A traumatic fracture in a giant Eocene penguin from Antarctica

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Abstract: A fractured femur of a giant fossil penguin from the *Anthropornis nordenskjoeldi* Biozone (Late Eocene), Isla Marambio (Seymour Island), Antarctica (La Meseta Formation) is described. Palaeoecological, palaeopathological and taphonomical implications derived from the analysis of the kinds of fractures identified are also discussed. The main fracture has irregular margins, indicating there was collagen in the bone at the time of the impact. In this fracture, a mineral deposit was also identified as a fracture hematoma. According to the antemortem classification of fractures, it was produced by an indirect mechanism, provocating a "butterfly wing" or "third fragment" fracture. The remaining fractures are assigned to times of biostratinomic and fossil diagenesis.

Introduction

Penguins are by far the dominant group of coastal marine vertebrates within the La Meseta Formation. After more than 30 years of palaeontological investigations on Isla Marambio (Seymour Island), the number of penguin-bearing localities has increased significantly. Many localities containing penguin remains from different levels of the La Meseta Formation and the Palaeocene Cross Valley formations present an almost complete record from the late Palaeocene to the latest Eocene. The bulk of the penguin-bearing localities lie within the upper part of the Submeseta Allomember in rocks of the Facies Association III of Marenssi *et al.* (1998).

The Submeseta Allomember (Fig. 1), in particular, carries abundant remains and a high number of taxa. Following Jadwiszczak (2006), or Tambussi *et al.* (2006) and Tambussi & Acosta Hospitaleche (2007), the number of Isla Marambio penguin species varies between 10 and 14 respectively in this allomember. It is a notably high number of sympatric species, higher than any other in current regional breeding places from the cold sub-Antarctic to cool temperate waters south of the subtropical convergence. There may be a palaeobiological or a taphonomical explanation for this, but it probably reflects the actual abundance of penguins, which appear to have been the dominant coastal birds in the late Eocene of Antarctica (Case 1996).

A new femur assigned to a penguin was recovered on the east flank of the plateau, facing the Weddell Sea, in the northern part of Isla Marambio (Fig. 1) stratigraphically located nearly 40 m below the top of the Submeseta Allomember (La Meseta Formation) at the locality DPV 13/84 (64°14'45.4"S, 56°35'58.4"W) and within the *Anthropornis nordenskjoeldi* Biozone (Tambussi *et al.* 2006).

Unlike bones of other fossil penguins, in which predation marks (Cione *et al.* 2010), and bioerosion (Acosta Hospitaleche *et al.* 2011) are evident, the femur described here has a distinctive pattern of fractures. We describe this new femur with a particular emphasis on its fractures. Palaeoecological, palaeopathological, and taphonomical implications derived from them are also discussed.

