Evidence of scale diversity in the late Jurassic Sauropod Diplodocus sp. from the Mother's Day Quarry, Montana (#55937)

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Evidence of scale diversity in the late Jurassic Sauropod Diplodocus sp. from the Mother's Day Quarry, Montana

Tess Gallagher Corresp., 1, **Jason Poole** 2, **Jason P Schein** 2

1 Biology Department, Union College, Schenectady, New York, United States

2 Bighorn Basin Paleontological Institute, Philadelphia, Pennsylvania, United States

Corresponding Author: Tess Gallagher
Email address: gallaght@union.edu

The life appearance of dinosaurs is a hotly debated topic in the world of paleontology, especially when it comes to dinosaur integument. In the case of sauropods, however, the topic is harder to properly discuss due to the limited amount of fossilized skin impressions that have been discovered. So far sauropod integument fossils include titanosaur embryos from Patagonia, diplodocid dorsal spines, foot impressions, and other isolated skin impressions found in association with sauropod fossil remains. Several prominent skin impressions have been found at the Mother's Day Quarry, located in the Bighorn Basin, Montana. These discoveries may bring new important information about diplodocids, specifically *Diplodocus sp*. Here we describe a newly uncovered skin mold that gives evidence of scale diversity in the *Diplodocus* genus. The scales themselves represent tubercles, and are conceived of various shapes including rectangular, oval, polygonal, and globular scales. The tubercles are small in size, the biggest of which only reach about 10 mm in length. Considering how diverse the scale orientation is in such a small area of skin, it is possible that these molds may represent a transition on the body from one region to another; perhaps from the abdomen to dorsal side, or abdomen to shoulder, etc. Based on analysis of extant integument and scale orientation of crocodilians and other reptiles, it is possible to hypothesize on the location of the integument relative to the body as well as the size and age of the individual.

Evidence of Scale Diversity in the Late Jurassic Sauropod *Diplodocus sp.* from the Mother's Day Quarry, Montana

Tess Gallagher[1], Jason C. Poole[2] and Jason P. Schein[2]

[1]Union College, Schenectady, NY [2]Bighorn Basin Paleontological Institute, Philadelphia, PA

Abstract

The life appearance of dinosaurs is a hotly debated topic in the world of paleontology, especially when it comes to dinosaur integument. In the case of sauropods, however, the topic is harder to properly discuss due to the limited amount of fossilized skin impressions that have been discovered. So far sauropod integument fossils include titanosaur embryos from Patagonia, diplodocid dorsal spines, foot impressions, and other isolated skin impressions found in association with sauropod fossil remains. Several prominent skin impressions have been found at the Mother's Day Quarry, located in the Bighorn Basin, Montana. These discoveries may bring new important information about diplodocids, specifically *Diplodocus sp*. Here we describe a newly uncovered skin mold that gives evidence of scale diversity in the *Diplodocus* genus. The scales themselves represent tubercles, and are conceived of various shapes including rectangular, oval, polygonal, and globular scales. The tubercles are small in size, the biggest of which only reach about 1cm in length. Considering how diverse the scale orientation is in such a small area of skin, it is possible that these molds may represent a transition on the body from one region to another; perhaps from the abdomen to dorsal side, or abdomen to shoulder. Based on analysis of extant integument and scale orientation of crocodilians and other reptiles, it is possible to hypothesize on the location of the integument relative to the body as well as the size and age of the individual.

Introduction

Life depictions of dinosaurs have changed considerably over time as a result of new discoveries and a better understanding of functional morphology. For example, our understanding of posture and locomotion of dinosaurs has improved based on anatomical interpretations of skeletons. Similarly, and more recently, the presence of feathers and feathered dinosaurs has been received with lots of interest (e.g. Xu et al., 2012). However, much less attention has been given to the morphology of scales, which is equally important to improve our understanding of dinosaur appearances. Over the past century, the number of studies published on dinosaur scales has dramatically increased (e.g. Kim et al., 2010). Despite this, research into sauropod integument remains rather limited. Some of the best preserved sauropod skin comes from titanosaur embryos in Patagonia (Coria and Chiappe, 2007), which show that these animals would have had diverse scale shapes and sizes as well as diverse patterns in terms of how the scales are oriented. Other information on sauropod skin is limited to footprints and skin impressions that show mosaic or pebble like patterning (Platt and Hasiotis, 2006, Gimenez, 2007, Kim et al., 2010, Foster et al., 2011, Czerkas, 1994). Diplodocid integument fossils in particular are only known from several skin impressions and carbon film fossils consisting of the patterns described above. The most noteworthy diplodocid integument discovered would be the dorsal spines found near the caudal region of a diplodocid in the Morrison Formation, as this discovery shed light on the potential diversity in the appearance of dinosaurs (Czerkas, 1992). The Mother's Day Quarry in Montana has recently unveiled new fossilized skin from *Diplodocus sp*. Some of the first skin fossils discovered at this quarry exhibited big polygonal scales (Myers and Storrs, 2007). However, information on these scale impressions are limited as in those previous studies, the skin impressions were primarily mentioned only as evidence for taphonomic interpretations, rather than descriptive analyses of the scale patterns and characteristics themselves. In this paper, we describe newly discovered *Diplodocus* sp. carbonous skin molds from the Mother's Day Quarry that consist of new scale shapes and patterns never before seen in this genus.

Site Background

The Mother's Day quarry, located in the Bighorn Basin, Montana, consists of Upper Jurassic deposits (Kimmeridgian; ~155 mya). The quarry has yielded over 2,500 fossils over the past two decades belonging to at least fifteen different *Diplodocus* individuals belonging to a single unnamed species (Myers and Storrs, 2007). All of the *Diplodocus* specimens were classified as juveniles and subadults due to their small size and unfused bones. However, more recent analyses revealed there may be a separate new dwarf species present in the Mother's Day Quarry as well (Woodruff et al., 2018). Only two other taxon have been discovered at this site as represented by allosaur teeth and a single crustacean.The reason for why this site contains mostly *Diplodocus* is that these individuals lived in a herd together, showing gregarious behavior (Myers and Fiorillo, 2009). Sedimentological and taphonomic evidence suggests that the *Diplodocus* skeletons are the result of a single mass mortality event, probably due to drought, followed by transportation and deposition in a high-density debris flow (Storrs, Oser & Aull, 2012).

Materials and Methods

The fossilized skin, designated MDS-2019-028, is still in situ but excavation is planned in the future. The skin molds were found in proximity to two dorsal ribs also in situ: MDS-2019-009 and MDS-2019-010, though it is unknown whether the skin and ribs belonged to the same individual based on preservation. The current plan for excavation is that first a mold of the skin will be made out in the field, so in case the skin becomes damaged during transportation, we will still have a replica. The skin will be deposited first at the Academy of Natural Sciences, where it will be prepped. After preparation of the skin is complete, it will then be sent to the collections at the Cincinnati Museum Center. The ribs will follow the same plan. Permits from The United States Department of the Interior Bureau of Land Management (permit numbers: MTM 109606, MTM 109606-e1, MTM 109606-e2, MTM 109606-e3, MTM 109606-e4) were issued to co-authors Jason Schein and Jason Poole in order to allow for excavation of fossils. A quarry map has yet to be made but locations of all fossils have been recorded with a surveyor's transit.

