

“HEALING CRACKS” ON FOSSIL TEETH: IMPROVEMENT OF ODONTOLOGICAL STUDY METHODS IN PALAEOONTOLOGICAL RESEARCH

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ABSTRACT:

A significant part of fossil findings, which are objects in palaeontological and palaeoanthropological research, is represented by teeth. Even if compared with skeletal remains, they are composed of highly mineralised tissues. This fact considerably increases their potential for being preserved withstanding destructive environmental factors. Nevertheless fossilisation process is accompanied by various changes in teeth including over the centuries with regard to their integrity or deformations. Thus among palaeontological findings there is a noticeable share of fragmented teeth. However we will focus in the current paper on a special group of teeth, which have preserved their most essential morphological features, being at the same time on the way to their fragmentation - cracked teeth.

Recent morphological and especially morphometric study methods applied to dental findings have been developed largely in line with high-resolution imaging techniques, such as microfocus x-ray tomographic scanning. They provide diversity of detailed digital reconstructions of teeth and application of image processing. This allows improvements of existing methods in odontological studies as well as and development of new as well, including those using automated algorithms, e.g. automated digital odontometry. This technique is sensitive to reconstructed surface quality, uninterrupted requiring surfaces as cracks hinder running the algorithms. Thus we propose method for reconstructing cracked teeth, which allows to obtain better results in morphological studies of teeth. The method proposed is based on consistent stages of surface curvature analysis and minimizing average distance between points opposing cracks surfaces.

1. INTRODUCTION

A significant part of fossil findings, which are objects in palaeontological and palaeoanthropological research, is represented by teeth. They serve for taxonomical, developmental and other studies shedding light on evolutionary processes (Smith et al., 2012., Xing et al., 2014., Pan, 2016.). Even when compared to skeletal remains, teeth are composed of highly mineralised tissues; this especially refers to dental enamel – the hardest tissue. This fact considerably increases their potential for being preserved over the centuries and to withstand destructive environmental factors. Nevertheless fossilisation process is accompanied by various changes in teeth (Dauphin, 2022.), and we will pay attention to those including with regard to their integrity and deformations. Thus among palaeontological findings there is a noticeable share of fragmented teeth. As a matter of fact such teeth have served as a source of information for enamel thickness measurements in the past, in line with physical sectioning teeth (Martin, 1983.), and today these and similar studies have received an impulse for development due to application of 3D imaging and image processing (Guy et al., 2015.). And we will focus in the current paper on a special group of teeth, which have preserved their most essential morphological features, being at the same time on the way to their fragmentation - cracked teeth.

Recent morphological and especially morphometric study

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methods applied to dental findings have been developed largely in line with high-resolution imaging techniques, such as microfocus x-ray tomographic or neutron scanning (Zanolli et al., 2020.). They provide diversity of detailed digital reconstructions of teeth including their outer (enamel) and inner (dentine) morphological layers. Thus studies of dentine surface (or enamel-dentine junction) shed light on dental morphology even when some features have been lost due to dental wear (Benazzi et al., 2011.). Application of image processing allows improvements of existing methods of studies; as a result a significant part of odontological studies can be conducted without physical sectioning of the studied sample which contributes to their preservation (Benazzi et al., 2014.). We should also mention that 2D and 3D analyses of dental morphology can be performed for more profound research providing more ample and detailed data on dental morphology (Guy et al., 2013.). In addition, new study techniques have been development and applied for dental morphological and morphometric studies in different disciplines as well. This technique is sensitive to uninterrupted surfaces as cracks hinder running the algorithms. Thus we propose method for reconstructing cracked teeth, which allows to obtain better results in morphological studies of teeth.