Depositional setting of MLP 11-II-20-5

The specimen MLP 11-II-20-5 was recovered from a horizon of the Submeseta Allomember of La Meseta Formation within a sequence described by Marenssi *et al.* (1998) as Facies Association III. This facies is composed mainly of fine- to medium-grained sandstones, both well sorted and cross-bedded with thin massive muddy levels. They are intercalated with thin shell beds, gravel beds and clay levels. Beds are mostly tabular and thickly bedded, although some channel deposits (mainly shell beds) also occur. These horizons contain relatively abundant marine fossils (veneroids, gastropods, brachiopods, and crinoids) and are intensively bioturbated. Most of the articulated skeletons of marine/coastal vertebrates (whales, fishes and penguins) come from these horizons (Fig. 2). Biostratigraphically the MLP 11-II-20-5 bearing horizon is within the *Anthropornis nordenskjoeldi* Biozone (Tambussi *et al.* 2006).
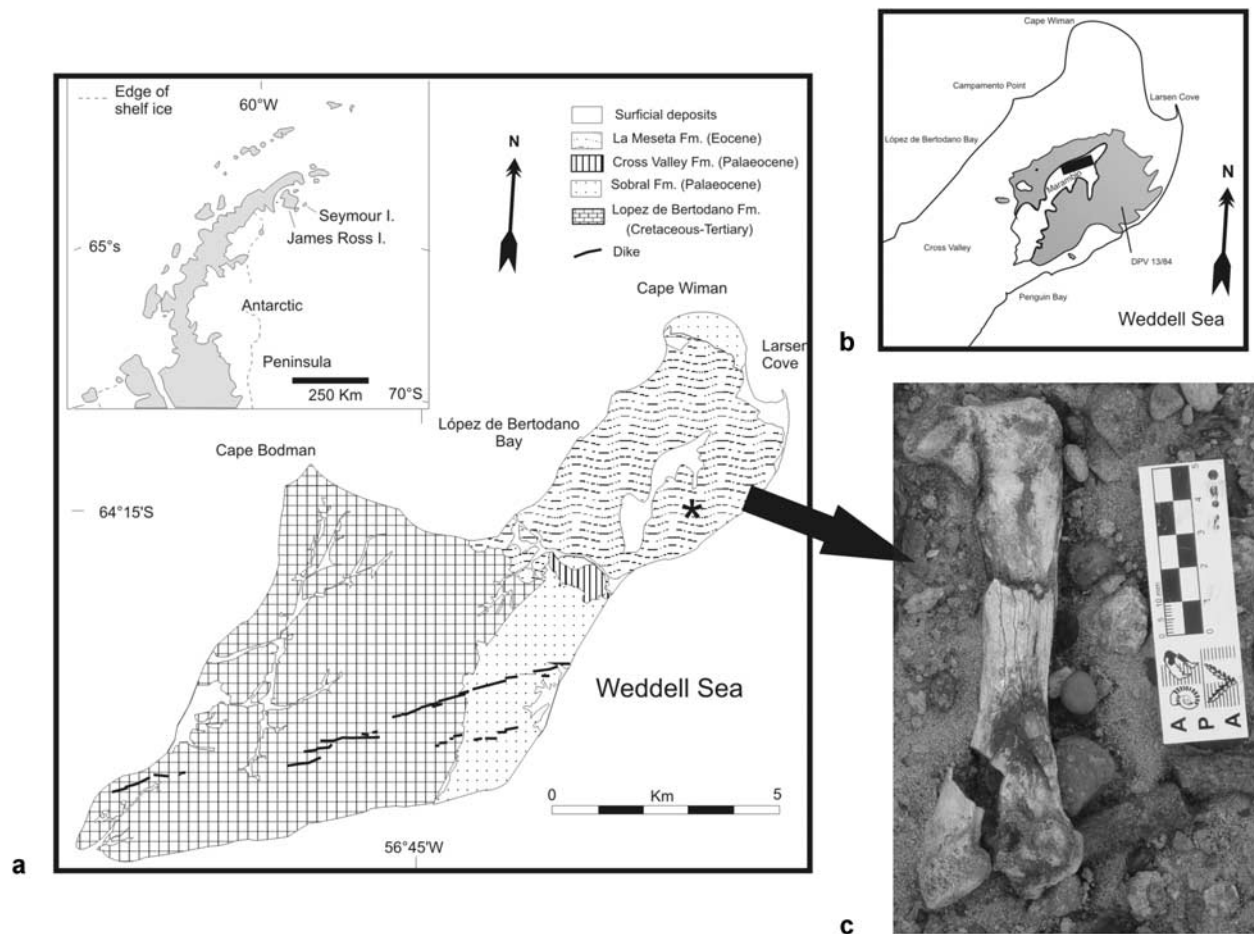
Fig. 1. a. Map showing the location of Isla Marambio (Seymour Island), Antarctic Peninsula. **b.** Sketch map of the northern part of Isla Marambio showing the areal distribution of the Submeseta Allomember (shaded grey area) and the fossil penguin-bearing locality (DPV 13/84). **c.** MLP 11-II-20-5, right femur as it was found in the field.

Dingle & Lavelle (1998) reported a ^{87}Sr/^{86}Sr derived age of 34.2 Ma (Priabonian) for the topmost meters of the La Meseta Formation. In addition, Dutton *et al.* (2002) also presented ages of 36.13, 34.96 and 34.69 Ma for different levels within the Submeseta Allomember (Marenssi 2006).

Material and methods

The material (MLP 11-II-20-5), a complete right femur, is housed at the Museo de La Plata, La Plata, Argentina.

