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The facies and biota of the oldest exposed strata of the Eocene La Meseta Formation (Seymour Island, Antarctica)

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La Meseta Formation is made up of estuarine and shallow marine, fossiliferous clastic deposits 720 m thick that provides a unique record of marine and terrestrial biota of Antarctic ecosystems preceding continental glaciation in the Oligocene. The lower limit of this formation has been poorly known, and therefore it has been carefully investigated. The lowest part of the La Meseta Formation, at the southern bank of a palaeodelta, is represented by relics of a prograding sequence of sediments deposited in the wave-dominated part of a deltaic system in the offshore and lower and upper shoreface environments. The sequence is completed landwards by younger tidal plain sediments deposited at 40 m lower altitude in a relatively protected, central estuarine basin, which was dominated by tidal activity and influenced by periodic fluvial inflow. These strata were deposited during a late Paleocene or Ypresian/Lutetian lowstand of sea level, which might reflect a glaciation event or glacioisostatic rebound of land following deglaciation of hypothetic Antarctic inland glaciers. Forced regression of sea level and seaward expansion of a deltaic freshwater environment, led to local extinction of a unique assemblage of marine echinoderms, bryozoans, corals and brachiopods. These marine fossils, representing a thanatocoenosis, are perfectly preserved due to syngenetic goethite permineralisation. This process owed its origin to excess reactive iron coming from sulphide-rich bedrock through weathering processes and acid sulphate drainage of the neighbouring land area.

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Key words: Antarctica, Seymour, Eocene, sediments, goethite, thanatocoenosis.

INTRODUCTION

The sedimentary and volcanic strata in the James Ross Island region, comprising the succession on Seymour Island, belong to the Larsen Basin and constitute the fill of an ensialic back-arc basin developed on the Weddell Sea flank of the Antarctic Peninsula (Elliot, 1988; Fig. 1). The Larsen Basin encompasses a succession of Jurassic, Cretaceous and Cenozoic strata. The upper part of this succession, covering the time period from the late Maastrichtian to the end of the Eocene, can be seen in numerous exposures on ice-free Seymour Island and adjacent islands (Elliot *et al*., 1975; Rinaldi *et al*., 1978; Elliot and Trautman, 1982; Askin, 1988; Sadler, 1988; Marenssi *et al*., 1998*a*, *b*; Fig. 2). The deposits are poorly consolidated and abundant in fossils that provide a unique record of preglacial environmental changes at the tip of the Antarctic Peninsula.

The Cretaceous strata of the Lopez de Bertodano Formation on Seymour Island are represented by clastic deposits accumulated in open marine environments. During the latest Cretaceous, then in the Paleocene (Sobral and Cross Valley formations) and early Eocene, the sedimentary environments changed progressively towards shallow marine and estuarine, in which marine and freshwater influences interfingered on a local scale (Macellari, 1988; Sadler, 1988).

There is no clear evidence and no consistent opinion on the environmental evolution from the Paleocene/Eocene boundary, through the Ypresian eustatic sea level perturbations, to an abrupt sea level fall at the Ypresian/Lutetian boundary. The fact remains that the younger deposits of the La Meseta Formation rest uncomformably on the older part of the succession. The position of the lower boundary of the formation is still uncertain, although a rich marine fauna from the boundary zone has been collected and described by several authors.

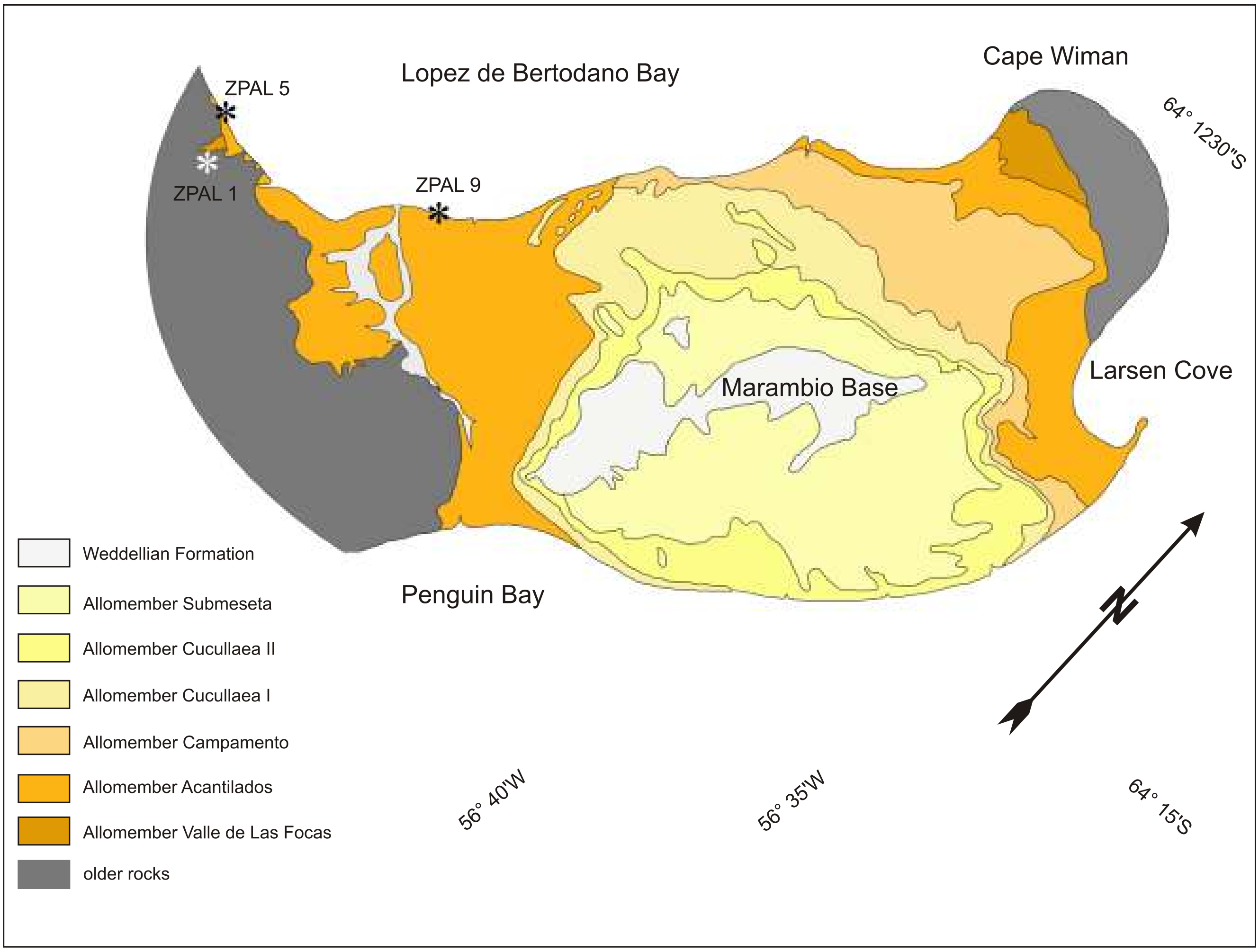

Fig. 1. Simplified geological map of north-east Seymour Island according to Marenssi *et al*. (1998*a*, *b*) with sites investigated marked

Localities ZPAL 1, 5, 9 introduced after Gaździcki *et al*. (2004)

The Eocene La Meseta Formation consists of fossiliferous sandstones and mudstones, which have a total thickness of *ca*. 720 m. They were deposited in the mouth of a tectonically-controlled, incised-valley estuary with alternating alluvial and marine-dominated sedimentary influences (Porębski, 1995). The formation provides the best palaeontological record of the Cenozoic (up to end of the Eocene) biota in the Antarctic. The sedimentological and palaeontological data it provides are essential not only to researching of global marine ecosystems and ocean evolution, but also in reconstructing the Antarctic terrestrial environments prior to the important deterioration of climate and the first glaciation of Antarctica at the beginning of Oligocene (Marenssi *et al*., 1998*a*, *b*; Gandolfo *et al*., 1998; Reguero *et al*., 1998; Viscaino *et al*., 1998; Case, 2006; Beu, 2009).