It is an interesting issue to explore the factors which can cause cracking fossil teeth, however most evident reason could be in fluctuations of humidity and probably temperature as well, at least with regard to the studied samples. For the support of this version of crack genesis we can mention an important fact

that these findings originate from sedimentary layers of solutional caves. The observed cracks have unequal distribution of width, are cuneiform in shape and getting narrower, depending on sample, towards root or enamel surface. This might be considered as a result of deformation of tension within the objects, which, if we refer to basic morphological and histological structure of teeth, are composed of layers with different density, mineralisation degree, porosity as well as water and organic substance content. This can be applied to one of the cracked teeth which possesses nearly complete morphology including roots sample number 269 (Figure 1).

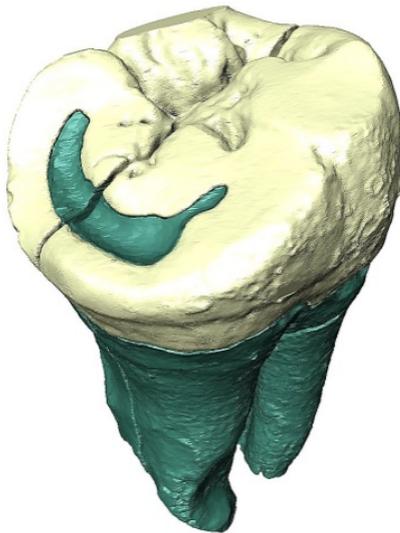


Figure 1. 3D reconstruction of sample 269 with highlighted enamel (yellow) and dentine (green)

The other cracked tooth has missing roots and chipped edges of dentine (sample number 82 Figures 2, 3). The observed condition can be influenced by combination of the mention above dental morphological feature with another determining factor – porcupine diet (these animals feed on highly mineralised diet, including dentinal roots of teeth; however they avoid consumption of dental crowns which are plated by very hard enamel).

Nevertheless the teeth described above are not unique for palaeontological and palaeoanthropological research. There are numerous similar samples studied which have been influenced by various taphonomic factors and therefore are in cracked or fractured condition. In some cases they are not registered as a hindering factor for the research – only fractures are described (Gulec et al., 2007.). Nevertheless detailed reconstructions of different morphological layers attract attention of researchers: initially as a matter of morphological description of the sample features and condition (Toussaint et al., 2009.), not only visible on the surface but penetrating through the bulk of dental tissues (Macchiarelli et al., 2004.). High-resolution imaging techniques applied allow to characterise crack direction and to create a more complete and ample profile of previously studied, by means of traditional techniques, samples (Benazzi et al., 2011., Benazzi et al., 2014.) . There are also examples of fracture correction as well as crack closure which, presumably, have been previously – before scanning procedure – restored by invasive fill (Pan, 2016.). The mentioned digital reconstruction was performed for further enamel thickness measurements.