The analysed fractures were classified according to their genesis, identifying the antemortem damage according to Bojrab (1996) and Slatter (2006) for live animals (see supplemental material found at http://dx.doi.org/10.1017/S0954102012000430), and the weathering and the diagenetic fractures following Behrensmeyer (1978). His approach was adopted for the taphonomic discussion, and the composition of the fracture hematoma was studied through a RX Diffractometer Philipps PW3710 (tube of Cu).

Results

The femur is 151 mm long, 18 mm in anteroposterior width and 21 mm in lateromedial width. The shaft is nearly straight and the whole femur is badly abraded. A set of fractures on the diaphysis and the epiphysis are described and discussed below.

Fractures developed in the femur were subdivided according to their morphology and relative chronology into three sets which were chronologically ordered based on cross-cutting relationships. The earliest fractures (fractures 1 and 1') are characterized by irregular margins. The second set of fractures (fractures 2–13) is constituted by eyelet morphologies, parallel to the main axis of the diaphysis and are only developed in the periosteal bone. Finally the third set (fractures 14–17) is represented by a perpendicular or oblique split with flat and "clean" surfaces.

Fractures 1–1' are cross-cut by all other fractures making them chronologically the first ones and the most important of the diaphysis. These fractures are developed in the middle shaft (Fig. 3) and have irregular borders. A fracture line,

Fig. 2. General view of the uppermost Submeseta Allomember (locality DPV 13/84) of the La Meseta Formation facing to the Weddell Sea. Black arrow indicates the place where MLP 11-II-20-5 was found.

transversal to the main axis of the bone, starts from the main fracture in the *facies cranialis* of the proximal fragment. This bone fragment is attached to a mineral deposit that occupies part of the bone marrow cavity. On the *facies caudalis* appears a third small bone fragment (between fractures 1 and 1'), associated to the proximal end. This tiny fragment is welded by a siliciclastic sedimentary deposit that is bound by reddish ferruginous cement of massive pulverulent habit.

An X-ray diffractogram of whole rock (Fig. 4), made on a piece of this mineral deposit shows the presence of a peak of maximum reflection of hematite (2.71 Å), together with associated peaks of minor intensity (2.532 Å, 1.84 Å, and 1.455 Å), in a sample where the predominant sediment has a quartzitic composition. This sample was compared with the results of the X-ray diffractogram from a piece of dark bone. It shows mainly fluorapatite (3.458 Å, 2.796 Å, and 2.247 Å), product of the original replacement of the hydroxyl (component of the hydroxyapatite) by fluorine, which is more stable and abundant in marine environments.

The eyelet-shaped fractures of set 2, which cross-cut fractures 1–1', parallel to the main axis of the diaphysis (Fig. 3, fractures 2–13) show no associated mineralization. They have a sub-parallel pattern with respect to each other and the longitudinal bone fibres, but they tend to diverge toward the epiphysis. This set constitutes at least twelve fractures developed on the *facies caudalis* of the femur.

The third set of fractures is characterized by a perpendicular or oblique split leaving flat and "clean" surfaces (Fig. 3, fractures 14–17).

Interpretation

Calculation based on Jadwiszczak (2001) estimates that the animal from which this specimen would have come would have been about 90 kg in weight and 1.80 m in height which is in agreement with the robustness of the bone.

Evidence for perimortem processes

The genesis of the fractures described above is interpreted. The simplicity of fracture 1 in conjunction with evidence for a "third fragment" indicate that it can be interpreted in terms of palaeopathology. According to fracture classification for live animals (Bojrab 1996, Slatter 2006), it corresponds to a "butterfly wing" fracture.

The presence of a high concentration of haematite associated with this fracture, and the absence of haematite associated with other fractures in the bone, suggest that this may represent high iron concentration associated with a fossilised clot or haematoma (Blasi 2008). Genesis of the fractures described above is interpreted. The presence of a concentrated fracture haematoma, particularly with the third bone fragment still in its original position relative to the main part of the femur, suggests that the penguin survived the initial fracture trauma and healing reached the inflammation phase. Periosteal reaction associated with new bone formation is not evident at the edges of the fracture, suggesting that the formation of osseous callus was not reached which can be inferred to suggest early post-trauma mortality.

