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SCIENTIFIC ILLUSTRATION AND RECONSTRUCTION OF A SKULL OF THE DIPLODOCID SAUROPOD DINOSAUR *GALEAMOPUS*

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ABSTRACT

High-quality scientific illustration is an important visualization tool for natural sciences. In paleontology, drawings help to guide the reader to important features of the fossils under study, and to remove irrelevant information or strong shadows that might obscure parts of photographs. Furthermore, drawings allow for the deformation of the fossils to be corrected. However, for an accurate interpretation of these reconstruction drawings, it is important to provide a detailed report about the creation of the drawings.
Herein, we describe the methodology of the reconstruction drawing of a skull of the sauropod dinosaur *Galeamopus*. After preparation and reconstruction of the skull in the laboratory, illustrations were needed to correct natural deformations, restore missing parts, and highlight critical features for anatomical recognition of the several bones. The illustrations were successful thanks to the collaborative work between the paleontologist and the illustrator.

Keywords: illustration report; drawing; reconstruction; diplodocid skull

RESUMO [in Portuguese]

Ilustrações científicas de alta qualidade são uma ferramenta importante de visualização nas ciências naturais. Na paleontologia ajudam o leitor a perceber as estruturas anatómicas importantes dos fósseis em estudo, removendo informação irrelevante, ou eliminar zonas escuras que escondam pormenores dos ossos nas fotografias. Além disso, as ilustrações permitem corrigir de ossos deformados. Para a correcta interpretação das reconstruções efectuadas, é importante existirem relatórios detalhados do processo da ilustração.
Vimos descrever a metodologia de ilustração de um crânio de dinossauro saurópode *Galeamopus* que foi reconstruído. Após a preparação e montagem do crânio no laboratório, as ilustrações tiveram de reajustar as deformações naturais, repor partes em falta, e realçar características essenciais necessárias à compreensão dos diversos ossos. As ilustrações são bem sucedidas graças à colaboração entre o paleontólogo e o ilustrador.

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INTRODUCTION

Paleontological research is often based on reconstructions (Benton, 2005). Initial descriptions of new species or specimens often include photographs or line drawings of the actual fossils, made by the paleontologist. In a further step, reconstructions can be produced, often together with an artist, by adding missing parts and restoring deformed portions. Reconstructions like these are more clear and appealing, because they omit information that might be confusing at first sight.

Generally, the paleoartist is not a paleontologist, and does not have the necessary knowledge about the extinct animals and environments he or she must portray (Ghilardi and Ribeiro, 2010). In order to prepare an accurate paleoreconstruction, it is thus important that the basic scientific data is compiled and simplified by the paleontologist supervising the work. Without a solid scientific knowledge the paleoartist will support him- or herself on deduction, and the artwork will be less consistent and could be more erroneous (Ghilardi et al., 2007) and, therefore, lead to mistakes.

CHALLENGES IN PALEORECONSTRUCTIONS

During the taphonomical process, nearly all fossils undergo some degree of damage and deformation (Benton, 2005; Tschopp et al., 2013). Such changes include both pre-burial (physical damage, scavenging), or post-burial events (compression, chemical alterations, erosion). It is the task of the paleontologist to recognize such alterations, and try to account for them in the studies based on deformed material (Benton, 2005). A first briefing helps the paleoartist to understand the goal of the paleontologist and the latter to understand the difficulties of the artist (Ghilardi and Ribeiro, 2010).

One of the most challenging problems encountered when reconstructing a fossil is that frequently no single complete skeleton exists for reference and assorted partial skeletons of the same or similar species differ in size. Sometimes, what is missing on one side of a specimen can be found on its other side (Paul and Chase, 1989), but if that is not the case, assumptions have to be made based on closely related species, where the bones lacking in the species in question are preserved. In cases, where information from more than one specimen is available to restore a single individual, it remains possible that no or only few parts are shared among the specimens used (Paul and Chase, 1989). In order to produce the most accurate reconstruction possible, careful guesstimates must be made of the animal’s proportions, preferentially based on closely related taxa, where such information is not available from the fossils under study. A bibliography should be provided at the briefing to illustrate how missing portions in the fossil to be reconstructed look like in closely related taxa (Ghilardi and Ribeiro, 2010).

In vertebrates, one of the most complex structures of the skeleton is the skull. In sauropod dinosaurs like *Galeamopus* - the study object of this paper - the skull is composed of more than 25 bones per side. Being so complex, skulls should preferentially be represented in five views (Correia, 2010): frontal, lateral (most commonly used), posterior (occipital), dorsal, and ventral. If the mandible is preserved, it should be either drawn articulated with the skull and slightly open so that no detail is obliterated, or isolated (in lateral, dorsal and ventral views). Each kind of tooth should be represented isolated and in apical, labial, and lingual views. Even though any illustrator should attempt to complete such an extensive work, we acknowledge that this can be highly dependent on the time and publication space available, especially when no additional funds can be found for the time the illustrator has to spend at the institution where the specimen is housed (as was the case here).

MATERIAL

History

After an invitation by the Sauriermuseum Aathal (SMA) to the illustrator (SM) to study their collection, the idea of making an illustration of a diplodocid sauropod skull (SMA 0011) emerged. The specimen is informally known as “Max”, and was at the time still classified as *Apatosaurus*, although preliminary studies indicated that it might belong to a new genus. ET was preparing the description of SMA 0011, and was the scientific supervisor of the illustration process.