The lower limit of the La Meseta Formation was originally placed at a muddy sand bearing two horizons of olistostrome containing large *Ostrea* and *Pecten* shells that overlap older deposits along an irregular unconformity at Capo Wiman. That *ca*. 20 m thick unit of clastic strata was named Telm 1 by Sadler (1988). However, beneath Telm 1 Zinsmeister and DeVries (1982) first suggested, and then Marenssi *et al*. (1994) and Elliot (1993) recognized, 160 m of older deposits that were included into the La Meseta Formation. In a new lithostratigraphic scheme proposed by Marenssi *et al*. (1998*b*), the former Telm 1 would be located at the boundary between Allomember Valle de Las Focas and Allomember Acantilados (Fig. 1). Askin (1993) confirmed the validity of that additional unit by dinocyst analysis and determined the age as late early Eocene. The next younger unit of Sadler (1988) – Telm 2 – refers to a thinly interlayered muddy sand deposited in a tidally affected estuary mouth (Porębski, 1995), and fossiliferous sandy deposits marking marine inflow along tidal channels were named Telm 2s.

The sections described in this paper represent the upper part of Allomember Valle de Las Focas and the lower part of Allomember Acantilados encompassing the transition from marine to deltaic environments exposed at the southern bank of the estuary. This part of the succession is expressed by different sedimentary features than at the northern bank of the estuary. The location investigated is here described for the first time, al-

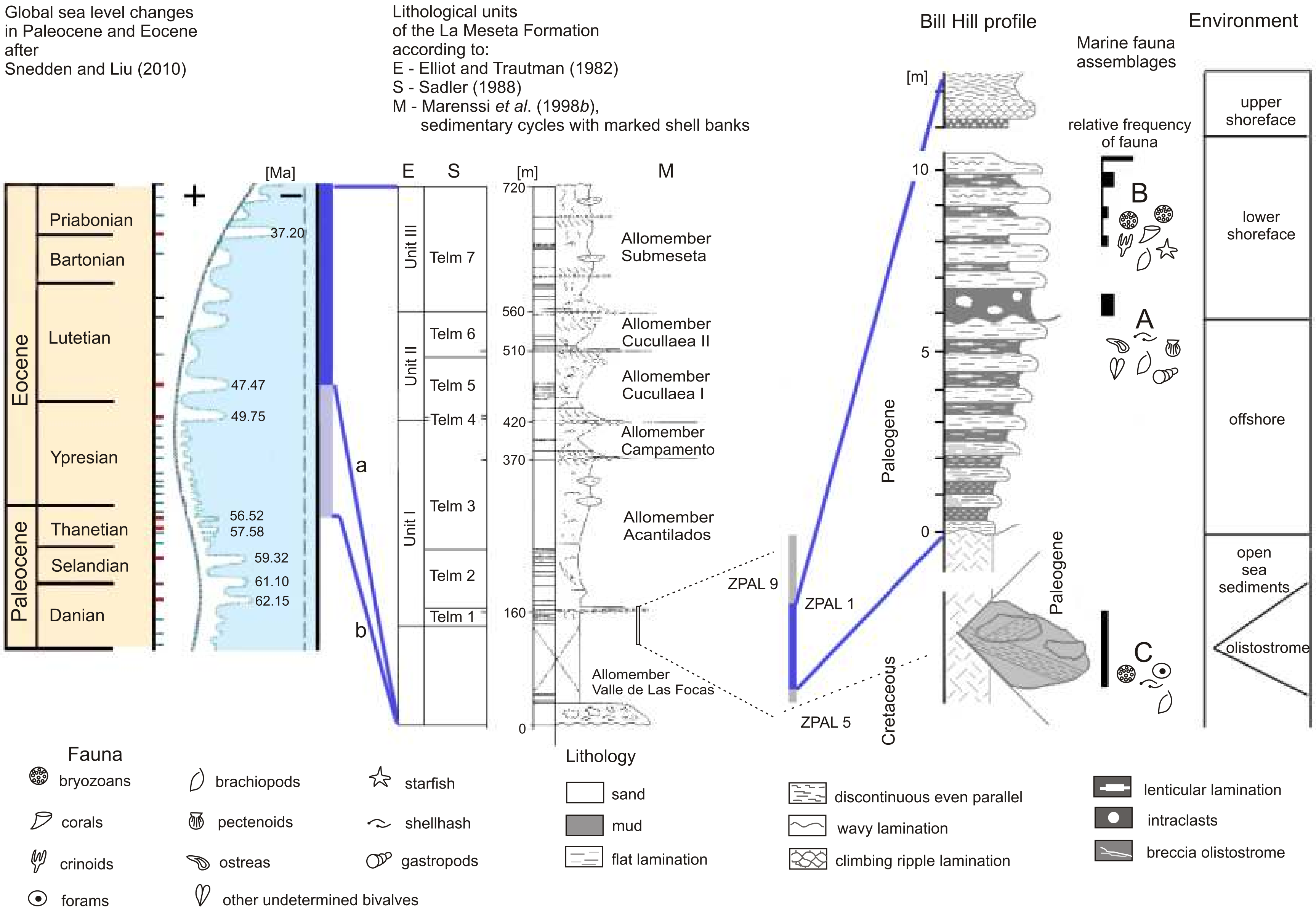

Fig. 2. Profile through the lowest part of the La Meseta Formation (Allomember de Las Focas) representing a delta front prograding sequence at Bill Hill (ZPAL 1)

Data on sea level changes taken from Snedden and Liu (2010), major relative sea level changes above 75 m marked by red colour; lithological subdivision of La Meseta Formation after Marenssi (1998*b*); ZPAL – sites of supplementary profiles described in text, see map – Figure 1; sign "a"– lower boundary of La Meseta Formation according to Sadler (1988), Stilwell and Zinsmeister (1992); sign "b"– according to Porębski (1995, 2000), Marenssi *et al*. (1998*a*, *b*) and Ivany *et al*. (2008); description of marina faunas A, B and C are explained in text

Fig. 3. Bill Hill, locality ZPAL 1 with abundant fauna of Telm 1 at the top

Fig. 4. Profile excavated along the slope of Bill Hill with sections of typical lithology enlarged

though it has been mentioned previously as an important fossil site (Fig. 1).

The main goal of our research was to determine and describe the depositional history of the lowest exposed part of the La Meseta Formation, and this led to the collection of a new data for reconstructing environmental changes during the global late Paleocene or the Ypresian/Lutetian lowstand of sea level (see global sea level changes in Fig. 2). The regression in Antarctica was a sudden event during the period of time covering the Paleocene–Eocene thermal maximum (PETM) and the middle Eocene climatic optimum (MECO) – climatic optima with rises of sea surface temperature (SST), atmospheric CO_2 concentrations at least two times greater than the present-day level, and little if any ice present on the Earth's poles (Zachos *et al*., 2001, 2008; Yapp, 2004; Bijl *et al*., 2009). However, according to several authors, temperatures and sea level fluctuations during Ypresian time (between both climatic optima) changed repeatedly over exceptionally wide range (Ivany *et al*., 2008; Vanhove *et al*., 2011). After the early-mid Eocene optimum, a gradual deterioration of climate took place and finally "the green paradise" was lost forever at the following cooling and glaciation of the Antarctic Continent from the beginning of the Oligocene (Prothero and Berggren, 1992; Case, 2006; Thorn and DeConto, 2006).

METHODS

Fieldwork was carried out by A. Tatur during the Argentine Antarctic Expedition to Marambio Station in austral summer 1993/1994. Strata in the Bill Hill section were described in detail in the field, and samples were taken from sites ZPAL 1, ZPAL 5 and ZPAL 9 (Fig. 1). All sites referred to "ZPAL" were coded as fossil locations (for details see Gaździcki and Tatur, 1994). The fossil fauna collected from the stations investigated had already been described in several publications. Importantly since the fossil-bearing surface at the top of Bill Hill was restricted in size to a few acres, almost all the specimens were collected and are now housed in the Museum of the Institute of Paleobiology, Polish Academy of Sciences in Warsaw.

Petrographic investigation of fossils was carried out using a *JEOL JSM-840A* scanning electron microscope (SEM) equipped with a Link Analytical energy-dispersive spectrometer *AN 1000/85S* (EDS) at the Institute of Geological Sciences, Polish Academy of Sciences in Warsaw. Freshly broken surfaces of fossils were analysed. To study thin sections a petrographic microscope was used. Mineral composition was determined using X-ray diffractograms.