Instead, we are utilizing an older quarry map from Myers and Storrs (2007) to indicate the location of the skin and ribs (Fig.1). Permission was granted from the Society of Sedimentary Geology for use of this figure. All other pictures, drawings, and figures were created by Tess Gallagher.

To make description of the skin easier and to keep track of where the different scale shapes are in relation to one another, different areas of the skin have been designated as fragments identified with capital letters such as A,B,C. On fragments A and B, sections of the skin that change in scale shape have been designated with lower case letters such as Aa, Ab, etc. Fragment C receives no such formatting since it lacks the scale diversity as seen on the other two fragments. The reason for organizing the skin this way is to help better explain our hypothesis that we are able to identify where different parts of the skin were on the body by examining scale orientation and change in shape.

Results and Discussion

The integument consists of non overlapping scales, or tubercles, similar to those observed on other dinosaur skin fossils(Czerkas,1994), so the scales shall be referred to as tubercles interchangeably throughout the paper. There are molds on both sides of the rib MDS-2019-010 (Fig. 1). The rib itself continues into the hill while the skin molds extend on the bedding plain surface. Although the skin and ribs were found in close proximity to each other, there are several variables that bring into question whether they belonged to the same individual. For one, the skin fossils are believed to be the skin itself, preserved as a positive carbonous mold. It would be expected to see skin molds preserved on the rib itself, however none have been found thus far. Instead, it appears that the skin goes underneath the rib on the bedding plane. It should also be noted that the skin fossil has more scale diversity then would be expected in such a small area on an individual of the rib owner's size. Although it's not impossible for a *Diplodocus* of the rib owner's size to have so much scale diversity, it would certainly be unexpected for reasons further discussed later in the paper. Fragments of the skin were assigned a letter (see Fig.2) in order to allow for easier description. The first and biggest mold found measures about 240 mm in height and 600 mm in width (Fig.2. A). This skin mold appears to go underneath the rib, and might be connected to fragment B, based on the similar scale size in both fragments. Fragment B is located on the opposite side of the rib to fragment A (Fig.2) and consists of three fragmented molds that range between 20-130 mm in length and 10- 40 mm in width. Fragment C is located on the same side as fragment A, next to the end farthest from the rib. Fragment C consists of multiple small fragments that range in size from 20-100 mm in length and 20-50 mm in width. Considering how close fragment C is to fragment A as well as fragment C sharing similarly sized and shaped scales to fragment A, fragment C was most likely once connected to fragment A.

Fragment A

Fragment A contains signature pebble and polygonal scales on its lower region (designated Ab in Fig.3) which measure roughly 5 mm. These are similar in shape to tubercles observed in other diplodocid skin fossils as described by Czerkas (1992).To the right of section Ab, the scales lose definition inside of two oblong shaped impressions in the skin itself (Fig.3). The current hypothesis is that this formation may represent a small dinosaur footprint, as this is the only area where the scales become non discernable and the consistency of the oblong shapes mimic the look of other known dinosaur footprints. However, it is also possible this formation could have been caused by other taphonomic processes. To the farthest left of section Ab, the tubercles are even smaller in size (~1mm) and may correspond to the small scales on the opposite side of the rib in section B. The tubercles change shape from small pebble and polygonal tubercles at the lower region of Ab into rectangular shaped tubercles in the upper region designated Aa. In section Aa, rectangular tubercles are visible ranging in size from ~5 mm to ~10 mm (Fig.3). The tubercles in section Aa change from miniscule ~1mm scales to the larger rectangle tubercles from right to left of the picture(see Fig.3 and 4) and change into polygonal tubercles at the top (Fig.4). Rectangular tubercles have been observed before in sauropods, most notably in preserved titanosaur fetuses scales from Patagonia (Coria and Chiappe, 2007). However, the rectangular scales of the titanosaur fetuses are neatly lined up and overlap each other. In addition, these rectangular scales observed in the Patagonian fetuses are much larger than the surrounding scales. The rectangular tubercles on the *Diplodocus* specimen instead do not display such a specific pattern, showing multiple rows of straightly aligned rectangular and square tubercles. These rectangular scales then diverge into more polygonal scales in section Ac that are around 5 mm in diameter. The polygonal tubercles transition into smooth oval tubercles in section Ad measuring less than ~10mm in length and are also more raised than the other surrounding tubercles(Fig.5). These tubercles are closely clustered together, and all oriented similarly; the pointed ends of the ovals pointing towards section Ac. This cluster measures roughly 30 mm by 70 mm. Between the cluster of tubercles and the polygonal scales of section Ac, there are two smaller tubercles that are slightly raised and smooth in texture, but are instead domed rather than oval shaped (Fig.6). They are located a few centimeters in front of the oval tubercle cluster, exhibiting no clear organized scale pattern. In addition to the dense cluster of oval tubercles, section Ad also displays another curious arrangement of scales. At the forefront of the cluster of oval scales, where the oval scales meet the polygonal scales, there is an arrangement of five oval tubercles in an arrow shape pointing towards section Ac. The arrow orientation consists of a single tubercle at the point and two tubercles on each side. The oval scales look similar in nature and orientation to tubercles seen dorsally on modern day reptiles. Also taking into consideration the existence of dorsal spines on diplodocids (Czerkas, 1992), these oval scales may be homologous and may have also been present on the dorsal side of the animal, though whether or not these oval scales would have eventually grown into dorsal spines or kept their shape throughout life is up to debate.

Fragment B

Skin fragment B (Fig.7) shows both similarities and differences with fragment A. Tubercles in fragment Ba are similar in size to those observed in fragment Aa, but are irregular in shape with bean and globular-shaped tubercles arranged in a puzzle-like formation, often seen “hugging” or folding over nearby tubercles of similar shape (Fig.8). The tubercles also display more rounded edges compared to the tubercles observed in fragment A, and have deeper, more visible indentations in-between each scale. Tubercles in Bb consist of square and polygonal tubercles, with sizes comparable to Ab. An interesting feature in section Bb is that the small square tubercles are organized in linear rows that arch downwards, interrupting the nearby polygonal scale patterning (Fig.8). There are at least two additional rows of arching scales next to the row closest to the polygonal scales. This patterning is very similar to scale patterning seen around crocodilian limbs (Fig.9), which may suggest that this section may have been from a limb region in life. Skin section Bc consists of small >0.5cm pebble like tubercles.