The SMA is a natural history museum focusing on dinosaurs. It is located 20 km east of Zurich, Switzerland, and has a substantial collection of dinosaurs from Howe Ranch, an abandoned ranch north of Shell, Wyoming, USA (Brinkmann and Siber, 1992; Ayer, 2000; Michelis, 2004; Siber and Möckli, 2009; Tschopp and Mateus, 2013; Foth et al., 2015; Tschopp et al., 2015).

In 1995, the SMA team found a new site on the ranch, now called Howe-Scott quarry (Ayer, 2000). The specimen SMA 0011 was one of the first and most complete dinosaurs recovered from this site and included a disarticulated skull. It was excavated in 1995, and the bones were spread over an area of 80 m^2 with the numerous skull elements spread over an area of 9 m^2 (Figure 1). Preparation of the postcranial skeleton was completed for the 10th anniversary exhibition in 2002 at SMA by Y. Schicker-Siber, M. Siber, E. Wolfensberger, and ET. The skull was entirely prepared and reconstructed by B. Pabst for a new display in 2004. During the preparation, some bones were glued and replaced, and lacking elements were reconstructed based on the preserved element from the other side of the skull (B. Pabst, pers. comm., 2011). The original bones included in the mount are both premaxillae, the right maxilla and nasal, both prefrontals, frontals, postorbitals, jugals, and quadratojugals, the dorsal half of the left lacrimal, the right quadrate, both squamosals and parietals, the

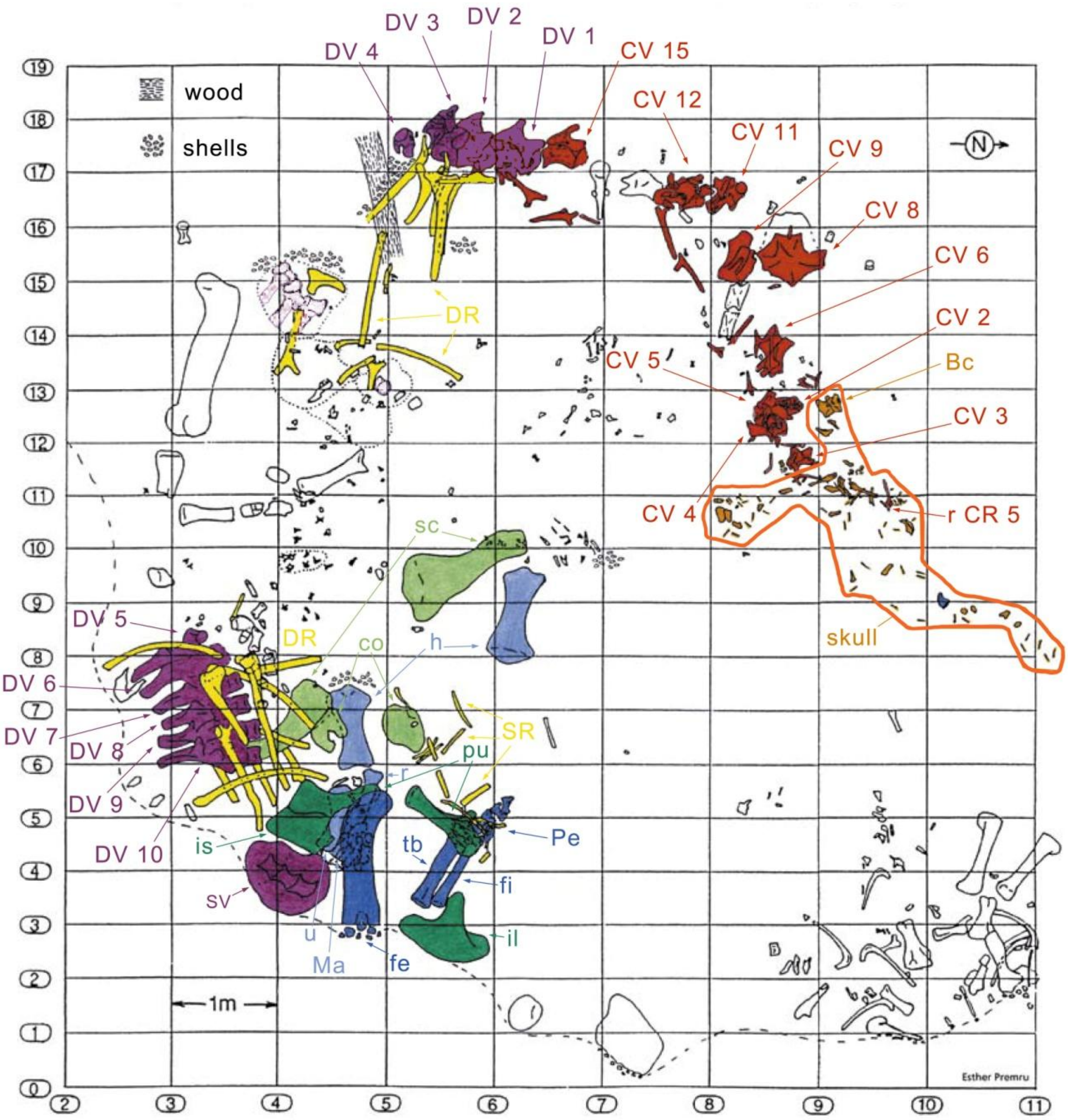

Figure 1: Quarry map of SMA 0011. Note how wide the single elements of the skull were spread among the quarry. Drawn by Esther Premru (Mönchaltorf, Switzerland), copyright Sauriermuseum Aathal, Switzerland.

