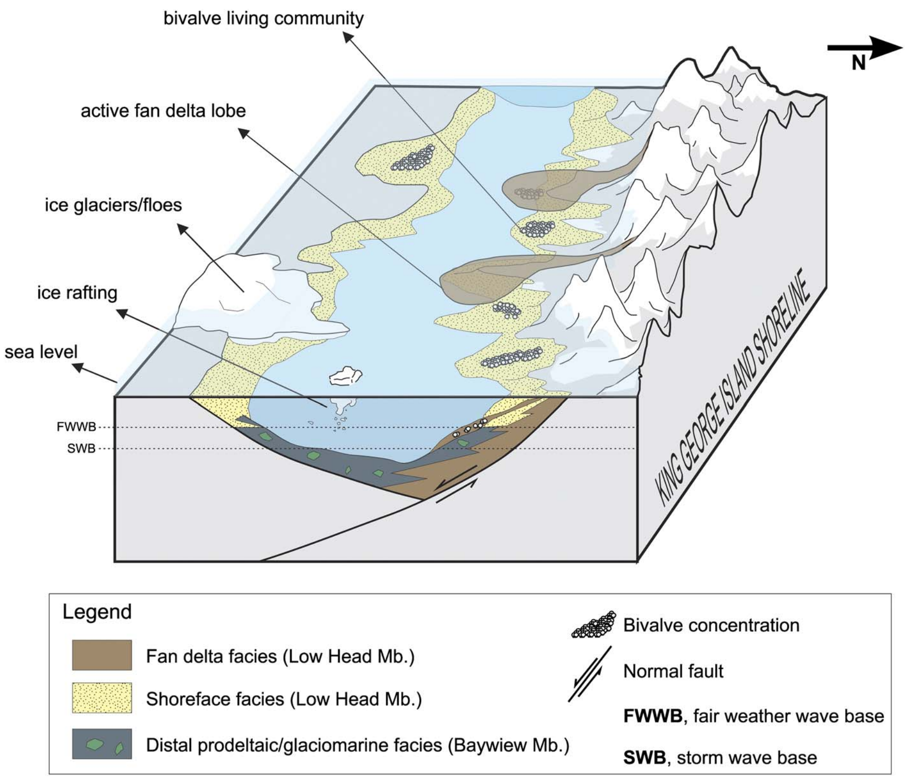


**Fig. 7.** Diagram showing deposition of pectinid shell beds of the Polonez Cove Formation, King George Island.

Convex-down is the more stable position for shells to settle through the water column in calm conditions (Allen 1984). A higher proportion of convex-down shells means that the bottom flow was ineffective so the valves settled in their most stable hydrodynamic position under calm conditions. During horizontal flow they will get flipped into a convex-up orientation, which is resistant to further current flipping. Therefore, a higher proportion of convex-up shells indicate predominance of laminar flow conditions. The lower layer shows proportionally more convex-down valves than the upper layer. Towards the top more tractive biofabrics occur, including imbricate and convex-up oriented valves (hydrodynamically stable attitude under laminar flow conditions). The upper layer is inferred to have been deposited under more intensive flow conditions than the lower layer. This could suggest that enough time elapsed for the bioclasts in the lower layer to attain their hydrodynamically stable position before their final burial, whereas the upper layer resulted from a higher energy, short-term flow with faster sedimentation.

The azimuthal orientation of the valve long axes (Fig. 6e) indicates the main flow of the lower layer was towards the south and west, and the main flow of the upper layer was to the south-east. This is probably because fan-delta inflow into the basin is not unidirectional; hence, some variation in similar orientation quadrants is expected. The upper layer is expected to have been deposited in higher energy conditions than the lower, which explains the single main direction of the upper layer. Other less frequent valve long axis azimuth measurements in both layers suggest slightly distinct flow directions, probably due to secondary currents. Both layers are estimated to be in the same coastal line at the time of deposition (Troedson & Smellie 2002). Hence, the valve long axis azimuth orientations indicate the main direction of prograding fan-deltas and the direction of basin deposition. Both layers indicate that the southern quadrant was the probable location of the basin depocenter in relation to the shoreline and final deposition site at the time of sedimentation. Small variations in direction, however, are due to erratic transport of some bioclasts, flow turbulence or even the presence of clasts blocking the bioclast flow. The presence of disrupted valves in the lower layer suggests that post-depositional compaction and soft deformation of water-saturated sediments affected this layer. This is supported by the presence of fluid escape and load-cast structures of finer sediments in those shell bed portions. The feature of the Sm facies confirms the fluidization associated with the sedimentary overload.

Although the differences between the layers indicate distinct depositional events, the process of deposition was similar. This interpretation fits the scenario of a prograding fan-delta front that transports shells for a short distance that then accumulate near the depositional site, possibly between fair-weather and storm wave bases (Fig. 7). Each layer of the shell bed resulted from different deposition events of distinct lobes of the same fan-delta system. The variation in lateral extension and thickness of each shell bed level and layer is probably due to a patchy pattern of the original living pectinid community as well as the bioclast source, which were not evenly distributed along the coastal extension. The nature of fan-delta systems advancing towards the depocenter in the shape of lobes enhances this patchy pattern.