Fragment C

Fragment C (Fig.10) consists of multiple small fragmented skin. The scales range in size from 5 mm to 10 mm. The scales appear to change in size depending upon their location: fragments closer to section Ad are smaller than those closest to Ac. The fragments exhibit the same polygonal shapes seen on section Ac and are also close in proximity and lay on the same bedding plane, so it can be assumed that these fragments were at one point attached to fragment A.

Juvenile hypothesis

Through close examination of the skin molds, the evidence suggests that the skin belonged to a small juvenile, possibly even an infant. The evidence we used to come to this conclusion is the presence of juvenile bones in the Mother's Day Quarry, the significant diversity of scale shapes over a small area of the skin molds, and the orientation of the scales implying the presence of a small limb. Each of these pieces of evidence is further discussed below.

The presence of young and small individuals from this quarry have been thoroughly reported between 38-75% the size of other known adult *Diplodocus* specimens. Woodruff et al. (2018) even reported to have found the smallest Diplodocus specimen ever uncovered, consisting of a skull and some vertebra. Therefore, it is not unexpected that skin fossils found in the same bonebed are from a small and young individual.

The skin molds represent a relatively small area in comparison to the overall body size of what would be an adult *Diplodocus sp*. Despite this, the molds show a significant diversity of scale shapes and orientations. This may indicate that this mold shows a transition from one body part to another, as evidenced by modern reptiles and how their scales change orientation and shape based on where on the body the scales are located. In addition to the diverse orientation of the scales, the polygonal scales described on MDS-2019-028 are much smaller than other known diplodocid scale fossils. For example, polygonal scales from Howe Quarry can be as big as 30 mm (Czerkas, 1994), while none of the scales observed in this study exceed 10 mm in size. The high diversity of scales over a small area combined with the small scale size, suggests that MDS-2019-028 belongs to a small individual.

The scales on section Bb curve downward at an extreme angle of 66˚ relative to the square scales closest to the polygonal scales. This type of patterning is often seen on crocodilian and monitor lizard limbs in order to allow for flexibility. Though there is no direct evidence of this scale patterning on dinosaurs, it has been noted that in exceptionally well preserved hadrosaur mummies like AMNH 5060 and AMNH 5240 that the scales are smallest around the limb regions for the same purpose of flexibility (Brown,1916,. Osborn,1912). It is, therefore, possible that the scales in section Bb may have had the same purpose, and most likely surrounded a limb. If this is the case, the limb in question would have been relatively small, considering the shoulder/leg would be no wider than 100mm (Fig.2).

Conclusion

The skin mold (MDS-2019-028) discovered at the Mother's Day Quarry shows new scale shapes and orientations never before seen in *Diplodocus sp.* Scale diversity and orientation on this small mold strongly suggests the skin belonged to a very small juvenile. If this can be confirmed, MDS-2019-028 may provide information on the ontogeny of diplodocid scales. This discovery also highlights the scientific significance of the Mother's Day Quarry and the potential to find additional skin fossils during future excavations.

Acknowledgements

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Figure 1

Quarry map of the Mothers Day site showing bone location.

Red circle indicates approximate location of skin and rib fossils. Quarry map modified from Myers and Storrs, 2007.

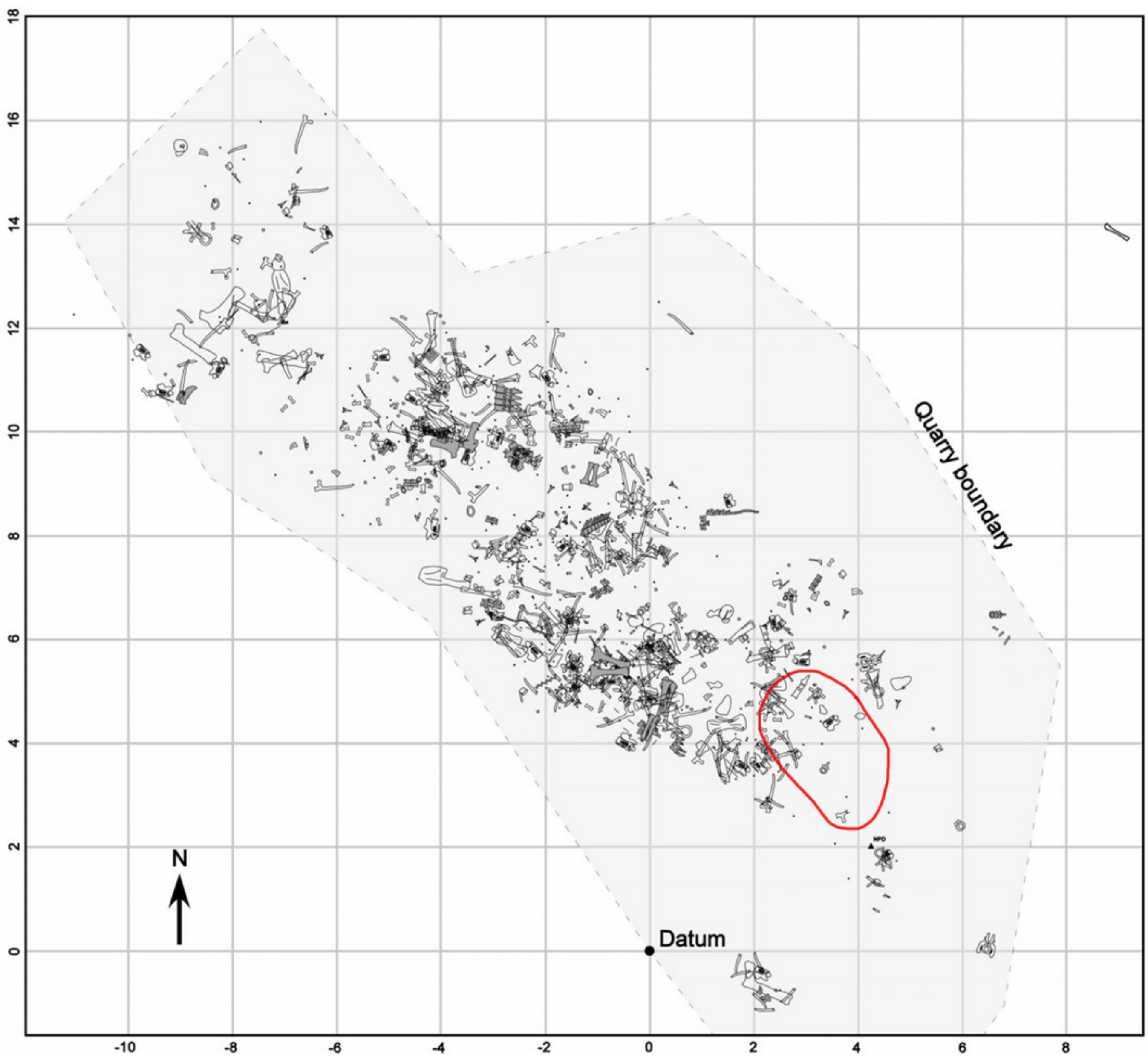


Figure 2

Diplodocus sp. skin molds in association with the two ribs.