RESULTS

FIELD INVESTIGATION: BILL* HILL 1; TELM 1 ALLOMEMBER VALLE DE LAS FOCAS
(ZPAL 1, at 41 m a.s.l.; Figs. 1 and 2)

The lowest exposed part of the La Meseta Formation at Bill Hill (Fig. 2) is made up of a coarsening- and thickening-upwards, almost horizontal sequence of silty sand deposits (Figs. 3 and 4). The deposits are loose, and only the uppermost sand beds are slightly consolidated. A Paleogene sequence 10.5 m thick (Fig. 2A) lies unconformably on Cretaceous sandy mud that belongs to the Lopez de Bertodano Formation (Fig. 2B). The lower part of section is barren, and consists of thinly laminated sand with interlayered sand-mud bedding. A thin layer of shell conglomerate occurs 5.8–6.5 m above the base. An abundant marine fauna (assemblage A) was recovered from a sandy mud layer containing intraclasts (mud balls). The fauna consists of crushed shells represented by pectenoids, oysters, brachiopods and a shell hash of bivalves with gastropods.

The marine bottom fauna of assemblage B is scattered through the overlying mud-sand interbedded deposits, being concentrated mainly in mud layers. Wavy and cross lamination was recognized in sand layers. An abundant surface concentration of this fauna occurs at the very top of the section in loose weathered muddy sand (9.8–10.5 m), which covers the summit of Bill Hill. However, this assemblage is quite different from that occurring below and consists mainly of bryozoans. More than 1000 specimens belonging to 40 species were collected from the top of Bill Hill. Minor constituents of this assemblage include echinoderms (crinoids, asteroids and echinoids) and corals. There is some admixture of reworked Cretaceous fauna that could have been either eroded from the bedrock during sedimentation, or may constitute contamination resulting from downslope transport from the exposed Cretaceous rocks during Quaternary or Recent times. All the fauna is perfectly preserved, due to staining of their surfaces and impregnation of internal structures by iron compounds and carbonates. Even entire crinoid calyces, starfish and delicate colonial bryozoans are perfectly preserved. The sediment sequence ends upwards in irregular patches of loose sand rich in glauconite. Truncated climbing ripple lamination can be observed in some poorly consolidated sandstone on the top of Bill Hill next to the profile described (Fig. 5). Beach-laminated sediment might occur above this.

Deposits exposed in the Bill Hill profile (see Fig. 1) were included, on the basis of faunal similarities to the uppermost part of the Allomember Valle de Las Focas and the very beginning of the Allomember Acantilados by Marenssi *et al*. (1998*b*) and the upper fossil-bearing part is equivalent to Telm 1 of Sadler (1988).

Fig. 5. Truncated climbing ripple lamination typical of an upper shoreface unit

FIELD INVESTIGATION: CRETACEOUS/PALEOGENE CONTACT IN CLIFF; TELM 2 LOWER PART OF ALLOMEMBER ACANTILADOS (ZPAL 5; Figs. 1 and 2)

The oldest deposits of the La Meseta Formation exposed in the cliff along Bahia Lopez de Bertodano rest unconformably on the Cretaceous Lopez de Bertodano Formation (Fig. 6). The La Meseta Formation starts with a sandy layer dipping 45°N, that bears muddy clasts of Cretaceous bedrock at the base and is overlain by a set of sand/mud bedding truncated about 2 m higher by a weakly lithfied sandy lens dipping 20°N. A few

Fig. 6. Erosive or soft tectonic contact between sandy clastic deposits of the Paleogene La Meseta Formation (on the left) with muds of the Lopez de Bertodano Formation (on the right)

Exposure in the cliff at the south-west bank of the estuary

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* named (see Gaździcki and Tatur, 1994) in honor of Wiliam J. (Bill) Zinsmeister, who first mentioned that site in 1985 (after Stillwell and Zinsmeister, 1992).

poorly preserved spherical bryozoans were possibly eroded from older deposits of Telm 1 that were preserved as a relic occurrence on the top of Bill Hill (situated about 200 m seawards and at a height of 40 m a.s.l.). Hemispheric bryozoans species are characteristic of the base of the La Meseta Formation and do not occur in any other locality of this formation (Hara, 1997*a*, *b*). The sand lenses are overlain by a set of monotonous thinly interbedded mud and sand that occasionally contains thicker lenses of sand. These deposits were described by Sadler (1988) as the lower part of the Telm 2 unit, that belongs to the lowest part of Allomember Acantilados according to the suggestion of Marenssi (1998*a*, *b*).

Southwards from this site, an olistostrome occurs that is tectonically incised in soft muds of the Lopez de Bertodano Formation (Fig. 7). The olistostrome (breccia) contains blocks of Paleocene Sobral Formation in a younger sandy fossiliferous (assemblage C in Fig. 2) matrix rich in glauconite dated (by dinocysts) to the late early Eocene. It is comparable with similar blocks occurring in the well-defined beds in the north bank of the valley, from where palynological data has been obtained (Askin, 1993). Therefore, in Polish palaeontological collections this outcrop is treated as part of Telm 1.

Fig. 7. Olistostrome block exposed in sea cliff, rich in large clastic deposits bearing fauna inherited from the Paleocene Sobral Formation

The block is tectonically incised in Cretaceous Lopez de Bertodano Formation muds (near ZPAL 5 in Figs. 1 and 2)

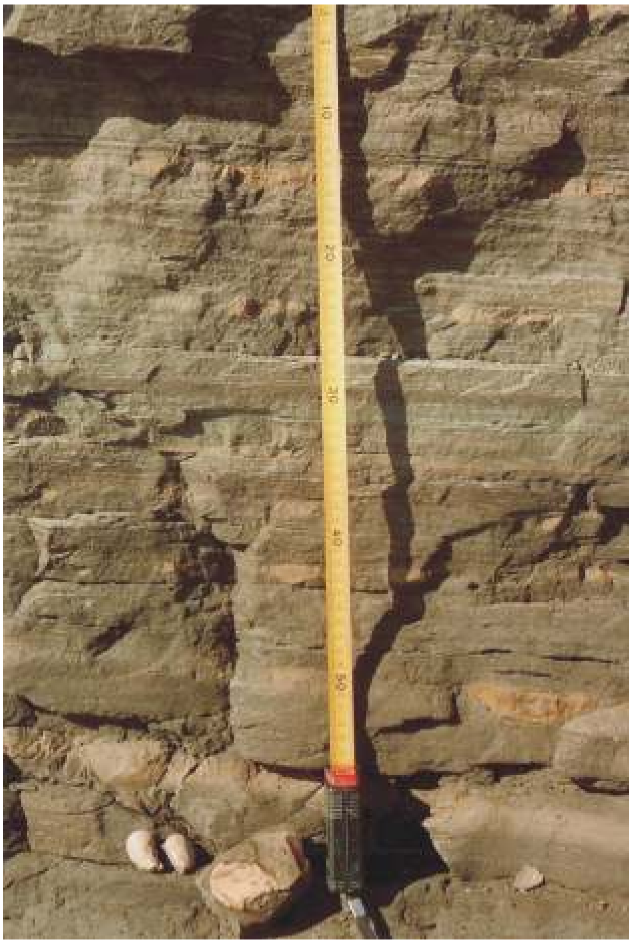

Fig. 8. Sediments in tidal ebb- and flood-affected estuary mouth

Close to ZPAL 9 locality in Figure 1

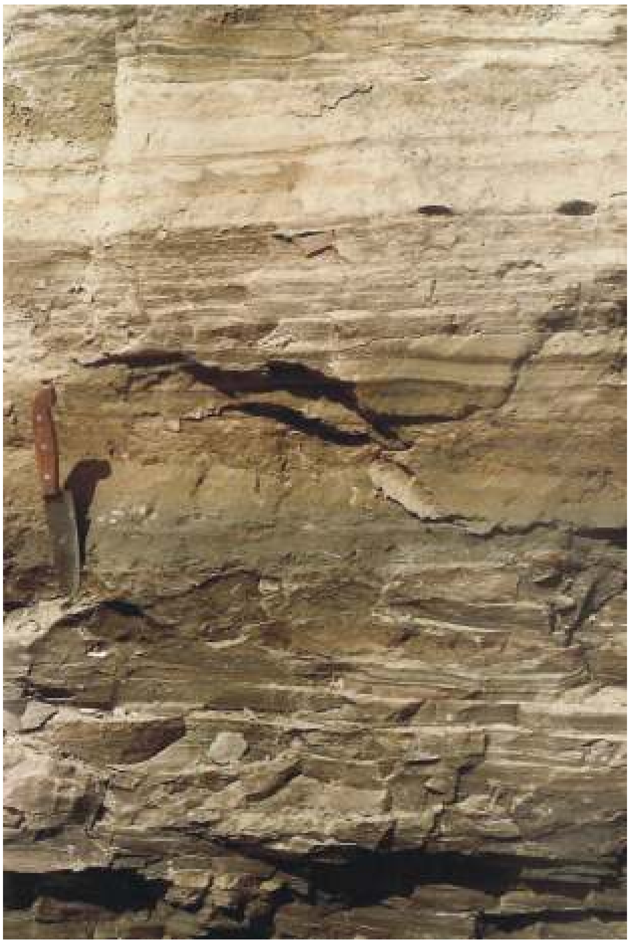

Fig. 9. Channel incised in tidal deposits, vertical scar infill

Close to ZPAL 9 in Figure 1; the knife shows the bases of the channels, note load structures at the top

