Evaluation of preliminary techniques used to assess taphonomic variation in silicified microbial mats preserved in the Angmaat Formation, northern Baffin Island, Nunavut

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This project is being led by researchers at The University of Tennessee–Knoxville in collaboration with the Astrobiogeochemical Laboratory at the National Aeronautics and Space Administration’s Jet Propulsion Laboratory. Logistical support for the project has been provided by the Polar Continental Shelf Program (PCSP). Funding for this project has been provided by the Levis and Clark Astrobiology Grant, the Southeastern Section of the Geological Society of America, the National Institute of Astrobiology and donations to the Robert Rex Research Fund at the University of Tennessee, Knoxville. The study area is located near White Bay on Baffin Island and comprises two 1:50 000 scale National Topographic System map areas (NTS 38B/4 and 38B/5).


Abstract

Silicified microbial mats of the upper Mesoproterozoic Angmaat Formation on northern Baffin Island preserve exceptional microbial-mat fabrics and individual microfossils. A range of microbial morphologies is preserved in these samples, from well-preserved pristine microfossils to poorly preserved or unidentifiable microfossils. This paper presents a taphonomic assessment of microbial fabrics preserved within Angmaat Formation chert to determine their potential to preserve geochemical biosignatures. Specifically, the results of two different petrographic assessments are presented. The first assessment employed traditional point counting using a light microscope. The second used a digital-image mosaic of the thin section. The criteria used to distinguish the taphonomic state of individual microfossils were the same for both assessments.

The results of the two methods are compared and the positive and negative features of these different methodologies are discussed. A traditional point-counting method performed using light microscopy was time consuming, and variation within the thin section often prevented the collection of a large sample set in one sitting. The same point-counting method performed using high-resolution digital-image mosaics of petrographic thin sections permitted more rapid assessment of taphonomic state and allowed for the assessment of both meso-scale characterization of mat fabrics (i.e., the degree to which the mat has been compacted) and micro-scale characterization of mat components (i.e., the taphonomic state of individual microfossils). Traditional point counting was difficult to replicate and proved insufficient to obtain the required microfossil count, whereas digital point counting provided greater ability to assess the taphonomic character of mat elements. Both point-counting techniques, however, were unable to accurately describe the meso-scale complexity of the preserved microbial mats.

Résumé

Des mattes microbiennes silicifiées trouvées dans la partie supérieure de la Formation d’Angmaat au nord de l’île de Baffin conservent des fabriques et des microfossiles individuels d’une qualité exceptionnelle. Une gamme de morphologies microbiennes a été conservée dans ces échantillons, qu’il s’agisse de microfossiles ayant conservé leur état originel ou de microfossiles non identifiables très mal conservés. Cet article présente une évaluation taphonomique des fabriques microbiennes conservées dans le chert de la Formation d’Angmaat et cherche à établir à quel point elles sont susceptibles d’avoir conservé des biosignatures géochimiques. Le rapport porte plus précisément sur les résultats provenant de deux...
Introduction

Proterozoic shallow-water carbonate strata commonly contain early diagenetic chert deposits that show exceptional preservation of microbial morphologies (Schopf, 1968, 1975; Hofmann, 1976; Nyberg and Schopf, 1984; Knoll, 1985). Coccoidal and filamentous microfossils in chert of the Angmaat Formation, Bylot Supergroup have been documented by Hofmann and Jackson (1991), Kah and Knoll (1996) and Knoll et al. (2013). Other studies have investigated the geochemical setting (Kah et al., 1999; Kah, 2000; Kah et al., 2001; Manning-Berg and Kah, 2017) and sedimentological setting (Iannelli, 1992; Narbonne and James, 1996; Kah, 1997; Sherman et al., 2001, 2002; Sherlock et al., 2004; Turner, 2004, 2009, 2011; Turner and Kamber, 2012; Hahn et al., 2015) of carbonate strata of the Bylot Supergroup. Distinctive microfabrics and microbial assemblages in the Angmaat Formation carbonate have been previously described (Hofmann and Jackson, 1991; Kah and Knoll, 1996; Knoll et al., 2013) and correlated with environments of deposition (Kah and Knoll, 1996; Knoll et al., 2013). Mat-building and mat-dwelling microfossil assemblages within the Angmaat Formation include coccoidal cyanobacteria and filamentous cyanobacteria. Coccoidal mats are commonly associated with shallow seawater precipitates, whereas filamentous cyanobacteria are associated with tufted and laminated mats (Knoll et al., 2013). Although a range of microbial morphologies is preserved in silicified deposits of the Angmaat Formation (Knoll et al., 2013), a taphonomic assessment has not been performed on these samples. In order to describe the taphonomic range of preserved microfossils, two distinct methods of taphonomic analysis and assessment are explored in this paper.