(A) the first and largest of the molds found; showcases various scale shapes and patterns including the never before seen rectangular tubercles as well as the convex oval shaped tubercles. (B) Skin fragments on the left side of the rib that most likely connect to A. The fragment consists of tubercles of various shapes, the biggest of which are smooth in texture and are approximately ~10mm in length. The other scales are smaller but vary in shape. They also appear to show a change in scale orientation. (C) Skin fragments that were most likely once connected to fragment A. These scales are located in a matrix of rock above A. Scale shapes include tiny ~1mm tubercles and larger ~10mm polygonal tubercles. The tape measure indicates the scale in centimeters.

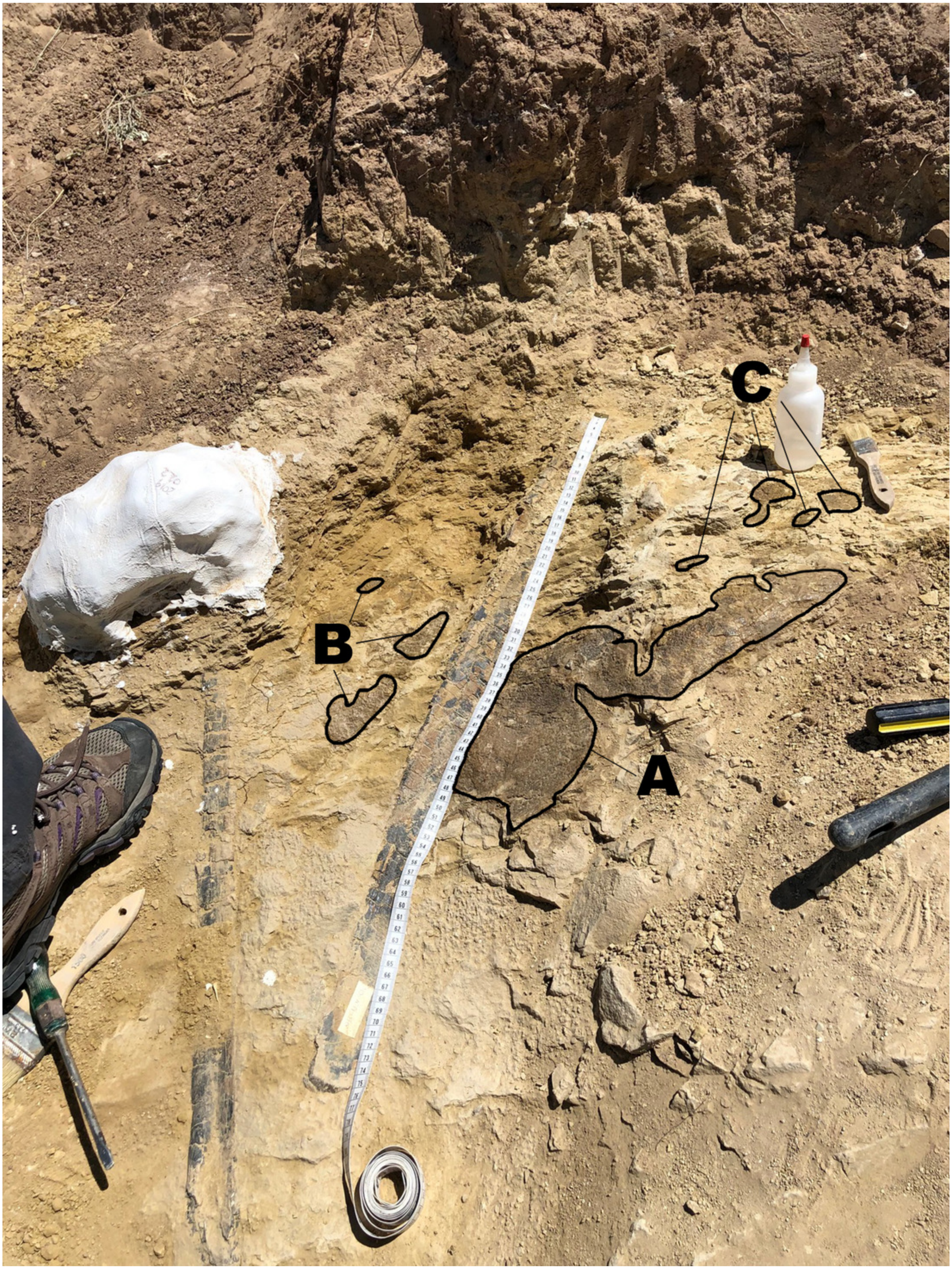
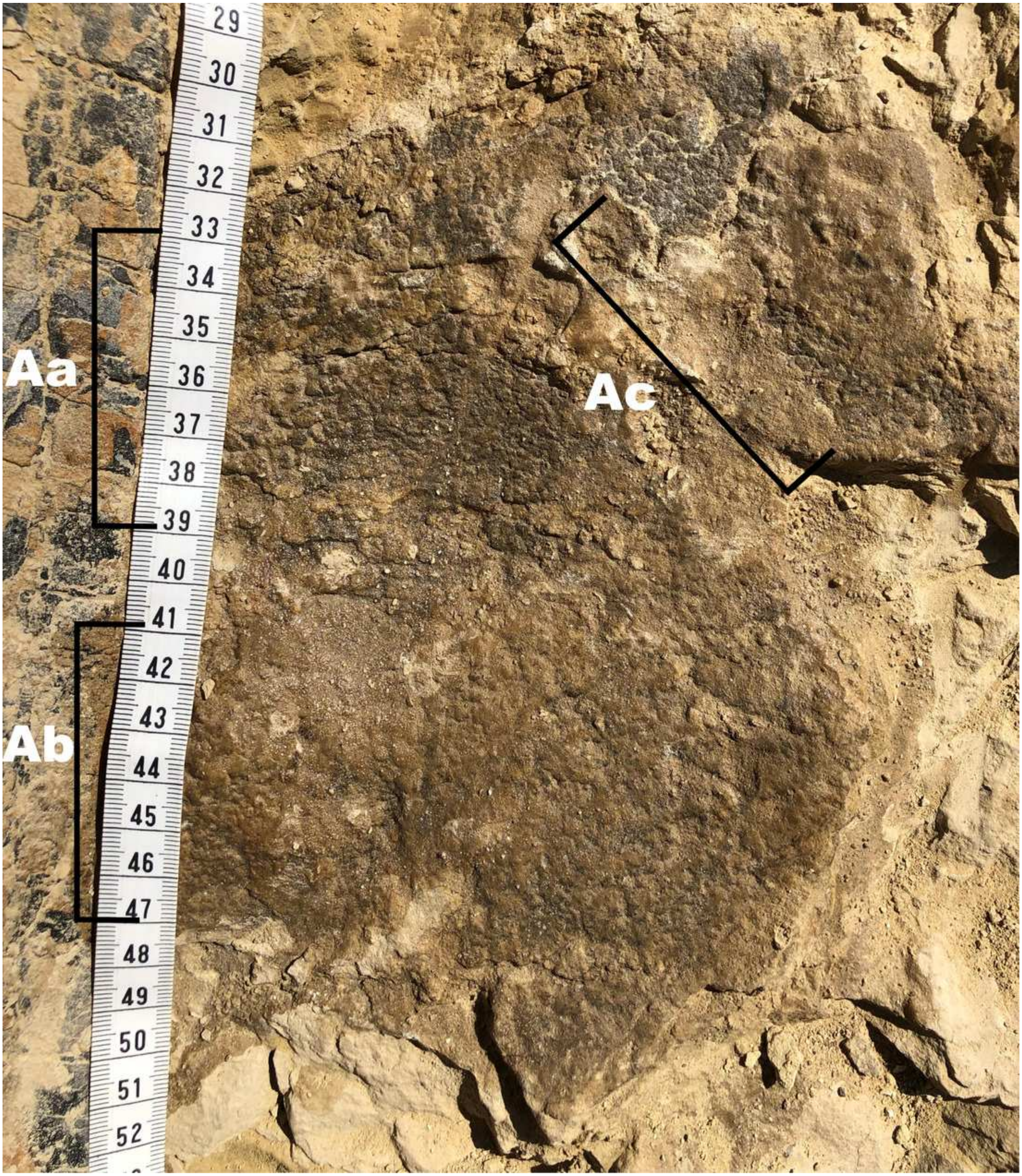