FIELD INVESTIGATION: TELM 2 OUTCROP IN CLIFF (ZPAL 9; Figs. 1 and 2)

The tidally influenced muddy strata deposited in the protected central estuarine basin (Porębski, 1995; lower part of Telm 2) are cut by tidal channels. Along these, episodic marine invasions delivered coarse clastic sediments and marine fauna to the channels bases. The channels usually cut the upper part of Telm 2. The sequence of estuarine deposits is slightly inclined to the axis of the palaeovalley and is exposed in a cliff 5 m high for more than 1 km along the coast. This site has been investigated earlier by Porębski (1995) and Doktor *et al*. (1988, 1996).

The tidal delta deposits consist of thinly interlayered mud and sand showing lenticular bedding. Sand lenses in the mud are up to a few cm thick and are locally cemented by carbonates rich in iron hydroxides, forming discoidal syngenetic concretions (Fig. 8). There are dispersed shells of *Nucula* and locally abundant plant detritus and rare leaves.

The tidal channels cut the tidal flat succession. The vertical channel infill described (Fig. 9) has a fining and thinning upwards signature, and includes a normally graded sandy conglomerate with abundant reworked marine shells and shell hash at the base. Slump structures and muddy intraclasts are common. Crushed carbonate concretions derived directly from the lower unit have also been found. Ripple bedding with mud flasers are frequently noted in sandy layers, though asymmetrical current ripple marks may also be found (Fig. 10). In the fine-grained deposits load structures (Fig. 9) and in coarser beds trace fossils – *Nereites* and *Cruziana* may be identified. The infills may contain occasional plant and fish fossils (Fig. 11). The leaves collected from this site belong to six species and one clupeoid fish is a new species (Doktor *et al*., 1996).

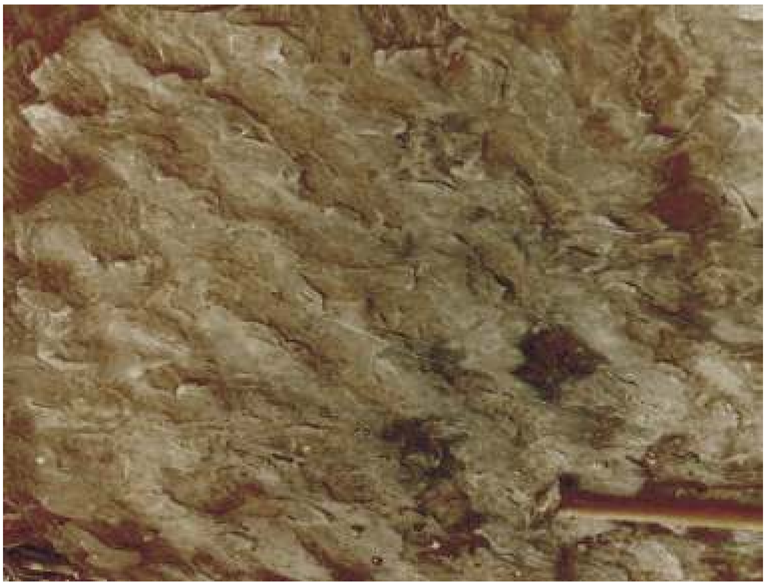

Fig. 10. Channel incised in tidal deposits, vertical scar infill

Asymmetrical ripple marks

Fig. 11. Channel incised in tidal deposits, vertical scar infill

Head of fossil fish

LABORATORY INVESTIGATIONS

Two hemispherical and multilamellar bryozoan specimens collected from the surface of Bill Hill (Telm 1 of Sadler, 1988) were investigated by SEM and their chemical composition was determined by EDS. Concentrations of iron hydroxides and silica form – external brown veneers covering the carbonate skeletons. All zooecial openings in the skeletons are covered by a resistant silicates-silica-iron hydroxide crust showing compositional changes on a microscale (Figs. 12–15). Below this crust, the zooecial tubes are often empty, although a thin micro-druse of well-crystallized rhombohedral goethite crystals usually cover the inner wall of tubes (Fig. 14). The goethite forms thin plates (Figs. 16 and 17) often terminated according to Weidler *et al*. (1996) by 110 and 021 faces (Fig. 18). EDS analyses confirm a stoichimetric chemical composition of the goethite crystals. On the surface of the goethite crystals minor accumulations of pyrite and gypsum were occasionally identified. Channels left by epibionts (serpulid polychaetes) feeding on the bryozoa colonies are also filled with goethite (Fig. 19).

In some inner parts of the bryozoan colonies a second generation of permineralisation was commonly observed. Empty spaces may (following goethite crystallisation on the walls) be entirely filled with well-defined crystals of calcite. Pseudomorphs of calcite after fibrous aragonite was also commonly observed in the carbonate skeletons of the colonies (Fig. 20). The mineral composition of the bryozoan skeletons and the mineral composition of permineralisation was confirmed by X-ray analyses.

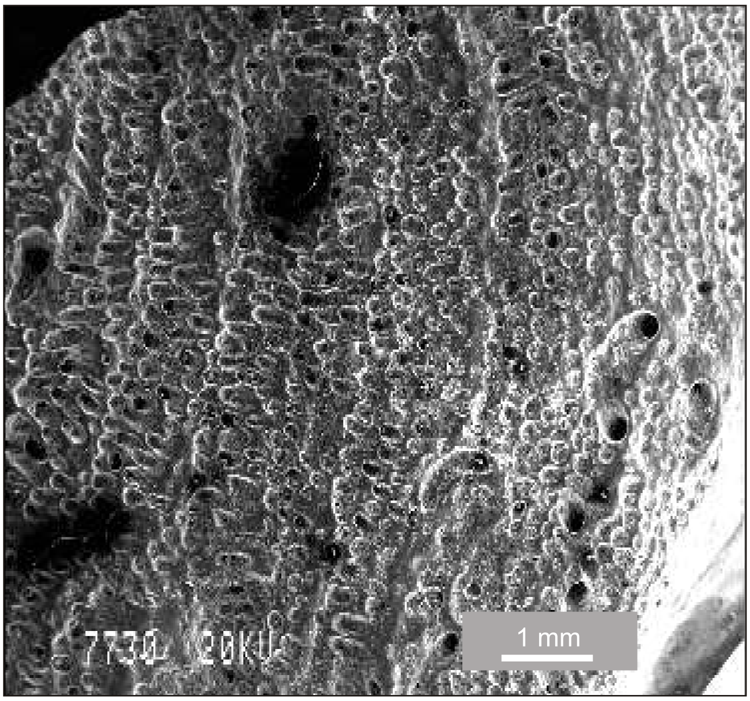

Fig. 12. Bryozoa, fractured fragment of hemispheric colony

Inner structure showing tangential section through zooecial tubes

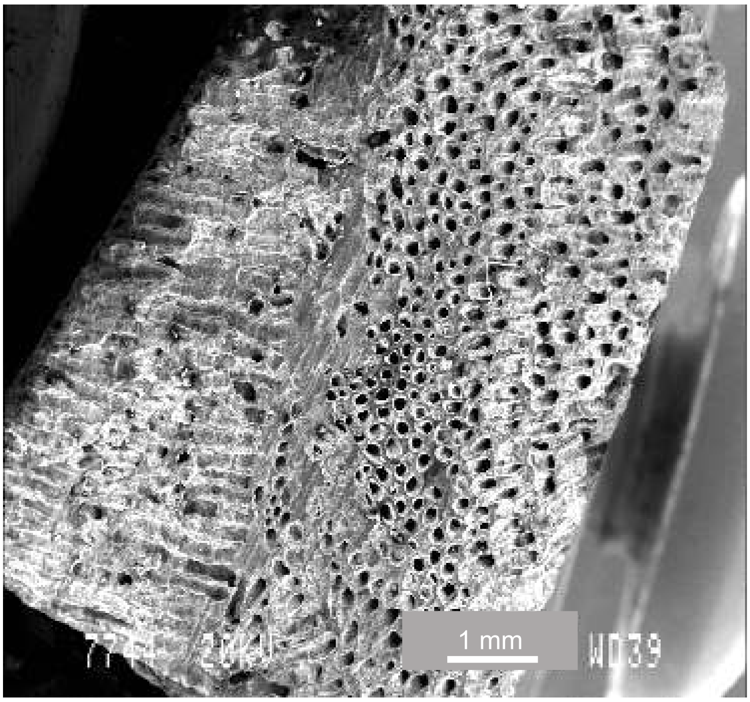

Fig. 13. Bryozoa, fractured fragment of hemispheric colony

Inner structure showing tangential and longitudinal sections through zooecial tubes