Geological background

Bylot Supergroup

The Bylot Supergroup is exposed within the fault-bounded Borden Basin of northern Baffin and Bylot islands, and contains approximately 6000 m of unmetamorphosed sedimentary rock (Jackson and Iannelli, 1981; Kah, 1997; Kah et al., 1999; Turner, 2009). Three stratigraphic groups, the Eqalulik Group, the Uluksan Group and the Nunatsiaq Group (Figure 1), record overall basin development. Initial rifting of the basin is recorded by tholeiitic-basalt flows and sandstone of the Nauyat Formation that overlie Archean basement (Jackson and Iannelli, 1981). Basalt of the Nauyat Formation is putatively associated with the McKenzie large igneous province, based on paleomagnetic correlation (Fahrig et al., 1981; LeCheminant and Heaman, 1989), and constrains the Bylot Supergroup to an age younger than 1270 ± 4 Ma (LeCheminant and Heaman, 1989). Fluvial to shallow-marine sandstone of the Adams Sound Formation overlies the Nauyat Formation and indicates the onset of shallow-marine deposition (Jackson and Iannelli 1981). Deposition of the Arctic Bay Formation shale stratigraphically above the Adams Sound Formation has been interpreted as marine (Turner and Kamber, 2012), restricted marine (Gibson et al., 2018) and lacustrine (Hahn et al., 2015).

Shallow-marine carbonate deposition characterizes the Uluksan Group in the southeastern portion of the basin, where the Angmaat Formation is represented by chert-rich, peritidal carbonate deposits that replace evaporite-rich and terrigenous deposits of the underlying Iqqittuq Formation. In the western portion of the basin, the Nanisivik Formation consists of a thinly bedded, laminated carbonate (Turner, 2009). The upper Uluksan Group, stratigraphically overly-
Figure 1. A) Location of the study area near White Bay on northern Baffin Island is highlighted by the dashed red outline. B) Geology of the study area (modified from Kah et al., 1999); black squares are the localities where samples were collected during the 2017 trip to Baffin Island. C) Stratigraphic column of the Bylot Supergroup (modified from Gibson et al., 2018). Legend is for part (B). Abbreviations: EQA., Eqaluliq Group; NUN., Nunatsiaq Group.
ing the Angmaat and Nanisivik formations, is represented by storm-dominated carbonate-ramp (Sherman et al., 2001) and offshore-reef (Narbonne and James, 1996) deposits of the Victor Bay Formation. These deposits record evidence of tectonic reactivation of the Borden Basin (Sherman et al., 2002), leading to thick, lithologically variable sandstone and carbonate deposits of the Nunatsiaq Group.

Gibson et al. (2018) dated shale of the Arctic Bay Formation (upper Eqalulik Group) and the lower Victor Bay Formation (upper Uluksan Group) at 1.048 ± 0.012 Ga and 1.046 ± 0.016 Ga, respectively, which constrains the age of the Uluksan Group carbonate strata to the latest Mesoproterozoic Era. Dykes that crosscut the entire Bylot Supergroup have been dated at ca. 723 Ma and are related to the Franklin igneous event (Pehrsson and Buchan, 1999), which suggests that deposition of upper Bylot Supergroup strata ended sometime before this.