C
B
A

Figure 3

Close up of the largest area of skin fragment A with labeled sections of change in scale shape.

(Aa) Rectangular tubercles that range between ~5 mm to ~10 mm. (Ab) Small polygonal tubercles that range in sizes of around ~5 mm as well as small pebble tubercles of about ~2 mm in size located to the left of the picture. (Ac) Larger polygonal tubercles of similar size to the rectangular tubercles. Scale in cm.


Aa
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Ac
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Figure 4

Section Aa exhibiting rectangular tubercles with drawing for clarity.

(A) Close up picture of section Aa. (B) Drawing of section Aa to help distinguish individual rectangular tubercles.

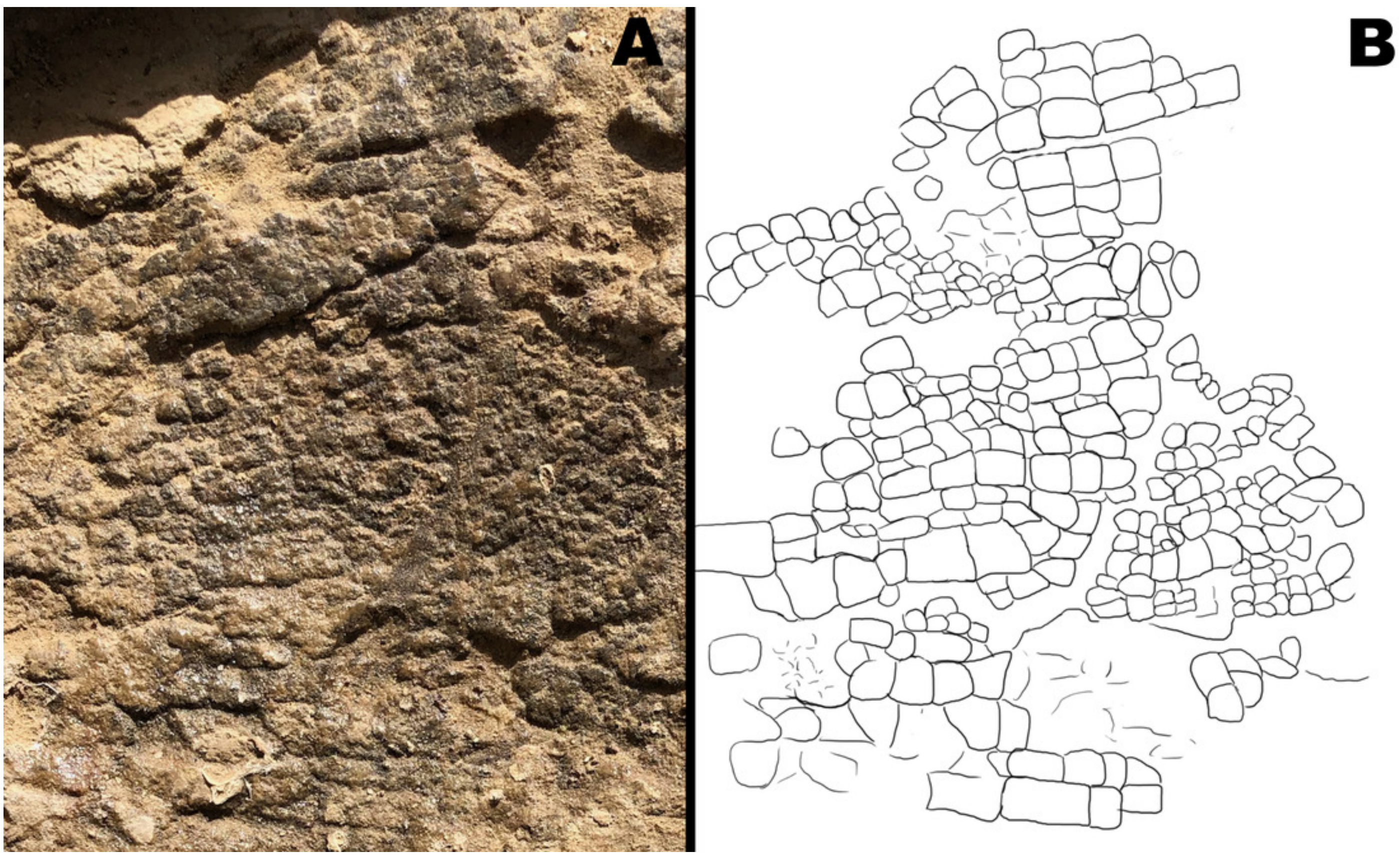

Figure 5

Close up picture of skin section branching off from section Ac containing oval and dome scales.

(Ac) Polygonal tubercles. (Ad) Polygonal scales of similar size to scales from Ac, these then transition into the dome(<5mm) and oval scales(~10mm). (C) Pieces from fragment C.