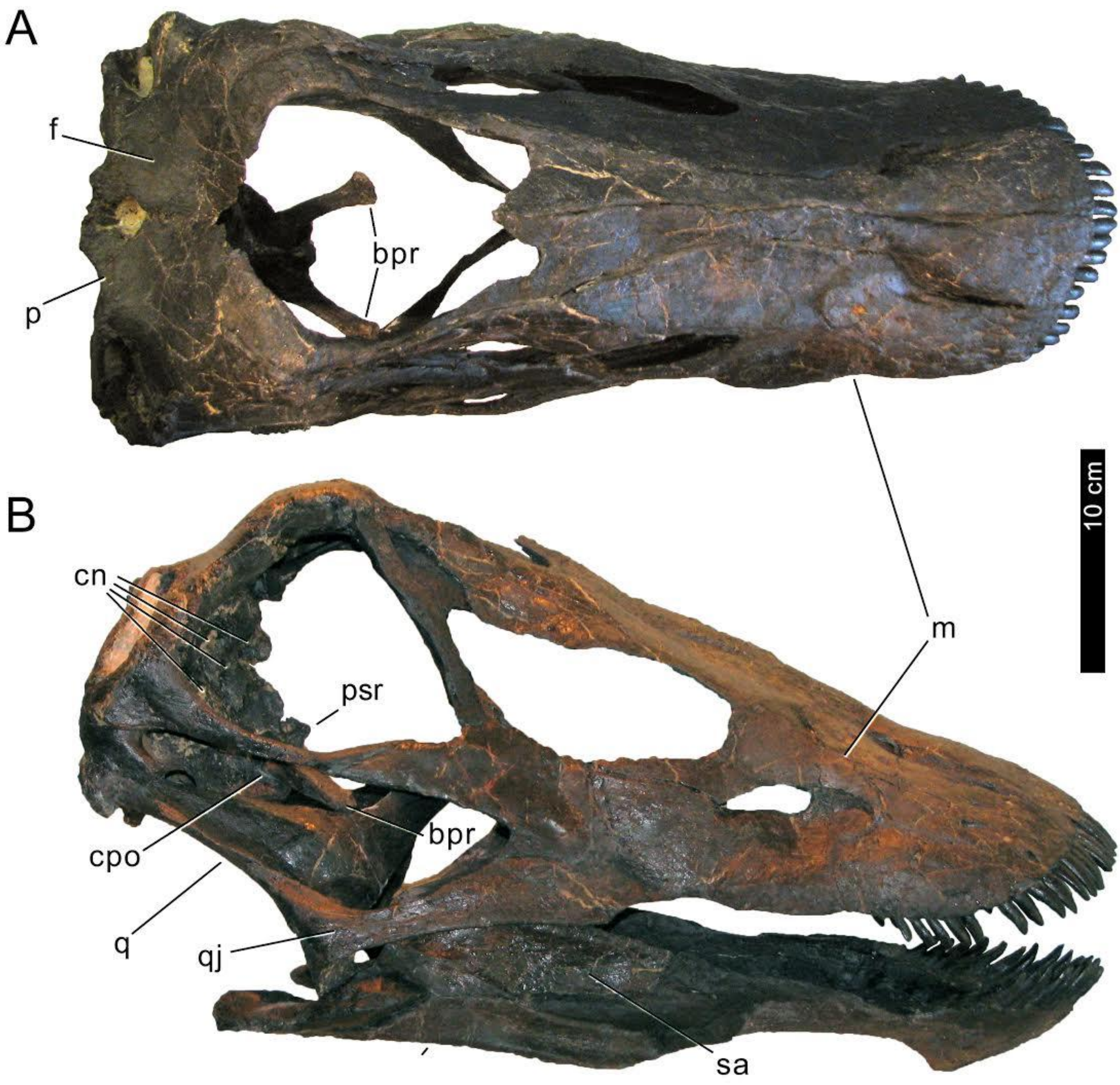

Figure 2: Original skull of *Galeamopus* sp. SMA 0011 in dorsal (A) and right lateral view (B). A different photo had to be used for the lower jaw, because the latter is shown in slight laterodorsal view herein. The indicated bones were the ones that needed most interventions by the illustrator due to breakage, deformation, or potential individual variation displayed, which we decided not to show in the drawing. Abbreviations: bpr, basipterygoid process; cn, cranial nerve opening; cpo, crista prootica; f, frontal; m, maxilla; p, parietal; psr, parasphenoid rostrum (broken here); q, quadrate; qj, quadratojugal; sa, surangular. Photos taken by Octávio Mateus, used with permission.

supraoccipital and the other braincase elements, both dentaries, surangulars, and angulars, as well as some teeth. Not included in the mount, but preserved, are a pterygoid, a possible prearticular, both hyoid bones, and numerous teeth, of which casts were produced and used in the mounted skull (Figure 2; B. Pabst, pers. comm. 2011).