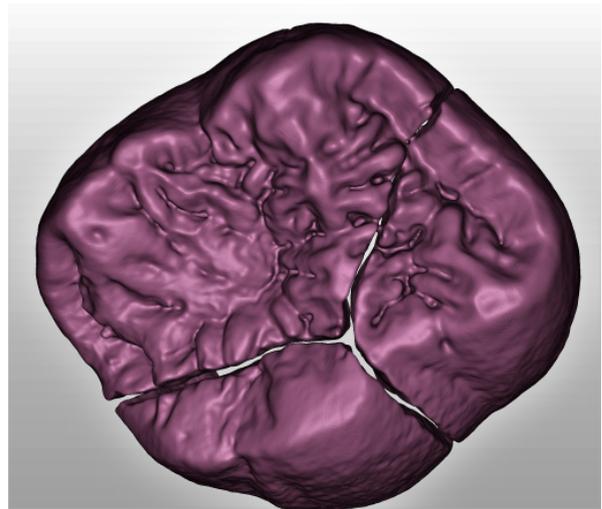


Figure 2. 3D reconstruction of enamel layer of sample 82

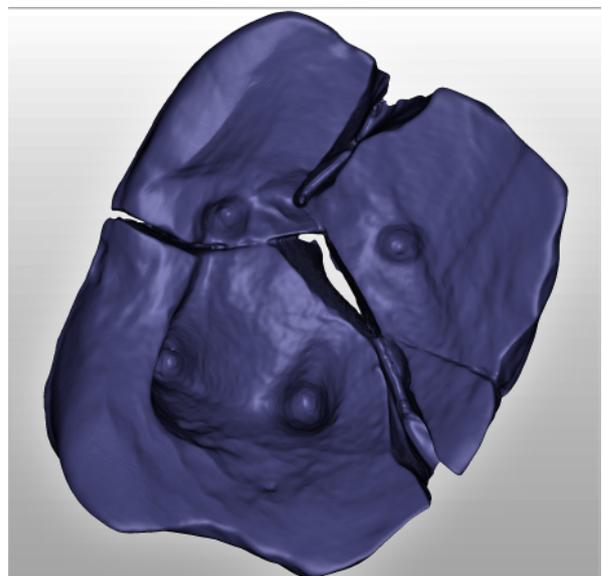


Figure 3. 3D reconstruction of dentine layer of sample 82

2. MATERIALS AND METHODS

The teeth presented in this paper belong to Orangutan (*Pongo*) species, which inhabited continental regions of South-East Asia during the Pleistocene. They were found during joint mission of Borissiak Paleontological Institute of Russian Academy of Sciences (Moscow, Russia) with vietnamese colleagues from the Joint Russian-Vietnamese Tropical Scientific and Technological Center. The research was conducted as a part of project “The Composition of the Fauna of Primates (Cercopithecidae, Pongidae) and Rodents (Rodentia) of the Pleistocene and Holocene of Vietnam as an Indicator of Environmental Change” (2020-2022) (Figure 4).

2.1 Studied teeth

Both teeth (PIN 5826/82 and PIN 5826/269) were found in Pleistocene sediments of Tham Hai Cave (Binh Gia District) which can be dated within an interval from 300 to 200 thousand years (the second part of the Middle Pleistocene) (Schwartz et al., 1995.).



Figure 4. Excavations in Tham Hai Cave

Excavations conducted in 2021 have revealed remains of at least 15 species of large mammals of the Pleistocene fauna of Gigantopithecus - Stegodon (Morkovin et al., 2021). This fauna has been widespread from the end of Early Pleistocene until the beginning of Late Pleistocene (in the interval between 1,500,000 and 90,000 years) in the territories including regions from the Southern China to Greater Sunda Islands. Chronology of mammal species, its distribution in different periods within the above-mentioned time interval of the Pleistocene is of high interest for reconstructions of environment in the past as well as for short- and long-term prognosis of changes of biological diversity of the region.

The major part of sediments which contain osseous materials (mainly coronal parts of teeth) is represented by bone breccia (Figure 5) based on red-soil loams of different mineralisation degree. The studied posterior teeth belong to adult Pleistocene orangutans tentatively determined as subspecies of *Pongo pigmeus kahlkei* (Bacon, Vu The Long, 2001., Schwartz et al., 1994., Schwartz et al., 1995.) This subspecies has been occurred in the Middle Pleistocene on the territories of Northern Vietnam, today's Lang Song Province.



Figure 5. Fragment of osseous breccia from the Tham Hai Cave

Both studied teeth have preserved integrity of their coronal parts, even though cracked, but not separated into pieces. These cracks do not have strong influence affecting morphology of enamel. However inner dentinal layers are significantly dislocated, which can be noticed on scans and 3d reconstructions.

2.2 3D reconstruction procedure

The teeth were scanned on high resolution 3D micro-computed tomographic scanner Skyscan1172 (Bruker, Germany). Scanning information is presented in Table 1. Two teeth from the series, being of high interest for the research, showed significant cracks. Their reconstructions were picked from the entire sample, and are presented in the current paper.

Camera	SHT 11Mp
Source Voltage, kV	70
Source Current, mA	129
Image Pixel Side Size, μm	12.00
Exposure, ms	600
Rotation Step, deg	0.400
Scanning Trajectory	ROUND
Type Of Motion	STEP AND SHOOT

Table 1. Scanning parameters of teeth

General study plan required obtaining separate reconstructions of enamel and dentin for each tooth. Image processing was performed by means of Avizo software (version 9.0). Initial processing of planar images reflects cracks passing through dental tissues (Figure 6).