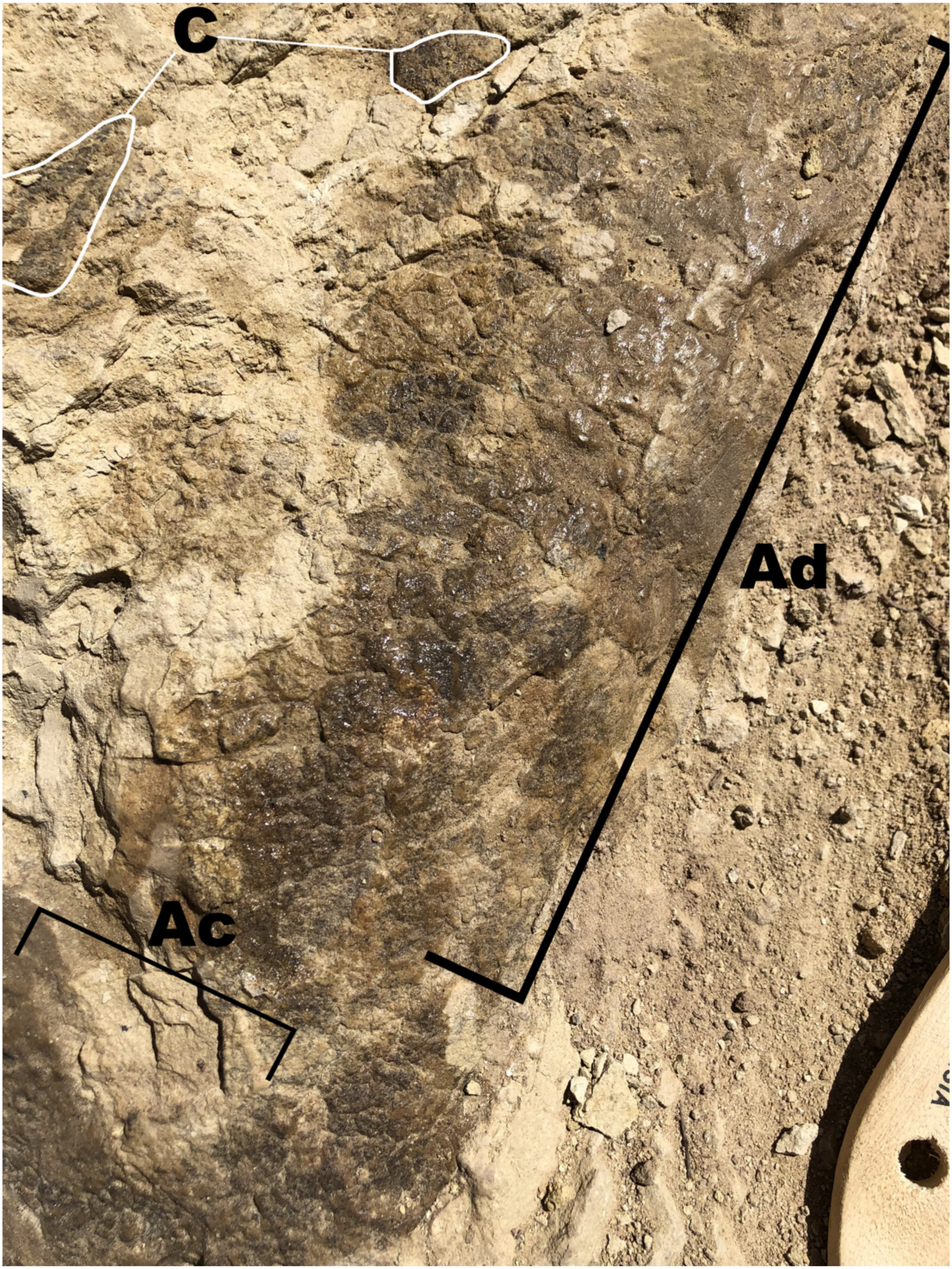
C
Ad
Ac

Figure 6

Close up of section Ad with a better view of unique scale shapes.

(A) Dome scales and oval scales oriented in a cluster orientation. (B) Drawing to help highlight oval and dome scales from section Ad. Abbreviations: d; dome scales, o; oval scales.