The herein proposed skull drawing was based on this reconstruction, but includes corrections of the position of some elements that were initially mounted in slightly wrong locations. We thus preferred to produce a corrected and undistorted drawing instead of reproducing the actual mount. The reproduction shows the skull in dorsal and right lateral view. The final work will be used in a detailed description of the entire specimen SMA 0011 (Tschopp and Mateus, in prep).

METHODS

Following Ghilardi and Ribeiro (2010), an introductory briefing between illustrator (SM) and scientific supervisor (ET) was held, where methods, necessary views, access to original material, deadlines, and purpose of the artwork was discussed. Right lateral and dorsal views were decided to be drawn. The limitation to these two views was necessary due to time constraints. Given that an undistorted, hypothetical, perfect lateral view should be produced, the chosen side does not actually matter. The right side was chosen here because it is more complete than the left, where e.g. the maxilla is lacking. The dorsal view was added for two reasons: 1) many earlier reconstructions included a dorsal view, and 2) many typical diplodocid features are best visible in this view, as are some peculiar features in the skull of SMA 0011 (ET, unpublished data). Finally, a portfolium with photos and illustrations of diplodocid sauropod skulls was provided to the illustrator (e.g. Wilson and Sereno, 1998, fig. 6; Whitlock, 2011, fig. 3).

As a first step, the illustrator took new pictures of the skull at the SMA that served as a basis for a first raw pencil sketch. In order to avoid lens distortion, a focal length of 50 mm was used for photography and the camera was oriented such that the fossil fit on the central area of the photograph when imagining the picture divided into a grid of nine equal parts. The inclusion of a scale bar is crucial at this stage, especially in case the illustrator has no access anymore to the original material afterwards. An inclusion of the scale bar here will also allow to add a more accurate scale bar in the final drawing.

For the first sketch (Figure 3), soft pencils (B, 2B or higher) were used, because they are

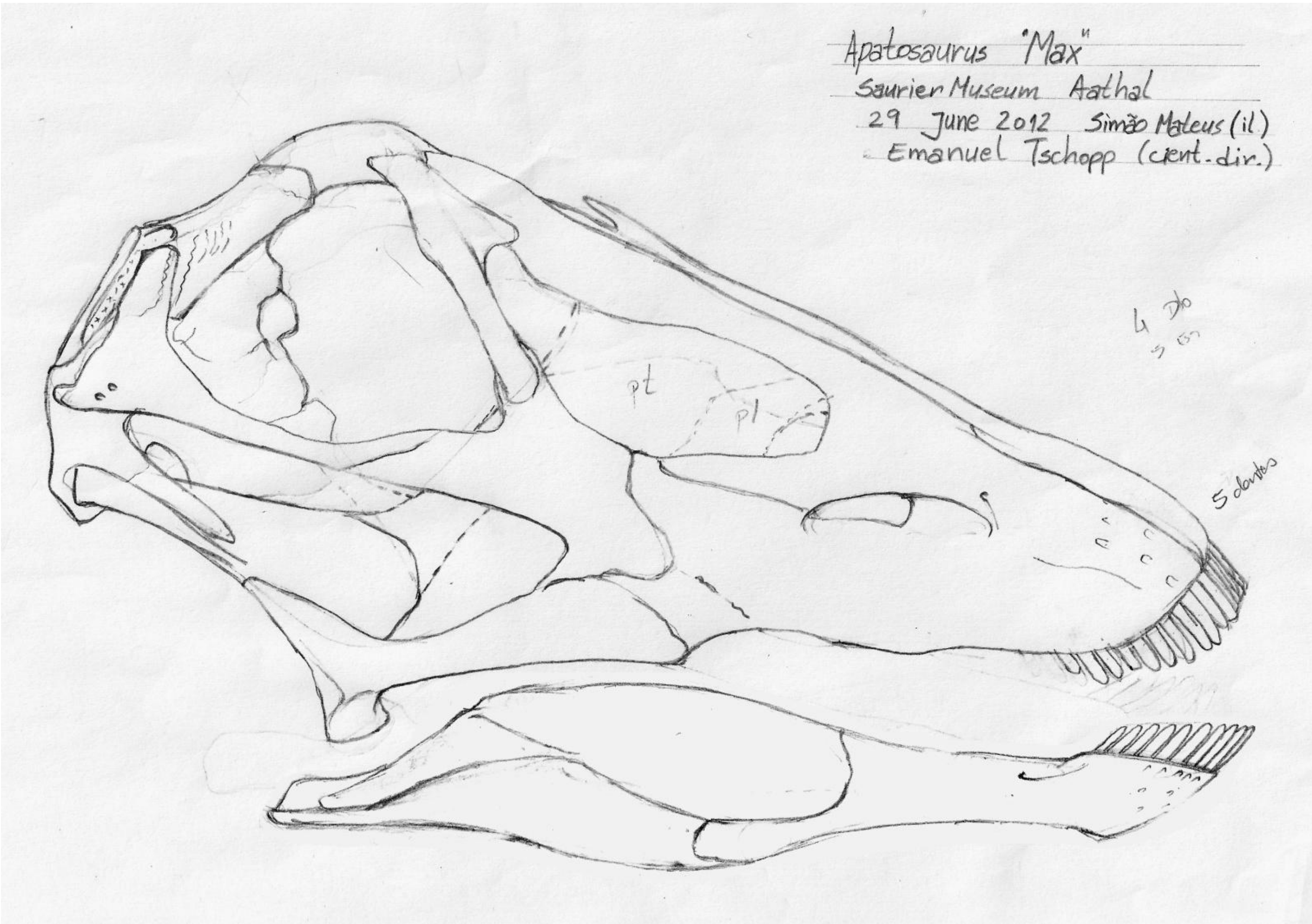

Figure 3: Initial pencil drawing of the skull of SMA 0011.