DISCUSSION

Documentation of the prograding sedimentary sequence in the lowest exposed part of the La Meseta Formation necessitates constraints on both age and conditions of thanatocoenosis formation. Petrographic studies have shown that the loose and/or poorly consolidated deposits on Seymour Island and Vega Island have undergone only negligible diagenetic alteration (Pirrie *et al*., 1994; Marenssi *et al*., 2002).

AGE OF THE DEPOSITS

Sadler (1988) suggested that the late Ypresian lowstand of sea level at 49.5 Ma could account for the erosion prior to deposition of the La Meseta Formation. This date is consistent with a taxonomic inventory of molluscs (Stillwell and Zinsmeister, 1992) and Antarctic mammals that are comparable with well-known South America species. Porębski (1995, fig. 2; and 2000, fig. 4) suggested that the late Ypresian lowstand correlates rather to a hiatus observed within the La Meseta Formation, and that the base of the formation is much older. Marenssi (2006) and then Ivany *et al*. (2008), after detailed consideration of all available evidence, proposed the 56 Ma sea level lowstand as the time of possible initiation of the La Meseta Formation. Unfortunately, this age problem cannot be resolved unequivocally using strontium isotope stratigraphy (SIS) as the strontium isotope curve fluctuates during this time interval, and two or three alternative age estimates can be obtained for a given isotopic value (Ivany *et al*., 2008). The K/Ar and Ar/Ar methods cannot be applied to glauconite, because the glauconite grains are widely redeposited from older units. The Paleocene Sobral Formation is particularly rich in glauconite. Finally, the age of the olistostrome matrix at the base of the La Meseta Formation (top of Allomember Valle de Las Focas, Telm 1 of Sadler, 1988) near Capo Wiman was estimated to be late early Eocene on the basis of dinocysts (Askin, 1988, 1993; Wrenn and Hart, 1988; Cocozzac and Clarkec, 1992). Sandstone blocks occurring in two levels of the olistostromes were dated as Paleocene, showing a dinocyst assemblage similar to the one in the Sobral Formation bedrock. However, a high-resolution record of palaeotemperature variation inferred from stable oxygen and carbon isotopes as well as carefully considered SIS data support shifting the lower limit of the La Meseta Formation back to the upper Paleocene (Ivany *et al*., 2008). Despite different opinions on the age, all authors agree that a lowstand of sea level initiated deposition of the La Meseta Formation, although with limited evidence of shallow-water environments supporting this interpretation. This paper provides data that fills this gap.

According to Haq *et al*. (1987, 1988), global sea level fell at the end of the Paleocene and close to the Ypresian boundary by more than 100 m in a relatively short time geologically. However, in a new compilation by Snedden and Liu (2010), the late Ypresian lowstand of sea level had two minima at 47.47 and 49.75 Ma. These are located in zone Yp 10 that straddles the Ypresian/Lutetian boundary. The Paleocene sea level lowstand was interpreted to represent the time interval between 56 and 58 Ma, i.e. zone Th4. However, recent opinion suggests that the sea level changes probably did not exceeded 100 m over both time intervals.

GENESIS OF THANATOCOENOSIS AT THE TOP OF BILL HILL

The depositional history of the La Meseta Formation (according to Sadler, 1988) began with a regressional trend that terminated in a sea level lowstand. The organisms of a shallow marine benthic biocenosis (assemblage B from Bill Hill) were killed as a result of a sudden inflow of fresh, muddy water from a prograding river system that followed a regressional trend. The reaction of marine biocenoses to such stress has long been observed, and it is a subject of ongoing research in marine ecosystem studies (Mac Ginitle, 1939; van Woesik *et al*., 1995; Hutchinings *et al*., 2009). Sea level changes (both rises and falls) and their ecological consequences are considered as a primary reason of thanatocoenosis formation (Hallam and Wignall, 1999).

The abundant marine benthic fauna occurring in assemblage B at the top of Bill Hill (Telm 1, locality ZPAL 1) is finely preserved. It seems to represent a typical thanatocoenosis formed as a result of the local extinction of all marine benthic organisms during a very short period of time. The co-occurrence of stylasterids (Stolarski, 1998) with abundant scleractinians (Stolarski, 1996), bryozoans (Gaździcki and Hara, 1994; Hara, 1997*a*, *b*), echinoderms (Baumiller and Gaździcki, 1996; Radwańska, 1996) and brachiopods (Bitner, 1996) has been noted from the Bill Hill locality. Preservation of numerous articulated brachiopod shells, complete echinoid tests with attached spines as well as crowns and pinnules of crinoids testify to quick *in situ* burial by in iron-rich muddy sediment (Stolarski, 1998). Thus, the reason for benthic faunal extinction and thanatocoenosis formation in Telm 1 is other than the storm wave action commonly invoked to explain the origin of fossiliferous layers in the higher units of the La Meseta Formation.

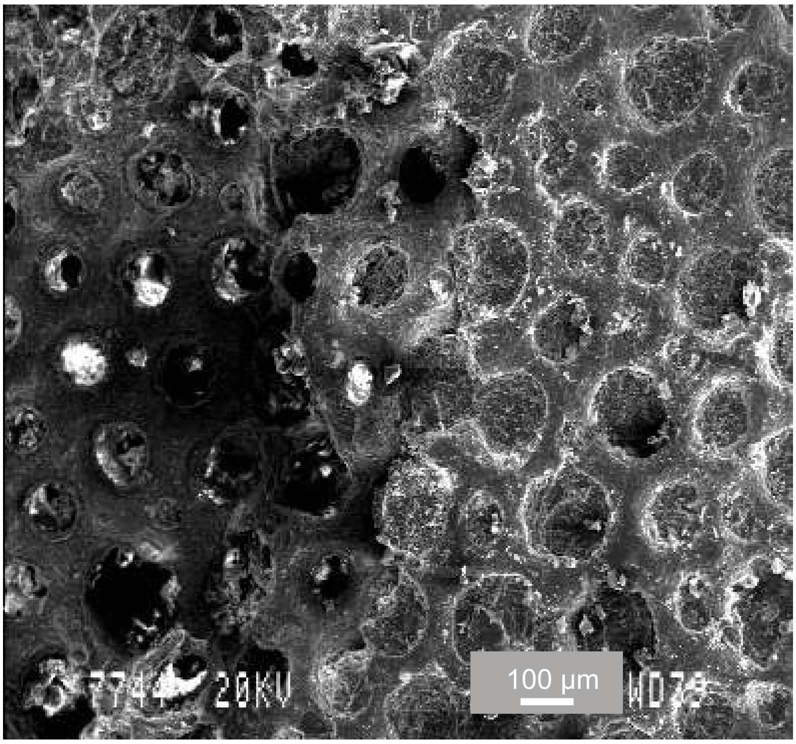

Fig. 14. Zooecial openings corked at external surface (on the right) and open in fracture zone exposing inner structure (on the left)