**Angmaat Formation chert**

The Angmaat Formation consists of peritidal microbial carbonate and precipitate-dominated carbonate strata that are separated from the main basin by an oolitic shoal (Kah, 1997; Turner, 2009). Periodic subaerial exposure of the oolitic shoal resulted in restriction and evaporation of associated nearshore environments (Kah, 1997). These deposits are dominated by microbial dolostones, sea-floor precipitates (Kah and Knoll, 1996; Kah et al., 2001) and abundant early diagenetic chert (Knoll et al., 2013; Manning-Berg and Kah, 2017). Deposits of black chert occur as centimetre-scale irregular lenses and nodules and as semicontinuous beds up to 10 cm in thickness. Chert occurs throughout the formation and preserves the morphology of primary sedimentary textures, including both microbial laminae and primary mineral deposits, such as aragonitic sea-floor cements (Figure 2B; Jackson and Iannelli, 1981; Kah and Knoll, 1996; Manning-Berg and Kah, 2017). These chert deposits are interpreted to have formed during early diagenesis, based on ubiquitous microfossil preservation (Hofmann and Jackson, 1991; Kah and Knoll, 1996; Knoll et al., 2013). By contrast, yellow to grey chert occurs as concentrically laminated nodules that crosscut bedding; yellow and grey chert has not been reported to preserve microfossils.

Microbial-mat communities of the Angmaat chert are preserved across a range of peritidal environments: subaqueous subtidal environments and lower intertidal environments are dominated by filamentous communities and more commonly exposed intertidal to supratidal environments record more abundant coccoidal communities and low-diversity filamentous communities (Kah and Knoll 1996; Knoll et al., 2013). Filamentous communities are characterized by the ubiquitous presence of microbial sheaths that show a variety of populations. Smaller sheaths (6–12 µm) are interpreted as representative of Lyngbya- or Phormidium-type cyanobacteria and classified as *Siphonophycus* sp. (Hofmann and Jackson, 1991; Kah and Knoll, 1996; Kah et al., 1999). Larger sheaths (20–50 µm) are classified as belonging to *Eomicrocoleus* sp. (cf. Hordyks and Donaldson, 1980) and interpreted to be analogous to the extant cyanobacterium *Microcoleus chthonoplastes* (Knoll et al., 2013). The dominant populations of coccoidal organisms include a Gloeocapsid-like cyanobacterium assigned to *Eogloeocapsa* sp., which consists of multiple coccoids floating within a single external envelope; and simple, undefined coccoidal populations assigned to *Myxococcales* sp. (Knoll et al., 2013). Populations of *Eoentophysalis* sp., *Gloeodiniopsis* sp. and *Polybessurus* sp. are also preserved in these microbial mats (Knoll et al., 2013). The eukaryotic red alga *Bangiomorpha pubescens* (Butterfield, 2000) also occurs in several samples (Knoll et al., 2013).

**Methods**

**Sample collection**

The samples used in this research were collected during multiple field seasons. The first set of samples was collected during the field season of 1993 and 1994. Taphonomic analyses were performed on these samples, followed by the geochemical analysis of preserved organic matter. Initial material was found to be insufficient in mass for geochemical analyses, so additional samples were collected in 2017. Both sample sets were collected from carbonate strata exposed between White Bay and Tay Sound (Figure 1).

**Taphonomic assessment**

Descriptive categories for taphonomic schemes are based on systematic observations of material: categories are determined so as to ensure that data are reproducible, despite their inherent qualitative nature (Behrensmeyer, 1978; Bartley, 1996). The classification scheme created to assess the microfossils in the Angmaat Formation is modified from a microbial grading scale developed by Bartley (1996), which was created to describe changes to modern cyanobacteria during actualistic taphonomy experiments. To sufficiently describe the preserved microbial mats of the Angmaat Formation samples, taphonomic grading schemes were applied at both the meso scale, which characterizes taphonomy on the scale of a thin section and represents the overall preservation of the microbial mat, and the micro scale, which classifies the taphonomy of individual microfossils.