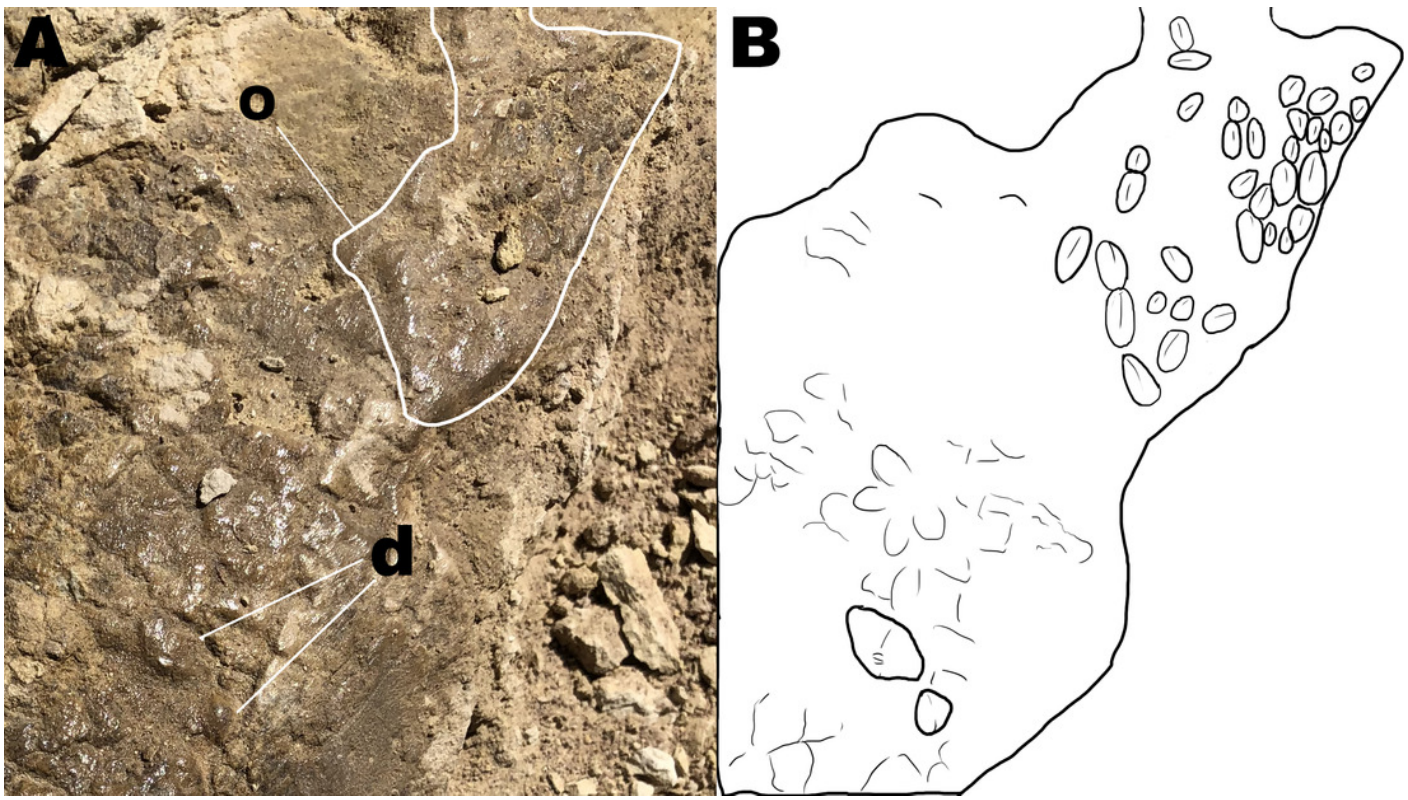

Figure 7

Skin fragment B, located on the opposite side of the rib as to fragment A.

(Ba) Smooth globular tubercles that measure ~10mm. (Bb) Polygonal and square shaped tubercles that measure <5mm.(Bc) Pebble shaped tubercles that measure ~2mm.

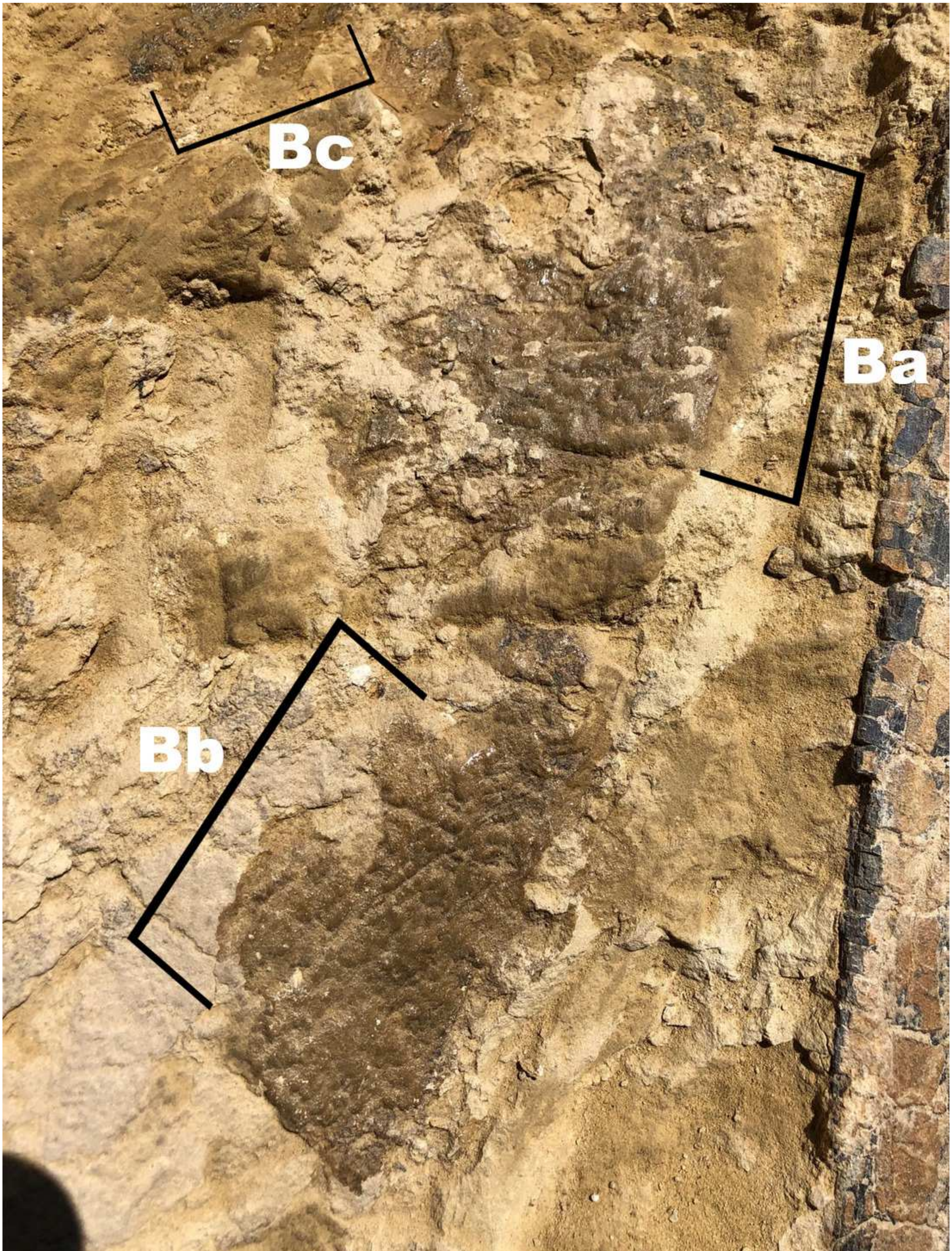
Bc
Ba
Bb

Figure 8

Close up pictures of section Ba and Bb for better view of the globular scales and arching orientation.

(A) Close up of section Bb. (B) Drawing of arching scale alignment from section Bb. (C) Close up picture of section Ba. (D) Drawing of globular scales from section Ba.