easier to see and to erase if needed. Hard pencils (e.g. 3H) produce a more precise, but less dark line. Although levels and curves can be used in Photoshop to increase their darkness, this will also increase the visibility of slight blurs resulting from the drawing process or erasing. Therefore, scanning of a sketch made with soft pencils is less likely to miss a pencil line, and less work is needed afterwards in Photoshop. The first drawing was then compared to the original skull, in order to correct it for possible optical distortions. An additional briefing with the scientist was necessary while correcting the first sketch in order to point out deformed or wrongly mounted bones in the restored skull. Subsequently, the pencil drawing was scanned and revised with a graphic tablet device (hardware) on Photoshop (software) in order to obtain a cleaner drawing.

There are several graphic tablets on the market. One of the most important features for illustrators is the size of the so-called active area, which is the working area of the tablet. To have a better control and definition of the drawing, we preferred an active area of at least 10 per 15 centimeters.

We used a resolution of 300 pixel/inch (dpi) for an initial area of 20 per 30 centimeters, which results on 2362 x 3543 pixels. These values guarantee a file of a resolution high enough to produce optimal quality printing on a DIN A4 page, because printers usually work with a resolution of 150-300 dpi. Given that the drawing was intended to be published in online journals, it was not necessary to use a higher resolution, and computing time could be reduced considerably. It is important to specify the dimensions of the working area, as it is also possible to have a 6 pixel drawing with 300 dpi, thus measuring only 0,3 x 0,2 mm.

For the working steps in Photoshop, the working document was split into several layers. The background layer was always left white. Different layers were created for each photograph (dorsal and lateral views of the skull, and lateral view of the mandible). All of these images were resized to the same scale and their layer were locked, such that they could not be changed accidentally. The photograph, the pencil sketch, and the final working drawing were placed in different layers. Finally, a layer with a reconstructed skull of the closely related *Diplodocus* (Wilson and Sereno, 1998; fig. 6) was added for comparative purposes and to help understand the shape of distorted or incomplete bones. We used folders to organize the several layers, in order to keep track more easily in which layer we were supposed to work, and which layer was not necessary to see and could be hidden at that time. It is also useful to have a notebook - or an additional layer - to write some information about the brush or pencils tools used, specifically the master diameter and hardness used for outlines or for texture details.

A first version of the computer drawing was saved as "Max_skull_v1.psd" and sent to the scientific supervisor for corrections and comments.

Eight changes were proposed by the scientific supervisor, and directly highlighted and sketched in a copy of the original first drawing (Figure 4). All these proposed changes were discussed with the illustrator with the original skull at hand. Some of the necessary corrections concerned additional shape changes because of deformed or fractured parts of the fossil skull of SMA 0011: deletion of lines on the lateral side of the braincase that were based on features that were due to breakage or deformation (Figure 4, number 1); correction of the lateral outline of the braincase, which was necessary because some parts of the anterior edge and the parasphenoid rostrum were broken off during diagenesis (Figure 4, number 2); deletion of a line indicating a feature on the surangular bone that was due to deformation (Figure 4, number 4); changes to the outline of the frontal due to deformation (Figure 4, number 5); closure of what appears to be a large pineal foramen and a smaller postparietal foramen, but which have broken edges on the frontal and parietal bones, indicating that the presence of these foramina is due to taphonomic breakage (Figure 4, number 6); and the deletion of two wavy lines indicating a deformation in the posterior process of the maxilla (Figure 4, number 8). Other proposed corrections aimed for a clearer visualization of the single bones, and other morphological features: addition of the major foramina for the cranial nerves visible in lateral view (Figure 4, number 1); and the substitution of the lines illustrating three-dimensional morphology of the articular ramus of the quadrate by the outline of the quadratojugal, in order to show the exact shapes of the single bones (Figure 4, number 3).