Before segmentation Gaussian smoothing procedure was performed at level 3 nucleus size setting. Further segmentation steps were performed through application of Magic Wand, Threshold Tool, 3D Lasso, Shrink Selection and Remove Islands tools, as well as additional smoothing at level 9 nucleus size setting. Ready-to-use models were converted to .stl format.

2.3 Cracks "repairing" algorithms

Unfortunately, direct 3D reconstruction of the of the teeth does not allow performing accurate measurements of tooth land-

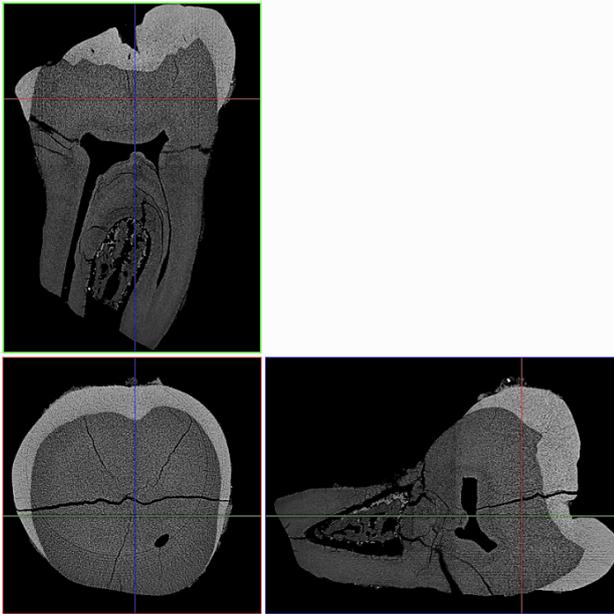


Figure 6. Flat images of sample 269 as sections in three perpendicular planes

marks, that are needed for analysis of tooth morphology. In addition cracks stop running of automated algorithms which are responsible for orientation and morphological feature detection during the measurements. So the technique for restoration of the initial 3D shape is developed as a part of the study. The algorithm for "healing the cracks" finds the parameters of system coordinate transformation for each part of the tooth, that provide the best alignment of the adjacent surfaces of the tooth parts.

First phase of the reconstruction of initial 3D shape of a tooth is separating it into the parts to be subsequently collected into one whole tooth. For this purpose, firstly, the borders of the cracks are found using Gaussian curvature as indicator of a crack (Figure 7, blue colour).

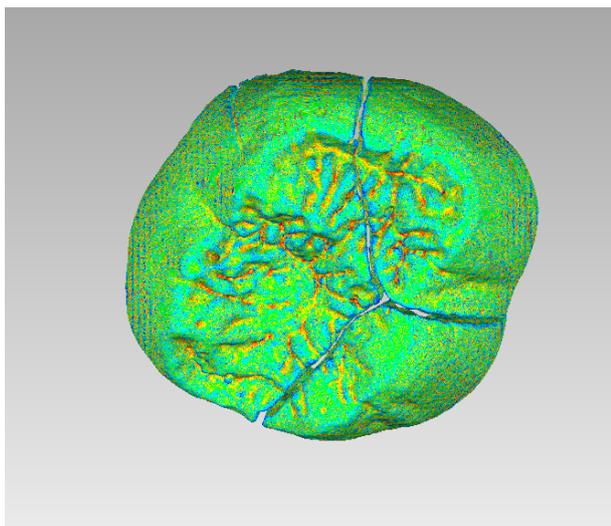


Figure 7. Detected crack borders (marked by blue color in the tooth 3D model)

Then surfaces of cracks are found as regions, that are inside the

found borders, and parts of the tooth are separated into separate 3D models (Figure 8).