Penguin trampling plays an important role in bone fracture. Penguins go to the sea for feeding along the same paths every day. According to Cruz (2007b), permanent transit along the same paths affects bones in several ways. Damage by trampling is easy to differentiate from the weathering (Cruz 2008), and it has been attributed to trampling by the penguins themselves (Cruz 1999). It is one of the most probable causes of fractures in the breeding colony. In southern Patagonia, trampling is very intense and is one of the main causes of fractures and destruction of bones in breeding areas (Cruz 2000, 2007a, 2007b). However, we cannot discount the possibility that animals outside the colony caused the damage.

The commonest factor for this type of injury is a single trauma with sufficient force to cause fracture. This most probably results from bending (Fig. 4), in which force is applied to the distal part of the femur while the proximal part remained fixed. The *facies cranialis* would have been under compression, while the *facies caudalis* would have been in tension (Fig. 5). Since bone is less resistant to traction than compression, this would have resulted in decohesion at the point of maximum convexity, producing a "butterfly wing" or "third fragment" fracture.

Fracture set relative chronology

The chronological order of the fractures was initially established based on separation into those fractures damaged
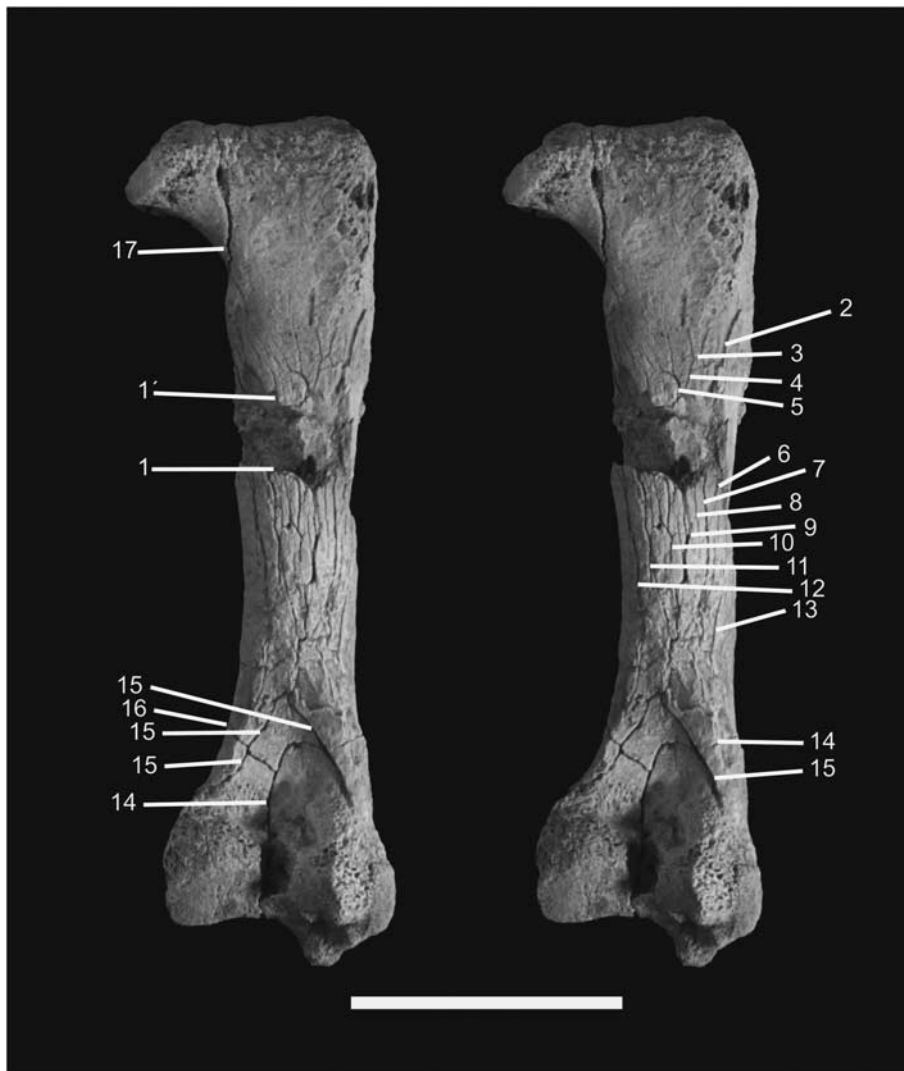
Fig. 3. Femur MLP 11-II-20-5 showing the identified damage (fractures 1–17) in stereo-pair images. Scale bar: 50 mm.

in life (set 1) and post-mortem fractures (sets 2 and 3). The latter category was separated into biostratinomic fractures (set 2) or pre-burial damage, and post-burial or fossil diagenetic fractures (set 3).