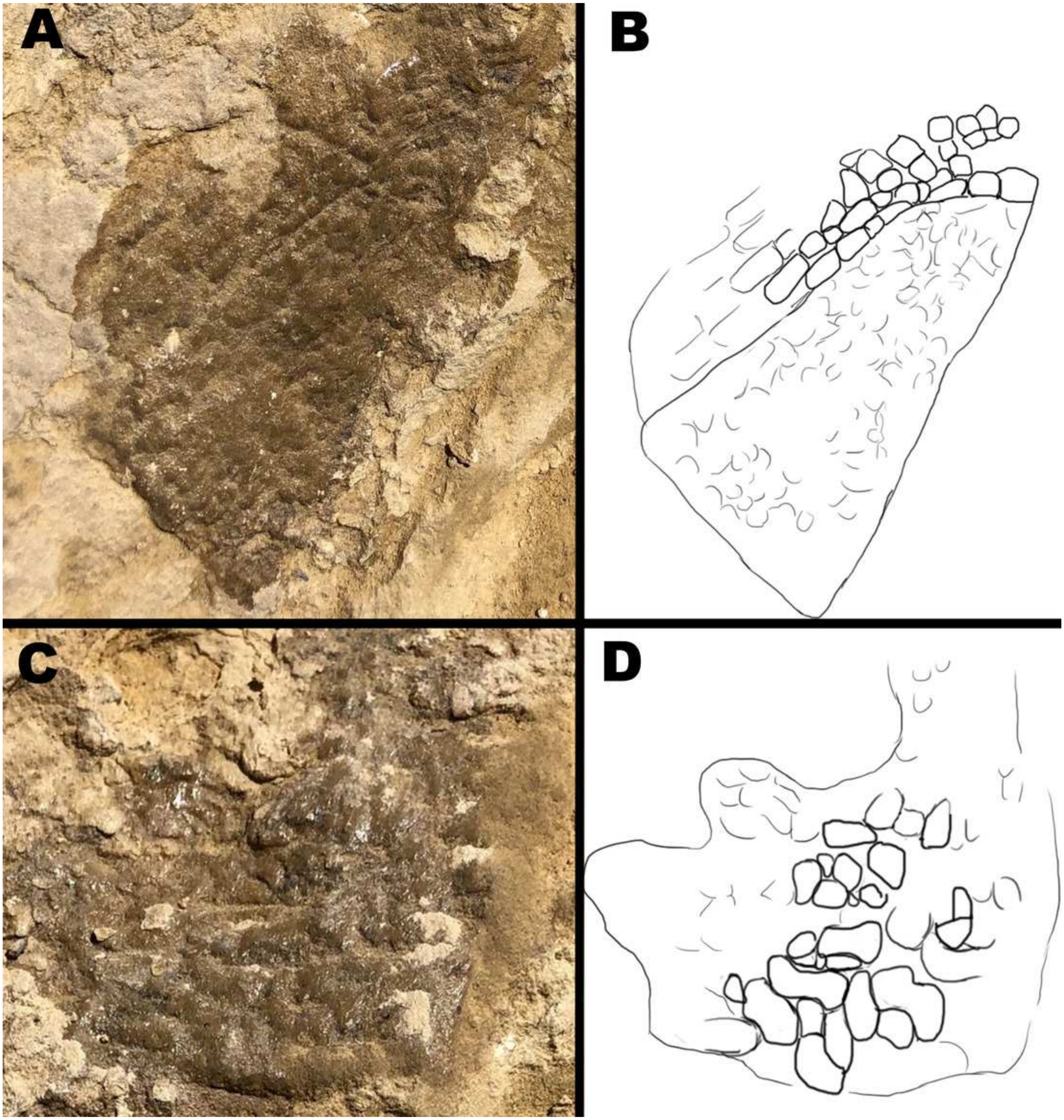
A
B
C
D

Figure 9

Comparison between scales around an *Alligator mississippiensis* limb to downward aligned *Diplodocus* scales.

(A) Close up picture of section Bb. (B) Hindlimb of a juvenile *Alligator* with scales arching around the limb. (C) Arching scale rows of Bb outlined by red lines. (D) Arching scale rows of juvenile *Alligator* outlined with red lines.

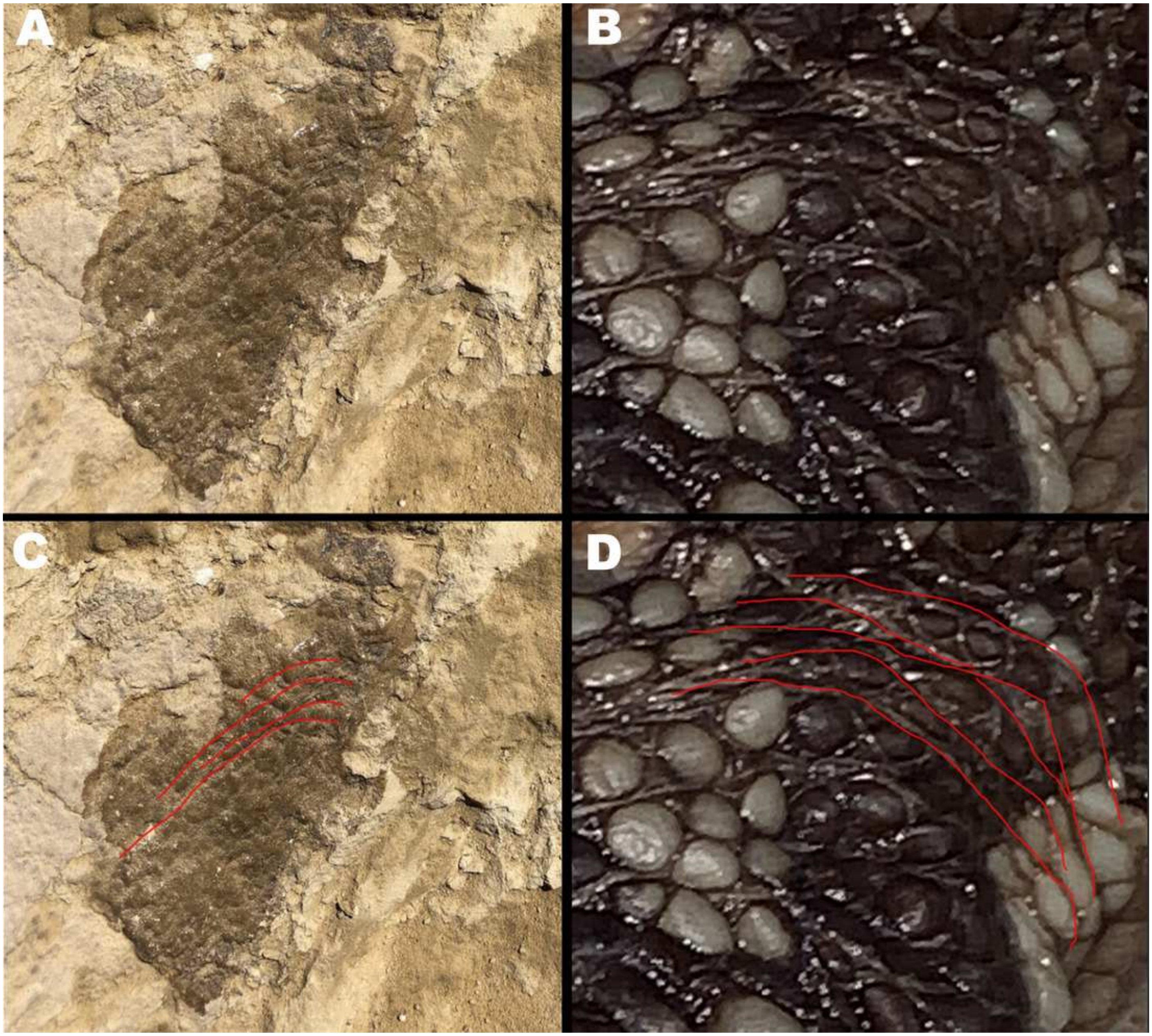
A
B
C
D

Figure 10

Skin fragment C with glue bottle and brush for size reference.

These tubercles are within close proximity to section Ad, and show similar polygonal patterning.


1"
WHITEWAR
100% PURE BRISTLE
MADE IN INDONESIA