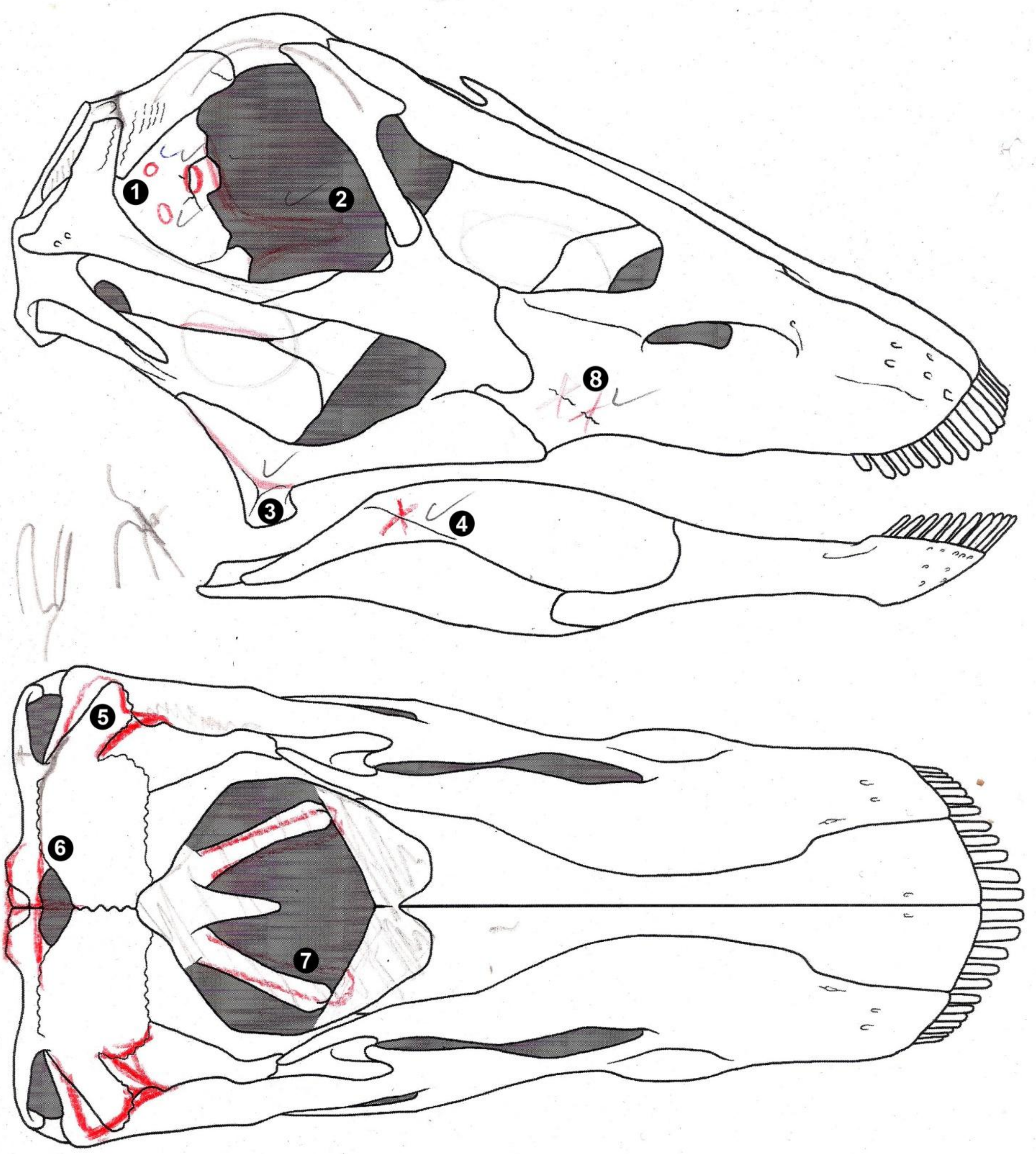

Figure 4: The digitized drawing of the skull of SMA 0011 with the comments of the scientist. The numbers indicate the changes requested: 1) deletion of lines due to breakage and major foramina for cranial nerves; 2) broken parasphenoid process; 3) outline of quadratojugal; 4) deletion of line indicating a feature on surangular bone that is due to breakage; 5) adaption of frontal outline due to deformation; 6) closure of openings due to taphonomic breakage; 7) wrong orientation of basipterygoid processes; 8) wavy lines indicating a deformation on posterior process of maxilla.

Finally, one correction was necessary because the broken off basipterygoid processes were erroneously mounted in a position dorsal to the crista prootica (Figure 4, number 7). The input of the supervisor were integrated in the second version of the drawing, and saved as "Max_skull_v2.psd". Duplicate copies of the work steps were saved on an external hard drive as a safety backup. Small details were corrected in another meeting between illustrator and scientific supervisor (e.g. the orientation of the reconstructed basipterygoid processes). During this third meeting, an additional layer was created in the drawing, adding the grey gradients. These gradients significantly increased the three-dimensional understanding in the two views of the skull (Figures 5-6). We preferred these gradients over weighted lines because thin lines were already used for bone textures that are at the same level as the edges of the bone they mark. Using the same line width for these textures and for elements that lie below others could therefore have been confusing. Finally, during the revision process of the descriptive paper (Tschopp and Mateus, in prep.), some corrections proposed by the referees had to be included in the reconstruction drawing as well. These included a shallow groove on the premaxilla, a better separation of the squamosal and the paroccipital process, and foramina on the dentary and surangular (Figure 5). Their position and morphology was discussed on skype with shared screens, where the scientist indicated the features on the reference photos, and the illustrator added them to the drawing simultaneously. The final drawing is shown in Figure 6.