Prominent taphonomic changes at the meso scale involve a loss of structure that results from compaction of the microbial mat. Meso-scale fabrics were classified as ‘good’, ‘fair’ or ‘poor’, based on visual inspection of the thin sec-
tions (Figure 3). Thin sections classified as ‘good’ contained individual microfossils that were readily visible with only quick visual inspection. These samples also commonly contained irregularities in lamina thickness that are attributed to differential growth within the microbial mat, and frequently contained chalcedony-lined voids that represent primary constructional voids (cf. Knoll et al., 2013) within the microbial mat. By contrast, most of the microfossils observed in meso-scale fabrics defined as ‘fair’ were concentrated in specific laminae. ‘Fair’ fabrics commonly contained variously pigmented laminae, representing differential compaction and organic content. With compaction, laminae were generally smooth. Finally, meso-scale fabrics defined as ‘poor’ were typified by an absence of rapidly identifiable microfossils, highly compacted laminae and homogenization of organic matter. Such samples were often so strongly pigmented that they appeared nearly opaque in thin section, and fabrics were referred to as ‘unrecognizable’.

For individual microfossils, taphonomic grading describes both filamentous sheaths and coccoidal microfossils. Microfossils that exhibited pristine sheath preservation with no compaction were given a taphonomic grade of ‘good’. Filamentous sheaths classified as ‘good’ had morphologies that did not show evidence of tearing, bulging or compaction. Coccoidal microfossils classified as ‘good’ commonly preserved an outer sheath, with a rounded cell wall preserved within the sheath (Figure 4). A grade of ‘fair’ was given to microfossils that showed initial signs of compaction or preferential loss of pigmentation. Commonly, these fossils had collapsed or folded sheaths that included tearing or bulging. In coccoidal organisms, a grade of ‘fair’ was also indicated by collapse of the cell wall inside the outer sheath (Figure 4). Finally, a grade of ‘poor’ was given to microfossils that had been heavily distorted by compaction or had lost the morphology of the sheath, and to fossils in which the organic matter was homogenized and unrecognizable. Although it is possible to identify a broader range of taphonomic variation, this three-category grading scheme allows an entire sample to be characterized and can be visualized on a ternary diagram (Kowalewski et al., 1995).

Figure 2. Black chert deposits occur throughout the Angmaat Formation within carbonate facies. These deposits tend to follow primary sedimentary textures and bedding as continuous chert beds (A, B) and chert lenses (C) or nodules (D).
Taphonomic methods

Taphonomic assessment of microfossiliferous chert was undertaken using traditional microscopy and the analysis of image mosaics. When using standard microscopy, traditional point-counting techniques were used to score individual microfossils. Thin sections were moved on the microscope stage in 2 mm increments from right to left and from top to bottom of the thin section. At each step, microfossils observed under the ocular crosshairs were scored as ‘good’, ‘fair’ or ‘poor’, and added to the overall count. The goal was to count and classify 600 microfossils for each thin section.

To address the difficulties experienced during traditional point counting, a method of taphonomic assessment was developed that used image mosaics. Image mosaics were taken on a Leica DFC400™ camera attached to a Leica DM6000B™ microscope in the Astrobiogeochemistry Laboratory (abcLab) at NASA’s Jet Propulsion Laboratory. For each thin section, 3000–4000 individual images were taken using a 20× objective. Prior to image acquisition, the borders of each thin section were delineated in the software and predictive focus points were set up across the thin section. White balance was set using a frosted glass slide. Image acquisition was performed by Leica Acquisition Software™ and images were stitched using the same software. An example of one of these image mosaics has been uploaded to the GigaPan website for public viewing (Angmaat Formation microbial mat mosaic; Williford, 2015). Such mosaics allow the user to view a thin section from a mesoscopic view (e.g., the entire thin section), which allows for visualization of the relative amounts of silica and carbonate phases, the colour and opacity of mat components, and the identification of general lamina structure and constructional voids. The same mosaic also allows users to rapidly zoom to specific regions to identify whether laminae characteristics reflect a fundamental difference in the composition or preservation of the mat components. For this study, image mosaics were manipulated within Adobe Photoshop™ to provide a reproducible method of taphonomic evaluation.

Analyses using mosaics

Once image mosaics were created, a 60 × 60 grid was overlain on the mosaic in Photoshop™. Microfossils were only counted toward the assessment if they were located directly beneath the intersection of two gridlines, which acted as a proxy for ocular crosshairs. As with the assessment done using light microscopy, the goal was to classify approximately 600 microfossils for each image.