### *Depositional implications*

Even though our hypothesis agrees well with a relative high energy scenario, it differs in detail from the hypothesis of storm-wave deposition previously conceived (Gaździcki 1984, Porębski & Gradziński 1987). Densely fossiliferous deposits recorded in marine (carbonatic and siliciclastic) successions are commonly interpreted as shelly tempestites (Aigner 1985, Einsele *et al*. 1991). Storm deposits (tempestites) are usually described as generated by combined flows associated with unidirectional rip currents and oscillatory flows, commonly generated in shoreface and offshore settings by storms and hurricanes (Aigner 1985, Fürsich & Oschmann 1993, Clifton 2006). Storm deposits bear a graded nature and typically erosional base with different types of sole marks, small-scale ripple bedding and amalgamation (Pérez-López & Pérez-Valera 2012). This type of deposit is succeeded by a laminated bed showing planar laminations at the base, followed by hummocky-swalley cross-stratification to climbing ripple laminations towards to the top (Aigner 1985, Pérez-López & Pérez-Valera 2012 and references therein). Closely packed, disarticulated bivalved shells (molluscs and brachiopods) showing oriented posture to bedding (normal grading, massive and laminated texture as indicated by Pérez-López & Pérez-Valera 2012), convex-up attitude and stacked and/or nested arrangement predominate. Shells are rarely broken, show little abrasion and are neither bioeroded nor encrusted (Fürsich & Oschmann 1993). However, these biostratinomic features may be viewed with caution, because they are mostly produced by combined physical, chemical and/or biological processes that operate during the background conditions, rather than during final deposition of the shells (Fürsich & Oschmann 1993). The good state of preservation of the bioclasts typically recorded in proximal tempestites suggests short-duration deposition, most likely generated by storm waves (Fürsich & Oschmann 1993).

The key storm-generated structures of combined flow (such as hummocky and swalley cross-stratifications) and/or reworking following re-sedimentation (e.g. beds with erosive marks at the top associated with normal grading deposits with cross-stratification, climbing ripples or other typical structure of bed form migration) are lacking in the examined shell beds of the studied stratigraphic sections. Also, the presence of gutter casts at the base of some levels of the Polonez Cove Formation is non-conclusive as indicative of storm deposits, as they are recorded in different sedimentary environments such as tidal flats, submarine fans (Whitaker 1973) and rivers (Smith 1995). Gutter casts are formed by dragging particles along the bed generating object marks similar to a track. In a high energy gravitational flow of a fan-delta front, in which transport of different granulometric class sediments occurs, pebble clasts can be dragged at the bottom of the substrate to form grooves similar to gutter casts.

On the other hand, the presence of gravelly sandstones and conglomerates with erosive bases, channelized deposits of outcrop scale, small proportions of suspension facies (representing the diurnal sedimentation), lateral extensions of lenses and layers, and the simultaneous transport of very coarse sediments together with mud, with rare layers showing normal grading, are indicative of episodic sedimentation under high energy conditions, typical of those generated by input from unconfined lobes in fan-delta fronts/slopes (Fig. 7). Our interpretation is supported by the tectonic context of rift opening of the Bransfield Basin in which the King George Island was related at the time of the Polonez Cove Formation deposition (Birkenmajer 2001), that would favour gravity driven flows.

## Summary

The highly fossiliferous Low Head Member of the Polonez Cove Formation bears one of the thickest and best preserved 3D bivalve concentrations in Antarctica. The unit is mainly composed of coastal marine sandstones, conglomerates and thin beds of finer grained facies deposited in fan-delta systems influenced by glacial events. The bioclastic facies preserved abundant pectinid bivalves of the species *L. gazdzickii* and, more rarely, other invertebrate remains. Figure 7 summarizes our interpretation of the depositional context of the Polonez Cove Formation shell beds: relatively high energy episodic subaqueous gravity driven flows associated with prograding fan-delta fronts between fair-weather and storm wave bases. The shell beds comprise at least three levels of accumulations that were size-sorted by tidal currents or wave orbitals during day-by-day conditions prior to final deposition by high energy flows. Once selected by winnowing in a low-energy environment, shells of almost the same size underwent short, episodic, high energy transport until final burial by gravity driven flows of fan-delta lobes. Other high energy episodes disarticulated once closed valves, which were suspended and deposited in nestled, stacked or imbricate positions. Successive episodes eroded and re-deposited other levels of coquina in different thicknesses according to the amount of transported valves and flow intensity. The final deposition of the shelly layers probably occurred near the original bivalve habitats, suggesting parautochthonous fossil assemblages. This scenario weakens the argument that storms were the final depositional agent of the Polonez Cove Formation shell beds, and raises the notion that not every shell bed with an erosive base bearing unfragmented, imbricated, chaotically-oriented bioclasts are the product of storm waves and flows.

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## Supplemental material

A supplemental table will be found at http://dx.doi.org/575 10.1017/S0954102013000783.

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