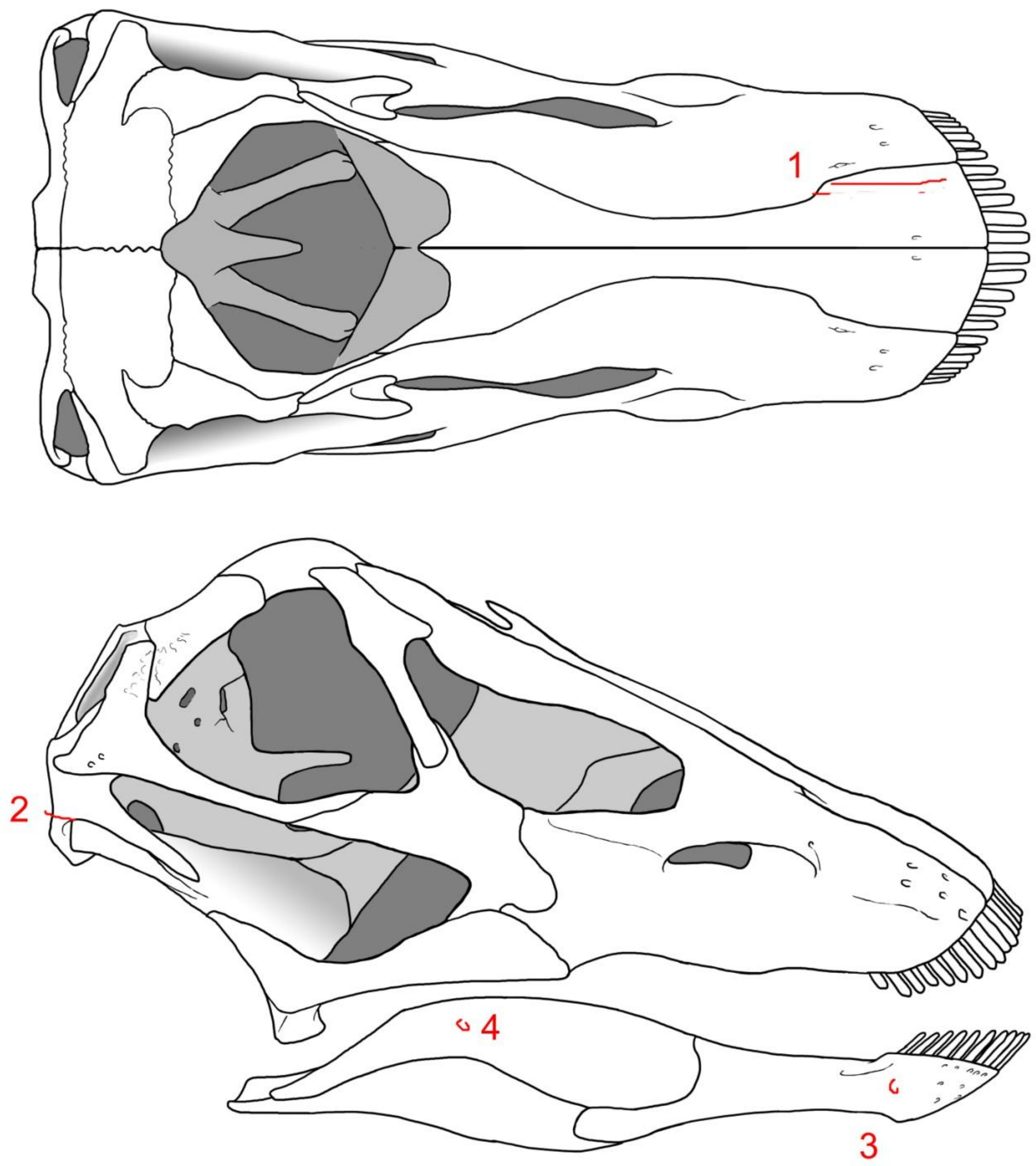

Figure 5: Last step of corrections in the drawing, with features to correct added in red by the illustrator. The features are the following: a faint groove on the premaxilla (1); the distinction of the squamosal from the paroccipital process, as visible in lateral view (2); and two distinct foramina on the dentary (3) and the surangular (4).