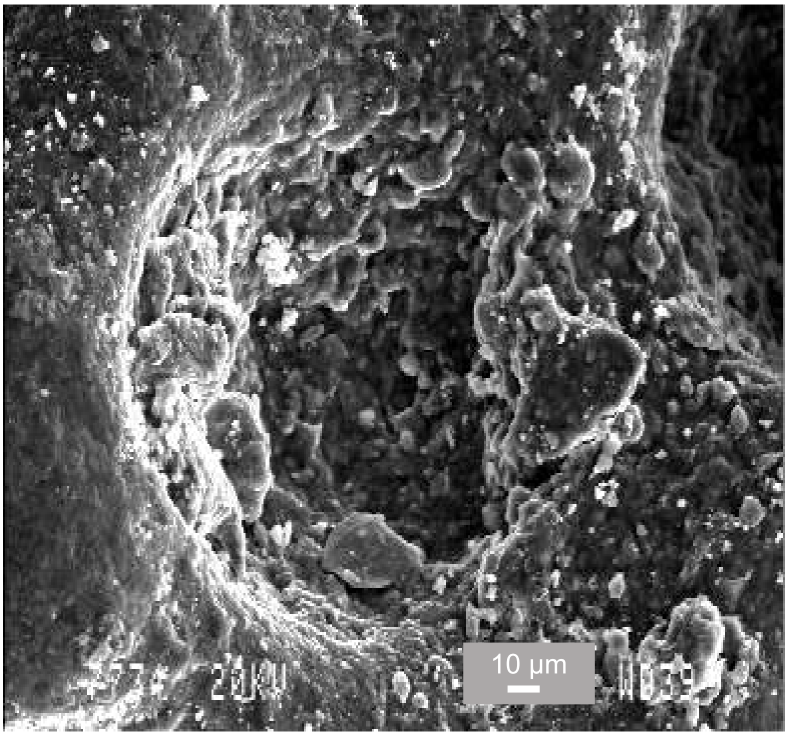

Fig. 15. Zooecial opening on the external surface of colony covered by hard silicate-silica-iron hydroxide crust

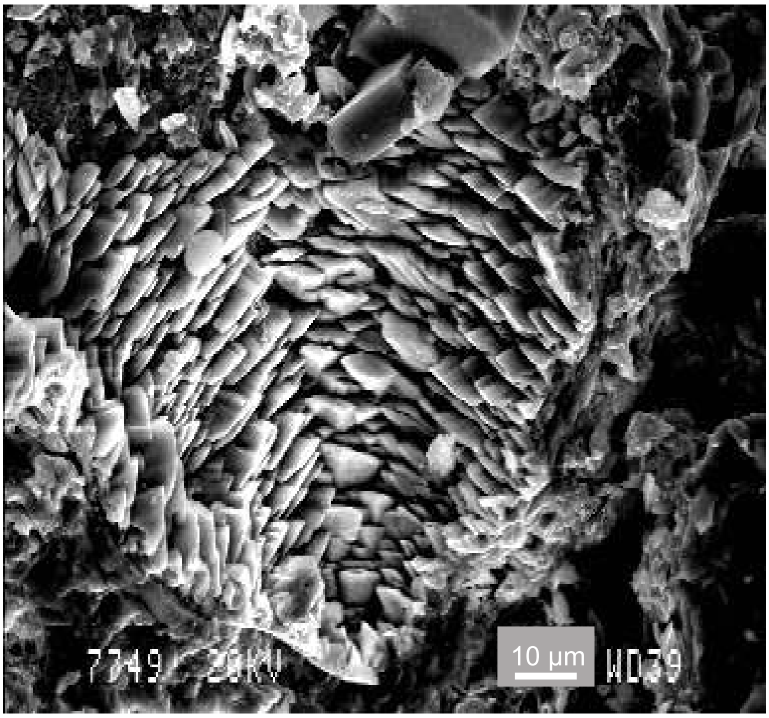

Fig. 16. Fracture, zooecial opening with goethite druse on the inner walls of tubes

Thin tabular plates of goethite

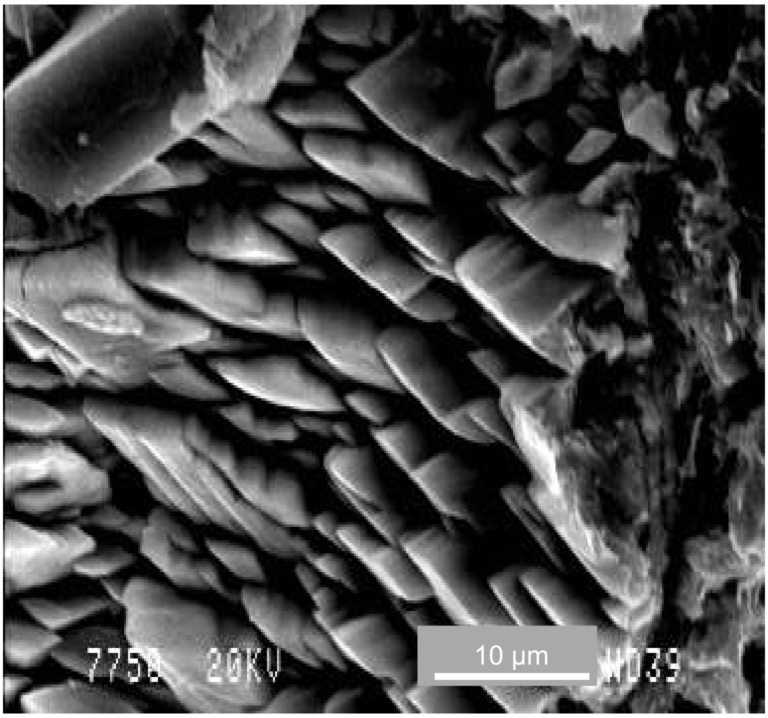

Fig. 17. Fracture, zooecial opening with goethite druse on the inner walls

Thin tabular plates of rhombic goethite

All marine fossils of assemblage B have been stained by and impregnated with iron hydroxides. Empty voids left by bryozoa colonies are filled with goethite in the process of permineralisation, that is defined as in which mineral deposits form internal casts of the organism (Schopf, 1975; Mani, 1996). Goethite permineralisation is usually observed in bones or wood fragments (Pfretzschner, 2001; Uhl and Montenari, 2011) although it affects also other organisms: echinoderms, foraminifera, bryozoans, and even Devonian soft-bodied worms (Cameron, 1967; Boiko, 2001; Paine, 2005). The polychaete worms occurring in the La Meseta Formation at the same stratigraphic position, but on the other side of the drowned valley are also coated by iron hydroxides but these are amorphous (Schweitzer *et al*., 2005). The second and final step of permineralisation that finally hardened most of the porous and fragile organic structures was recognized in assemble B of Bill Hill as the crystallisation of calcite.

The marine ecosystem of Telm 1 was developed in a relatively shallow estuarine environment near the front of a delta formed by a local river that cut Cretaceous (Lopez de Bertodano Formation) and Paleogene (Sobral and Cross Valley formations) rocks. Blocks, clasts and fossils from these formations are present in the lowest deposits of the La Meseta Formation. The Paleogene (pre-Eocene) rocks are composed of sand interlayered with bituminous mud with sulphides. Intense oxidation of sulphides mediated by microbiological processes is currently taking place in areas of surface exposure of these deposits (Tatur *et al*., 1993) and was likely also contemporaneous with deposition of the La Meseta Formation, since the course of the sulphide-weathering process is azonal. The excess of iron released in Recent acid sulphate drainage following sulphide oxidation is washed from soils and transported downwards by water and usually precipitates in depressions as iron oxides and gypsum (Fig. 21); alternatively acid solutions bearing divalent iron can enter river and marine water.

The supply of reactive iron ions to the seafloor helped to harden the fragile fossils by surface coatings and inner iron hydroxides permineralisation that in suitable conditions occurred in zooecial tube openings, locally forming perfect goethite crystals. However, the zooecial tube openings are not filled entirely by goethite since the process of permineralisation was interrupted immediately after the death of the colony and voids were closed by a cover of lithified sediment that inhibited further goethite mineralisation. Therefore, we suppose that goethite was formed syngenetically, and iron coating might be a direct reason for death of the benthic fauna. If the chemistry of the environment is appropriate, the organism or fragment of organism can act as a nucleus for the precipitation of minerals, resulting in a nodule forming around it. If this happens rapidly, before significant decay to the organic tissue, very fine three-dimensional morphological detail can be preserved (www.MuseumStuff.com). This type of fossilisation by iron hydroxides mobilised in the sulphate drainage process is documented in several studies in past and recent environments bearing sulphide from the watershed (Fernández-Remolar and Knoll, 2008). That process has also caused the fossilisation of echinoderm viscera (Haugh and Bell, 1980). The second step of permineralisation by carbonates (calcite) would be diagenetic.