Preliminary results

Results comparing the two point-counting methods on a single sample are presented here. The results of this com-
A larger number of microfossils could be counted on the mosaic (n = 400) compared to the thin section (n = 300). In this analysis, 7% of the microfossils counted and scored using the microscopy method were classified as ‘good’, while 25% and 68% were classified as ‘fair’ and ‘poor’, respectively. These percentages were close to those obtained using a point-counting method on an image mosaic of the same sample, in which 3% of the fossils were characterized as ‘good’, 28% were classified as ‘fair’, and 69% were classified as ‘poor’. These data indicate that the point-counting methods are repeatable and can be translated to image mosaics, although it is postulated that such methods are insufficient to address spatial variability within a preserved mat.

### Discussion

Several deficiencies were identified using the traditional point-counting method on the light microscope. First, this method was time consuming and it was often difficult to obtain the requisite 600 counts in one sitting. Identification of a single microfossil under the ocular crosshairs often required adjustment of the focal plane, making it difficult to maintain a uniform focal plane through the investigation. Finally, it was unclear whether a traditional point-counting method accurately produced a representative picture of the overall mat fabric. Local variation within the microbial mat, such as the spatial variability of mat constituents (e.g., regions of coccoids within a dominantly filamentous mat) or variable preservation of different mat constituents, may not be recognized with traditional point counting.

The creation of high-resolution digital images of petrographic thin sections of Angmaat Formation chert samples allowed for a taphonomic assessment to also be performed digitally, and for a comparison of the two methods. These images allow for meso-scale characterization of mat fabrics (i.e., the degree to which the mat has been compacted) and micro-scale details about the mats, such as the taphonomic

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
<th>Filamentous example</th>
<th>Coccoidal example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>• No compaction</td>
<td><img src="image1.png" alt="Filamentous example" /></td>
<td><img src="image2.png" alt="Coccoidal example" /></td>
</tr>
<tr>
<td></td>
<td>• Pristine sheath/cell wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Morphological details of sheath</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fair</td>
<td>• Little compaction</td>
<td><img src="image3.png" alt="Filamentous example" /></td>
<td><img src="image4.png" alt="Coccoidal example" /></td>
</tr>
<tr>
<td></td>
<td>• Initial collapse of sheath/cell wall</td>
<td></td>
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<tr>
<td></td>
<td>• Tearing/folding of sheath/cell wall</td>
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<tr>
<td>Poor</td>
<td>• Compactional distortion</td>
<td><img src="image5.png" alt="Filamentous example" /></td>
<td><img src="image6.png" alt="Coccoidal example" /></td>
</tr>
<tr>
<td></td>
<td>• Loss of sheath/cell wall morphology</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Homogenization of organic matter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unrecognizable</td>
<td>• Homogenized organic matter</td>
<td><img src="image7.png" alt="Filamentous example" /></td>
<td><img src="image8.png" alt="Coccoidal example" /></td>
</tr>
<tr>
<td></td>
<td>• Cannot distinguish microfossil morphology</td>
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</tbody>
</table>

**Figure 4.** Descriptions of the taphonomic grades used for the Angmaat Formation samples during this assessment and examples of ‘good’, ‘fair’ and ‘poor’ microfossils, as well as the homogenized material labelled as ‘unrecognizable’.

**Figure 5.** Ternary plot of the initial results from a taphonomic assessment of a sample by point counting and classification of 300 microfossils using traditional thin-section microscopy (circle) and 400 microfossils using a digital grid overlaid on a mosaic of the thin section (square). The results from both methods plot as ‘fair’, suggesting that the mat has fair preservation of the microfossils.
state of individual microfossils. Mosaics allow for rapid assessment of both meso- and micro-scale taphonomic variation of the microbial mats. Observed differences are used to relate the preserved taphonomic range of individual microfossils to the taphonomic range of mat fabrics. There were, however, challenges associated with the use of image mosaics for taphonomic assessment, including image size, pixilation and blurry areas on the image resulting from intuitive focus.