The eyelet-shaped fractures of set 2 correspond to the stage 2 of Behrensmeyer (1978). The complete set formed together. They are not completely open. This means periosteal bone is still conserved without any flaking or superficial damage.

The third set of fractures were produced subsequently, starting by fracture 14 that separates the *condylus lateralis* from the *condylus medialis* and the diaphysis. It begins at the middle of the distal end, splitting the condyla, but it rotates to the external face entering to the shaft. After that, v-shaped fracture, labelled as 15, interrupts the final segment of fracture 14. Its vertex points towards the diaphysis following the weakness zone of the femur. Fracture 16 cuts the less developed segment of fracture 15, but it does not interrupt fracture 14, which is the strongest and produces a structural

discontinuity in the bone. This set is completed by fracture 17, which cannot be interpreted in a relative chronological sense because it is located in the proximal epiphysis, and not associated with the others. Nevertheless it clearly post-dates the weathering fractures of the second group already described.

Summary and conclusions

Despite the fragmentary evidence for perimortem history of specimen MLP 11-II-20-5, analysis of the available evidence indicates two possible scenarios: predation or trampling. Although scavenger and predator action generally produce symmetrical bite patterns in fossil material, and these appear to be absent from the specimen, it cannot be ruled out that the bone was broken during an attack in which it did not incur damage caused by teeth. A much more probable interpretation is that breakage occurred due to trampling. The presence of a haematoma (Fig. 4) indicates
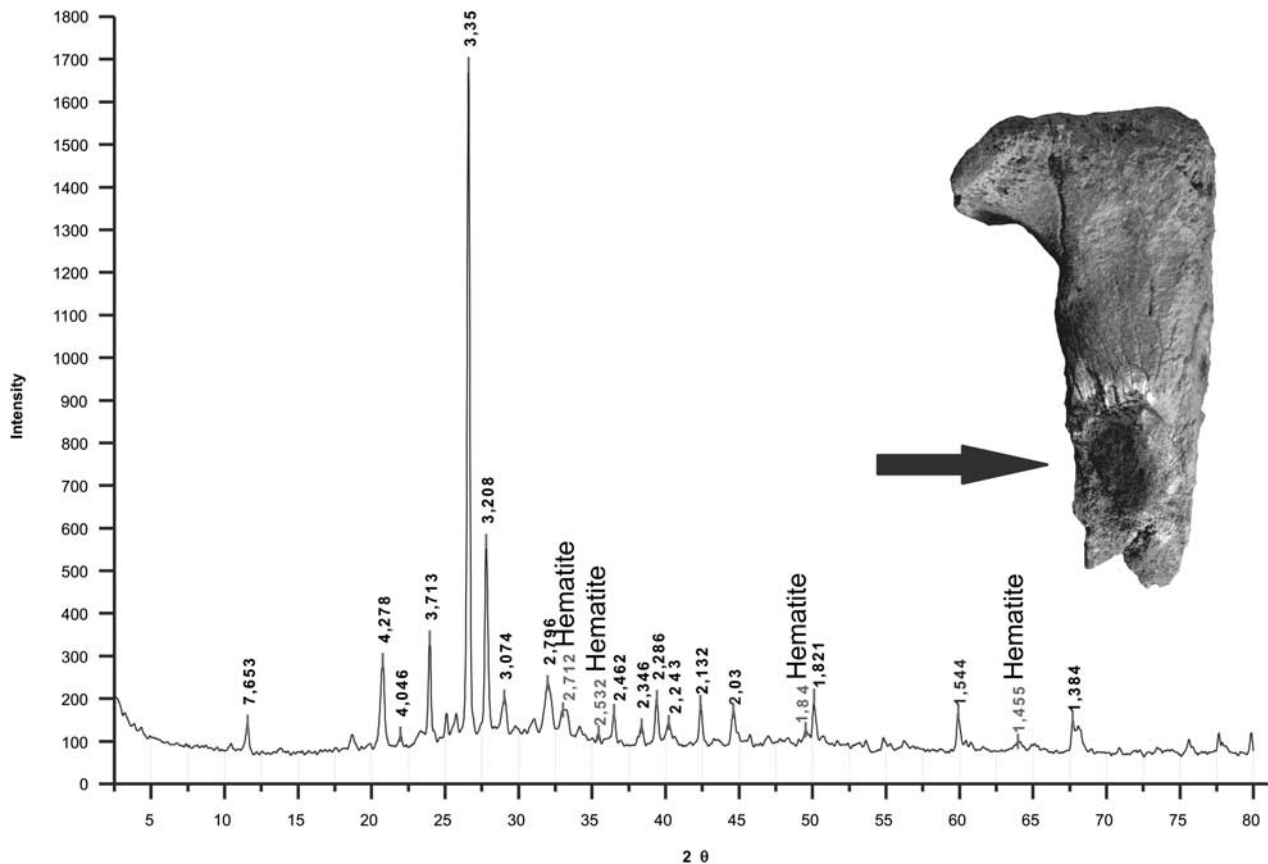
Fig. 4. X-ray diffractogram of the mineral deposit identified as a fracture hematoma, showing the presence of peaks of maximum reflection of hematite and the location from where the sample was taken.