PROGRADING SEQUENCE IN THE LOWEST STRATA OF THE LA MESETA FORMATION

Sediments of Telm 1 exposed at Bill Hill are interpreted to represent part of a delta-front prograding sequence in the wave-dominated part of a marginal sea-facing delta system (ZPAL 1; Figs. 1 and 2) starting from an offshore – lower shoreface to upper shoreface environment (Wise, 1980 in regressions and transgressions). That interpretation fits the regional concept of delta development at that time as "...a prograding delta front from inner estuarine or prodelta setting to the tidal dominated and storm influenced subaqueous delta plain..." (Marenssi *et al*., 1998*b*).

With generally regular discharge of sediment into the estuary, the occurrence of olistostromes (megabreccias) near the north (Sadler, 1988; Askin, 1993) and south-west (olistrome on Fig. 7 is lokalized near ZPAL 5 marked in Figs. 1 and 2) banks of estuary suggest that the rapid fall of sea level had characteristics of a forced regression. The prograding sequence from Bill Hill is completed nearby, but in a 40 m lower orographic position as a sediment deposited later in the protected central estuarine basin, dominated by tidal activity and influenced by periodic fluvial inflow (Porębski, 1995). This sediment belt is exposed along a cliff in Lopez de Bertodano Bay (ZPAL 9 in Fig. 1), and may represent a lowstand of sea level. The presence of a reworked bryozoan fauna suggests erosion of the older Telm 1 deposits. The prograding sequence at Bill Hill precedes the transgressive tidal estuary deposits forming the younger units.

The sea level fall at the end of the Paleocene at 56 Ma or alternatively in the early Lutetian at 47.47 Ma (Fig. 2) are considered as dates of a significant and distinctive event in the lowest part of the La Meseta Formation. We do not have convincing data to support any of these ages, alhough

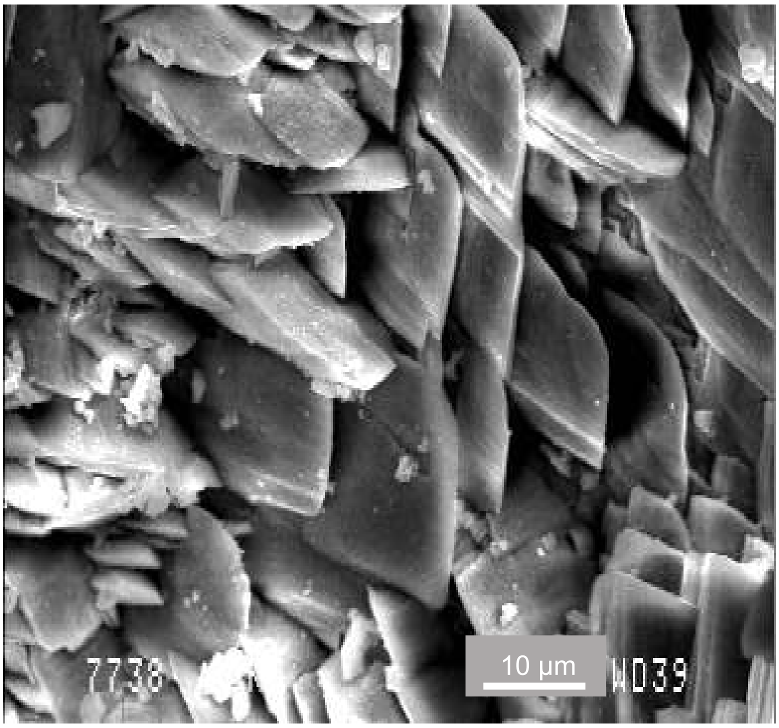

Fig. 18. Fracture, zooecial tubes with goethite druse on the inner walls

Thin tabular rhombic plates of goethite sharpened by 110 and 021 faces

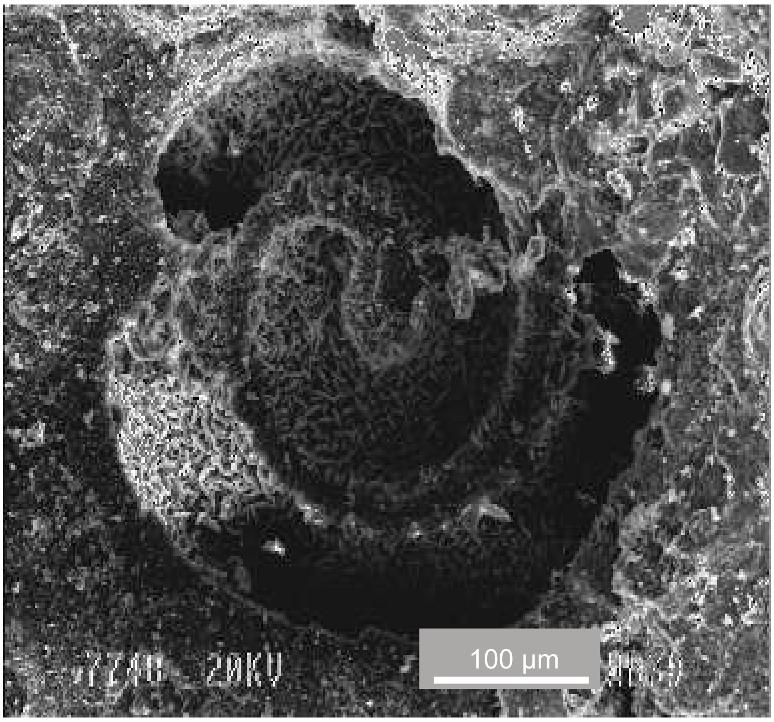

Fig. 19. Inner walls of channel left by epibionts feeding on bryozoan colony is also covered by druse of sharp crystals of goethite

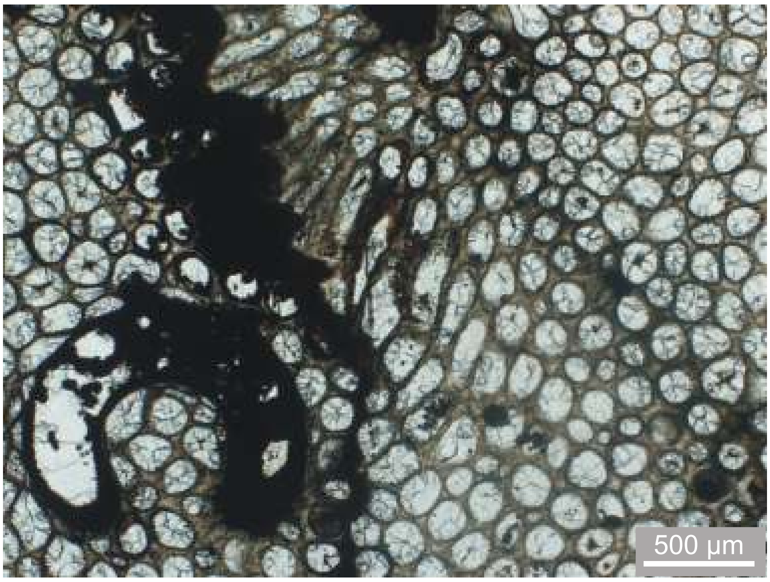

Fig. 20. Thin section of bryozoan specimen (plane polarised light)

Calcite pseudomorphs after aragonite make up frame and zooecial openings filled with goethite druse on the walls (thin dark ring) and calcite crystals (center) permineralisation

the sedimentological evidence of the lowstand of sea level in the Bill Hill section is unequivocal. The unique composition of the marine fauna of assemblage B collected at this locality makes it possible to correlate our section with the one on the opposite bank of the estuary and constrain its position in the stratigraphic architecture of the formation (Baumiller and Gaździcki, 1996; Bitner, 1996; Stolarski, 1996, 1998; Radwańska, 1996; Hara, 1997*a*, 2001; Szczechura, 2001).