Each of the mosaic files is about 2 GB, making it difficult to find image-processing software that would open the files. Photoshop® and GIMP were the only programs that were able to open the files without loss of resolution or without first partitioning the images. Other difficulties were inherent to the image, including pixilation upon increasing magnification to see nano-scale features and areas on the mosaic that were out of focus when the Leica software created the image. Counting and assessing microfossils on the mosaics did not fully address the deficiencies identified with the point-counting method using a microscope. Counting microfossils was faster with the mosaics, but it was still difficult to obtain the 600-microfossil count in one sitting because the overlain grid did not have enough intersection points and there was no way to add intersection points to the grid if the target of 600 microfossils had not been reached. Since the mosaics are static, the entire analysis was done in the same focal plane; thus, not all of the mosaic was perfectly in focus. As a result, identifying microfossils or observing the entire microfossil for ultra-structural changes was difficult. When using a microscope, changing the focal plane allows the user to move through the three-dimensionally preserved microfossil to see the morphology of the entire fossil. Using a static image meant that microfossils could not be observed in their entirety.

Neither point-counting method was able to accurately describe the variation within the microbial mats because they are complex ecosystems in life, and that complexity is retained during preservation of the silicified mats of the Angmaat Formation. Preserved mat fabrics are created by filamentous sheaths that are interwoven and range in size, preservation potential and colour. Some of the filaments were darkened and thus were much easier to see, whereas much of the mat is composed of smaller, thin filamentous sheaths that fade to transparent and cannot be counted. Finally, nanometre-scale black dots that occur clustered around sheaths and organic matter stains are interpreted as preserved heterotrophic organisms. These organisms are also difficult to count. Although these challenges are inherent to the microbial mats and not specific to the method used to assess the taphonomy of the microfossils, they must be overcome in order to best qualify the range of preservation observed in the Angmaat Formation microbial mats.

Economic considerations

The carbonate strata of the deeper water facies equivalent to the Angmaat Formation in the northwestern Borden Basin, the Nanisivik Formation, contains Mississippi Valley-type (MVT) mineral deposits (Clayton, 1982; Olson, 1984). These deposits have been dated to ca. 1.1 Ga (Hnatyshin et al., 2016) and are found across the Borden Basin (Turner, 2011), but they are constrained to brittle faults, fractures or dykes (Olson, 1984). Carbonate strata of the Angmaat Formation near White Bay do not contain MVT deposits (Turner, 2011). The only mineral deposits identified in the area are within the Iqqitulq Formation, which is stratigraphically lower than the Angmaat Formation (Turner, 2011) and was not observed in any of the strata studied or collected during this project. Although the research completed so far has focused on organic rather than inorganic geochemistry, petrography of the thin sections showed no evidence of the Zn, Pb, Ag and Cu minerals that are associated with MVT deposits.

Conclusions

A traditional point-counting method, using both light microscopy and image mosaics, was used to conduct a taphonomic assessment of the microfossils preserved in the silicified microbial mats of the Angmaat Formation. Both methods produced similar results. For each category, the results were within 2–3% of each other. Use of image mosaics can address some of the deficiencies identified when using a microscope to perform the assessment, including a shorter time investment, the ability to rapidly change scales between the meso and micro, and a static image that allows for the analysis to be performed on a uniform focal plane. However, neither point-counting method was able to accurately describe the variation within the microbial mats. The results presented here were subsequently used to create a taphonomic-assessment method that better describes the spatial complexity within preserved microbial mats. This new taphonomic-assessment method is applicable to other microbial-mat studies involving description of taphonomic variations within a microbial mat. This improved method is described in the senior author’s dissertation (Manning-Berg, 2018) and the results of that assessment are being prepared for publication (A.R. Manning-Berg et al., work in progress).

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References


Narbonne, G.M. and James, N.P. 1996: Mesoproterozoic deep-water reefs from Borden Peninsula, Arctic Canada; Sedimentology, v. 43, no. 5, p. 827–848.


Sherlock, R.L., Lee, J.K.W. and Cousens, B.L. 2004: Geologic and geochronologic constraints on the timing of mineralization at the Nanisivik zinc-lead Mississippi Valley-type deposit,


Williford, K.H. 2015: DOW2 20xt oil 2x red; GigaPan Systems, URL <http://gigapan.com/gigapans/52663df35ba3943cb7110452f8ebbce0> [November 2018].