that the animal lived long enough for some healing to occur. This would be much less likely in the case of a predatory attack. The evidence for the presence of collagen in association with fracture 1 also supports trauma in life.

On the other hand and regarding the post-mortem processes, it can be pointed out that sets 2 and 3 of fractures are the result of taphonomical processes. They generate fractures in bone material, generally produced by weathering as a result of sub-aerial exposure. Fractures produced during diagenetic processes are commonly flat, as observed for fractures 2–13 and 14–17. Fractures 14–17 between the epiphysis and the diaphysis, which constitutes the structurally weakest part of the femur, are likely to have occurred due to lithostatic load during burial or freeze-thaw action during fossil diagenesis.

In summary, damage in MLP 11-II-20-5 can be interpreted such that the irregular nature of the main fracture (fracture 1 in Fig. 3) and its morphology classify it as a "third fragment" fracture. Additionally, the recognition of haematite deposits at the fracture site may have been the product of a trauma in life probably within a breeding colony, but with death of the animal before complete healing had taken place. The fracture would be 1–10 days old, covering the stages of impact and inflammation.

Subsequently, secondary fractures (2–13) would have resulted from weathering before burial, and also in subsequent taphonomic stages (producing fractures 14–17) after the fossilization of the femur.
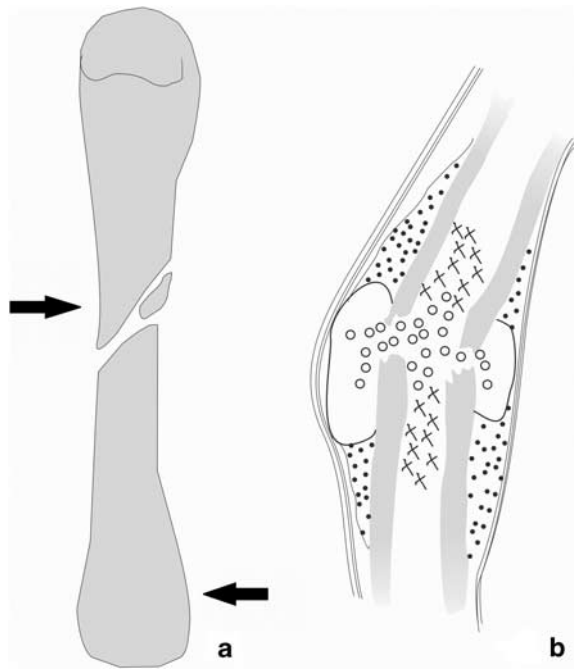
According to our the careful analysis, it is possible to state that specimen MLP 11-II-20-5 presents a set of fractures as a result of the action of palaeoecological, palaeopathological, and taphonomical processes.

Acknowledgements

Supplemental material

A supplemental table will be found at http://dx.doi.org/10.1017/S0954102012000430.

Fig. 5. Schematic drawing of the third fragment fracture of the femur. **a.** Arrows indicate possible forces acting during fracture. **b.** Alleged appearance of vascular buds invading the focus according to the presence of hematite.

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