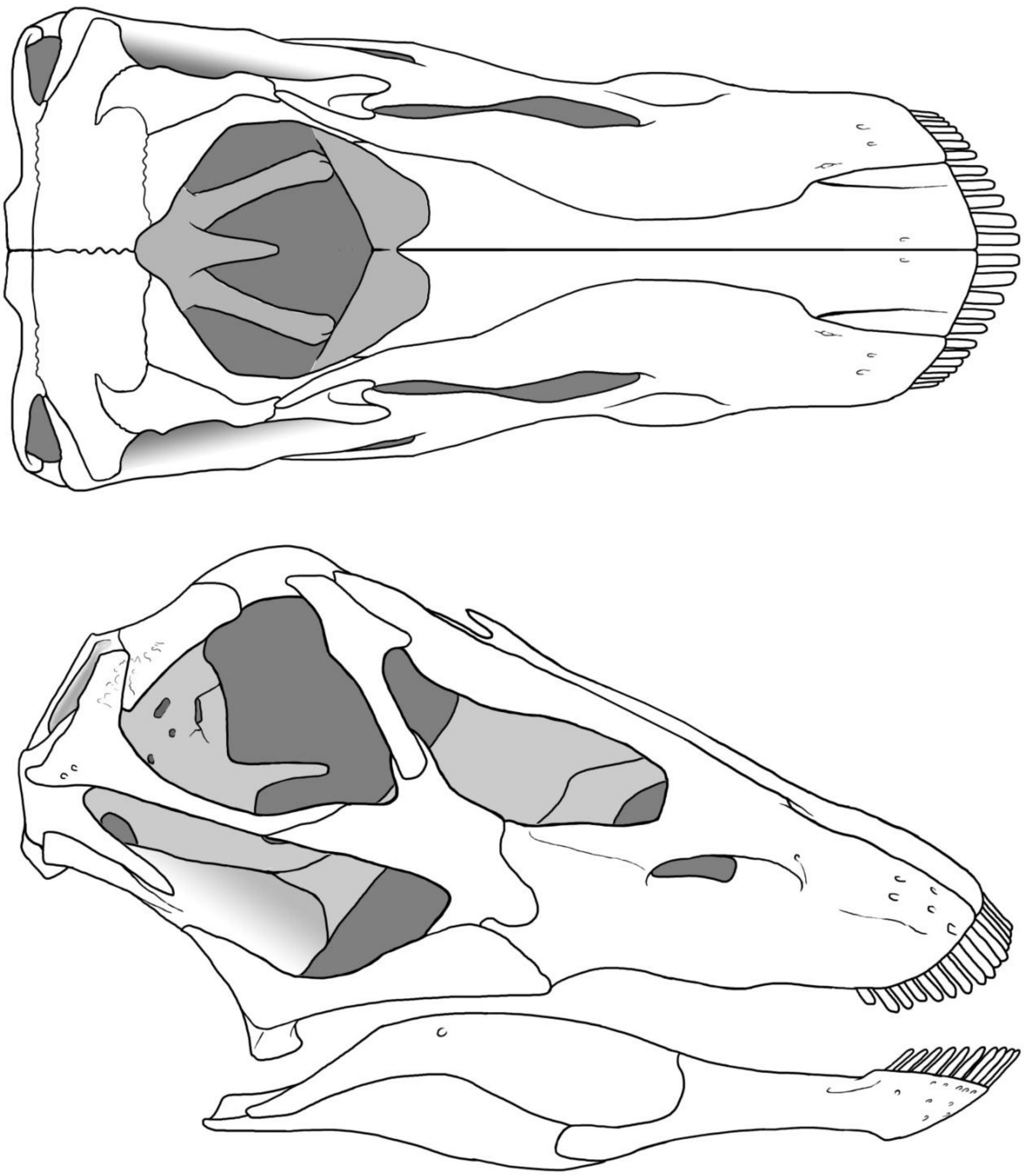

Figure 6: Final version of the drawing of the skull of *Galeamopus* sp. SMA 0011.

DISCUSSION

The geological record is incomplete. Already Darwin (1859) recognized that because along geological time not all the evolutionary sequences were preserved, we cannot expect to find all the organisms that once lived on this planet. We can also apply this concept to the fossil record of a single specimen, because complete skeletons or skulls are extremely rare, particularly in large organisms like sauropod dinosaurs. Furthermore, during the fossilization process the bones will be compressed and distorted and therefore, most fossils have altered ratios and angles (Arbour and Currie, 2012; Tschopp et al., 2013). Other bone deformation can occur through pathologies (Foth et al. 2015; Tschopp et al., 2016). In order to visualize the general, healthy, living shape of a fossil, we therefore need reconstructions.

In the current reconstruction, adding missing parts, or accounting for distortion was facilitated by the large amount of skulls known from very similar taxa (see reviews in Whitlock et al. 2010; Whitlock, 2011). In other species, however, the reconstruction can be more difficult because skulls from closely related taxa are lacking (see e.g. the changes in the reconstruction of *Nemegtosaurus* or *Euhelopus*; Upchurch 1999, fig. 2, and Wilson, 2005, fig. 16; Mateer & McIntosh 1985, fig. 6, and Poropat and Kear 2013, fig. 1). In such cases, illustrators usually use dotted lines or different shading to indicate the hypothetical shapes of unpreserved elements (e.g. Madsen et al., 1995; Wilson, 2005; Sereno et al., 2007; Tschopp and Mateus, 2013).

The biggest advantage of an illustration (compared to photographs or 3D renderings) is that it can be used to highlight important details and hide irrelevant ones, as for instance the grooves resulting from distortion in our case (see Figure 4, numbers 4, 8). Two of the biggest disadvantages are the time needed to produce a good illustration and the costs of hiring an illustrator. The supervision of the illustrator by the paleontologists is essential but not always easy, because visible features have to be reinterpreted in the light of deformation. In some cases, these differences between actual occurrence and interpretation are significant, and can result in long discussions between illustrator and paleontologist. One example of such a significant difference in the present artwork of the skull of SMA 0011 was the drawing of the parasphenoid rostrum that is visible through the orbit (Figures 4, 5). The parasphenoid rostrum is broken and lost on the fossil skull (Figure 2). During the illustration process, on the second sketch, the scientific supervisor added by hand the missing part. However, it was not easy for the illustrator to understand the size, shape or the orientation of the rostrum. Also the orientation of the basipterygoid processes (Figures 2-4) and therefore the interpretation of how much of them was visible on the drawing (Figure 4) was quite controversial. The basipterygoid processes pass in part behind the postorbital, and are thus partly obscured, depending on the exact angle of the view. In order to solve these issues, a good dialog between illustrator and scientific supervisor was essential and beneficial for both persons and the final drawing.

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