The sea level fluctuations in Eocene were considered according to Zachos *et al*. (2001) as eustatically controlled, since the Antarctic continent remained predominantly ice-free during Cenozoic until the middle to late Eocene. However, there is increasing number of suggestions that Antarctica was a subject of cyclic glaciations during Paleocene and Eocene, which were confined to the inner part of the continent. Payros *et al*. (2009) have shown that the cyclicity of sea level fluctuations during Ypresian that terminated in the lowstand at the Ypresian/Lutetian boundary might resulted from recurrent glaciation of the Antarctic continent. The Hervé Cove diamictite on King George Island, which is possibly a mountain-type tillite, supports this hypothesis (Birkenmajer *et al*., 2005; Nawrocki *et al*., 2010). That might mean that early Lutetian or late Paleocene lowstand of sea water resulted either from specific glacioeustatic global event at the onset of glaciation or from glacioisostatic delayed rebound of land in interglacial time after possible initial inundation event. This is typical very dynamic scenario observed during Quaternary, but usually carefully applied to geological past history (Haq *et al*., 1987, 1988; Snedden and Liu, 2010).

However, the range of sea level fluctuations in Paleocene and Eocene were much lower than in Quaternary and did not exceed 100 m. Glacioisostatic uplift followed melting of inland glaciers would harmonize with commonly postulated late Paleocene (PETM) or middle Eocene (MECO) climatic optimum. Considering sea level fluctuation during the La Meseta Formation, we have to take into account the rate of local fault subsidence of the valley floor against a vertical accretion infill. Although, it is hardly to treat vertical accretion infill as the reason of abrupt regression of the sea. Likewise, the tectonic activity in drowning valley might be rather a reason of transgression but not relative sea level fall. Therefore, the interpretation accepted in this paper points to short term and abrupt sea level fluctuations that may be effectively explained by hypothetic cyclic glaciations.

The sedimentological and palaeontological evidence collected provide evidence of bathymetric changes during progradation. Bathymetric estimates for the fossil assemblage B from Bill Hill (Telm l unit of the La Meseta Formation) based on bryozoans (1048 specimens than belong to 40 species in locality ZPAL 1 of Telm 1) suggest water depths between 20 and 80 m, by comparison with species structure in the well-documented Miocene of the Mediterranean region (Hara, 2001). Our sedimentological data support that inference: climbing ripple lamination in an estuarine basin with tidal channels and wavy bedding, while trace fossils from overlying deposits imply even shallow depositional conditions.

However, assessment based on scleractinians and brachiopods suggest palaeodepths at least *ca*. 100 m (Bitner, 1996; Stolarski, 1996). All known nine species of the genus *Conopora* are recorded from depths exceeding 100 m, but most of these (as with stylasterids in general) occur at depths of 200–1000 m (after Stolarski, 1998). Stolarski (1998) left the problem open and proposed to treat the occurrence of *Conopora* in shallow-water as an “interesting exception” for the population of this genus living at high latitudes in the Southern Hemisphere. Bitner (1996) suggests after Long (1992), who recognized in the lower part of La Meseta deep water sharks, that co-occurrence of shallow- and deep-water brachiopod species by the presence of local deep- and lengthy trenches. This way uneven bottom topography may lead to ecological “...heterogeneity of the environment...”.

To explain this discrepancy, different depth habitats for fossil and recent crinoids (Baumiller and Gaździcki, 1996) and echinoids (Radwańska, 1996) have been invoked. It is known that some Eocene bottom-living species shifted to deeper water following glaciation in the Oligocene, while some Eocene shallow-water species, formely regarded as extinct, were recently found at the bottom of the Pacific Ocean (Zinsmeister, 1986). However, deposits of the early to mid Eocene at the base of La Meseta Formation were deposited during a climatic optimum. Even if a within-continent glaciation then took place, the coastal zones and adjoining shallow basins would have been ice-free.

We would like to stress that the La Meseta Formation formed over several sedimentary cycles of onlapping and offlapping sediment sequences, in a subsiding estuary controlled by tectonic processes (Porębski, 1995; Marenssi *et al*., 1998*b*). Eustatic sea level fluctuations had amplitudes of up to

Fig. 21. Recent iron hydroxide precipitation on the surface as a result of acid sulphate drainage in the area of the Sobral Formation

100 m (Snedden and Liu, 2010). Local fault subsidence of the valley floor was never directly measured but the thickness of formation is estimated to 720 m (Marenssi *et al*., 1998*a*). Moreover, boundaries between sedimentary units are not always clear, and detailed description of fossil sampling locality is desirable. We confine our remarks to one locality at Bill Hill (ZPAL 1), where the problem in determining bathymetric context of different groups of taxonomically well-elaborated marine organisms is striking. We do not exclude the sophisticated explanations presented above, but we would like to stress that some simple common geological processes have been may aperative.

Fossil assemblage A is the oldest, found in the offshore/lower shoreface environment of a delta front prograding sequence representing the lowest exposed deposits of the La Meseta Formation. It contains abundant shell hash of bivalves and gastropods; among these, fragments of *Chlamys* sp. and *Ostrea* were recognized. These organisms were probably eroded from the shallow coastal zone by a retreating sea and deposited as reworked material in the deeper locality where they were mixed with relatively well-preserved brachiopods. Four metres above this horizon, there is level bearing another abundant fossil assemblage B, in the Bill Hill profile, that bears sediment features of a slightly shallower lower shoreface environment. However, the composition and state of preservation of fossils are totally different. Bryozoans dominate over crinoids, echinoderms, starfish single scleractinians, brachiopods and some Cretaceous fossils (including characteristic rotularia). The occurrence of bryozoans fits a generally shallow environment (Hara, 2001; Amini *et al*., 2004). Abundant individuals and their very good preservation suggest an *in situ* habitat, at least for bryozoans. A minor admixture of other organisms could have been either eroded from deposits formed during inundation that preceded marine regression, or were simply eroded from soft Cretaceous and/or Paleocene deposits formed near the east bank of the estuary. The finding of definite Cretaceous fossils supports such a possibility. Moreover, in the olistostrome occurring at the base of Telm 1, at the north and south banks of the estuary, most clastic material and fossils are inherited from bedrock.

The La Meseta Formation consists of three large sedimentary sequences, constrained by fault – controlled subsidence (a drowning delta) and eustatic sea level changes (Porębski, 1995, 2000). However, the ecological scenario of the basal prograding sequence of the La Meseta Formation was never repeated. A clear lithological profile that suggest progradation is available only at Bill Hill.

CONCLUSIONS

The lowest exposed part of the Eocene La Meseta Formation represents a delta front prograding in the wave-dominated marginal part of a delta system starting from offshore though lower and then upper shoreface. The sequence is completed nearby in sediment deposited in a relatively protected, central estuarine basin, which was dominated by tidal activity and influenced by periodic fluvial inflow. That might represent the lowest stand of sea water, but upwards, signs of a coming transgression are observed. The following units (from oldest to youngest) were recognized in the sequence:

– Unconformity with Cretaceous Lopez de Bertodano sandy mud:
  - offshore: interlayered mud-sand deposits to thinly laminated sand, barren;
  - lower shoreface: muddy sand with dispersed fossils, hash of *Pecten* and *Ostrea* in a basal layer, *in situ* thanatocoenosis with abundant echinoderms and bryozoans at the top of the unit;

  - upper shoreface: sands with climbing ripple lamination, with possible beach deposits at the top.
- Unconformity with Cretaceous Lopez de Bertodano muds (continuation with overlapping section nearby):
  - lower shoreface: sands with individual bryozoans, relict occurrence;
  - tidal delta: thinly interlayered mud and sand with lenticular bedding;
  - distributary channels in tidal flat deposits: normal graded sandy conglomerate at the base bearing abundant reworked paraautochthonous marine molluscs, occasionally fish and dispersed wood fragments and leaves; deposits getting finer and thinner upwards, load structures and trace fossils may be found at top.

Forced regression as a response to sea level changes during inland glaciations of Antarctica in the late Paleocene or perhaps during the Ypresian/Lutetian lowstand was probably a driving force that initiated the prograding sequence formation. Rapid sea level fall and probably freshwater input to the sea bottom resulted in a sudden local extinction of the rare assemblage of bryozoans, echinoderms, corals and brachiopods. Their skeletons were perfectly fossilised by syngenetic goethite permineralisation, and then by cementation with calcium carbonate during diagenetis, becoming the durable witness of a lost ecosystem. Excess reactive iron may have been delivered to freshwaters due to intense sulphide oxidation and acid sulphate drainage of bedrock formed by sulphide-rich clastic deposits of the Sobral Formation.

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