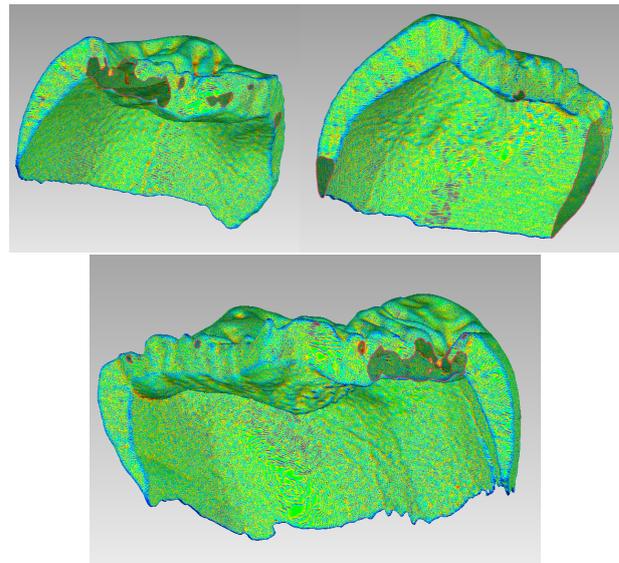


Figure 8. Separated parts of the tooth.

The procedure of tooth segmentation into the parts is presented as Algorithm 1.

Algorithm 1: Tooth segmentation

Input:

TIN 3D model of a tooth $\mathbf{T} = \{t_i, l_j\}$,

Output:

Segments $T_z; z = 1, \dots, N$

- 1 Segmentation of each piece of tooth;
 - 2 **Procedure** Segmentation(T):
 - 3 **for** each point t_i of tooth 3D model T **do**
 - 4 Find Gaussian curvature $K_i = \kappa_1 \cdot \kappa_2$ at point t_i
 - 5 **if** $K_i > K_{threshold}$ **then**
 - 6 find normal to the tooth surface n_i at point t_i ;
 - 7 **if** $n_i < 0$ **then**
 - 8 skip;
 - 9 save t_i in the boundaries of the segments $\{t_i^b\}$
 - 10 **else**
 - 11 skip;
 - 12 Combine the boundaries of the segments $\{t_i^b\}$ into
 - 13 curves by minimizing the distance between points;
 - 14 Count the number of curves and find the number of
 - tooth fragments N ;
 - Segment T into parts $T_z; z = 1, \dots, N$;
-

The next step is "healing the cracks" of the damaged tooth. Iterative Closest Points (ICP) algorithm is applied for finding the transformation of coordinate systems of the tooth parts, that provides their best conjunction in terms of minimizing average distance between points of corresponding cracks surfaces.

The procedure of "healing the cracks" using segmentation is presented as Algorithm 2.

Figure 9 shows the results of applying Algorithm 2 to found tooth parts.

Algorithm 2: "Healing the cracks"

Input:

TIN 3D model of a tooth $\mathbf{T} = \{t_i, l_j\}$,
Segments $T_z; z = 1, \dots, N$

Output:

TIN 3D model of a tooth $\hat{T} = \{\hat{t}_n, \hat{l}_m\}$

1 Connecting pieces of tooth along the boundaries of the chip;

2 **Procedure** Connecting(T):

```

3   for each part  $T_z$  do
4     for each point  $t_k$  of tooth 3D model  $T_z$  do
5       Find Gaussian curvature  $K_k = \kappa_1 \cdot \kappa_2$  at point
6          $t_k$ 
7       if  $K_k > K_{threshold}$  then
8         find normal to the tooth surface  $n_k$  at point
9            $t_k$ ;
10        if  $n_k < 0$  then
11          skip;
12        save  $t_k$  in the boundary of the segment  $\{t_k^b\}$ 
13          ;
14        else
15          skip;
16      determine the boundaries of the segment  $\{t_z^b\}$ 
17      along which the tooth has split;
18      store the boundaries of the segment  $\{t_z^b\}$  for
19      further processing
20  Use ICP to identify the appropriate boundaries of the
21  split of the tooth;
22  Use a linear transformation to connect the respective
23  split boundaries;
24  return  $\hat{T}$ ;
```

3. DISCUSSION AND RESULTS

Detailed 3D reconstructions of teeth, especially those which have been obtained through high-resolution scanning techniques – micro-focus computed tomography, possess a number of important features allowing to improve palaeontological and anthropological research and to find more evidence shedding light on the evolutionary process. This refers to the presented in the current paper sample material, which are planned to be studied in the near future. Various profound study techniques and their combinations can be applied on odontological sample avoiding destructive methods and thus preserving unique findings. Such methods as visual morphological assessment, odontometry, enamel thickness measurements and geometric morphometry have improved markedly having access to both inner and outer morphological layers of teeth (Pan, 2016).

In addition new automated algorithms, based on 2D and 3D surface analyses, which perform orientation and measurements of teeth have been developed (Knyaz, 2012, Knyaz and Gaboutchian, 2016, Gaboutchian et al., 2021.). And in case of this technique interrupted surfaces, such as cracks or holes, as well as superimposing surfaces, block running of algorithm, at least at its current development level. Thus on the one hand we possess a profound though sensitive technique for 3D analysis; on the other hand 3D reconstructions give opportunity to resolve the problem with cracks or other imperfections of surfaces. Here probably two approaches can be considered. The first is simple sealing of cracks which possesses a definite lack of reliability and potential to distort morphological features of teeth. Thereby a method of healing cracks is proposed in the current paper. It is based on accurate reposition of cracked surfaces, which provides appropriate restoration of original dental

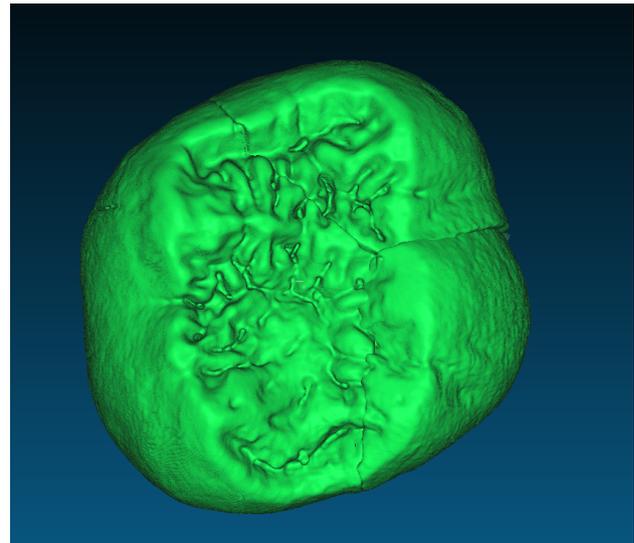


Figure 9. The results of applying Algorithm 2 to found tooth parts

morphology. However it is a certain challenge to develop the suggested technique as cracking teeth is accompanied by its deformation when the pattern of deformation in each particular case is unclear in its details.

Nevertheless the proposed technique allows to obtain uninterrupted surfaces by bringing closer together the edges of cracks. This approach doesn't require any "filling" procedures hence the obtained reconstructions are closer to initial shape of the studied sample. This especially refers to the enamel cap as the tissue has lower potential to shrinkage or other types of deformation due to very low organic substance and water content (if compared to dentine). We find this approach as an important stage of post-imaging processing as it enhances opportunities of unhindered application of different study methods and gives more opportunities to researchers to come to well-balanced conclusions in palaeontological research as findings belong to historical period of coexistence of different Homo species, including ancestors of modern man, as well as apes (extinct and extant).

4. CONCLUSION

We have suggested a method for restoration of initial dental morphology through "healing" cracks avoiding application "filling material" for closing cracks. This allows to enhance performance of different dental morphological study methods based on visual and measurement approaches. And the presented sample is going to be studied by means of automated algorithms in line with other material from the Tham Khai cave.

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