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Delft Meteorite Lab: a virtual environment to explore meteorites and meteorWrongs

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Assessing and classifying rocks on the basis of their visual traits has been a long standing practise for geoscience fields. For planetary geoscience the interaction with astrogeological materials such as meteorites and impactites contributes to the comprehension of their properties, alteration and, ultimately, solar system formation processes. In the wake of the SARS-CoV-2 (COVID-19) pandemic we explored alternative options to involve meteorites and impactites in remote teaching. Simultaneously, this opened up the integration of meteorites in teaching activities for large groups of learners. We have developed a workflow using Structure from Motion (SfM) photogrammetry to render high-resolution digital 3D models of meteorites and impact rocks. This procedure was used to create a virtual collection with tens of examples that were made publicly accessible in an online environment. The digital 3D models can be inspected by rotating and zooming, while annotations in clickable pop-ups direct users to key features or provide background information and data. We evaluated the user experience and discuss how virtual collections can be created and used for blended learning. Meanwhile, we have explored the use of models in the 'Delft Meteorite Lab' in academic teaching, public outreach and science applications. The virtual collection also offers a potential resource to aid the identification of putative meteorite finds by the general public. Looking towards the future, a new 'Dutch Meteorite Lab' aims become a national hub for education and research to explore meteorites and meteorite taxonomy based on specimen available in various study collections across the Netherlands.

1 Introduction

Evaluating the visual traits of rocks and minerals is a common approach in the field of geology to classify rocks. A common teaching practise to acquire these basic skills in geology is through the use of hand specimen. Similarly, we can use meteorites and analogue materials to familiarize ourselves with first-order properties of solar system materials, which can potentially offer an important formative learning experience for both students and experienced researchers. The main challenge with using meteorites is their preservation and handling due their vulnerability and heritage value. Prompted by the shift to remote learning formats during the SARS-CoV-2 (COVID-19) pandemic we started to explore an online format for a teaching activity with meteorites that takes consideration of the aforementioned aspects. This resulted in the creation of a virtual teaching collection of high-fidelity 3D models: the *Delft Meteorite Lab*. Our working premise is that we perceive and recognise features by moving, rotating and tilting of an object. This means that object motion of a digital 3D model on a screen can provide similar cues and information as that of a real-world object. In this light, digital 3D models can also convey more information than digital still photography. This suggests that it will be easier using 3D models to convey and point out key properties that helps users when assessing objects, than based on 2D imagery. With these concepts in mind, this paper will explored how digital 3D models can offer a rich source of information in a variety of user cases.

2 Prelude to a virtual collection

The creation of the Delft Meteorite Lab finds its origin in the events following the theft of the Serooskerke fragment of the Ellemeet diogenite meteorite in 2014 and its subsequent retrieval (de Vet, 2015). As only few pictures existed at the time of the meteorite, often from a similar viewpoint due to its exhibition years before, it raised the question about how Dutch meteorites were documented. A digital preservation project was started by the author to create 'digital twins' of the known Dutch meteorites. What started as an amateur initiative has now evolved into a novel virtual meteorite collection of 3D models embedded in an academic framework for research and education. The current workflow evolved based on practical experience gained over several years of method exploration (de Vet, 2016) and has contributed to identifying new applications (Aduru & de Vet, *this issue*; Veithen & de Vet; *this issue*). Here I will describe the experiences with creating 3D models and applications in science, education and outreach.

3 Photogrammetry and online collection

We used a workflow based Structure from Motion (SfM) photogrammetry using the software Agisoft Metashape Professional (v1.6.5 and later) to render high-resolution digital 3D models of meteorites and meteorWrongs (Figure 1). This procedure was used to compile a virtual

Figure 1 – Overview of the workflow to create a virtual meteorite collection. (a) The Broek in Waterland (L6) meteorite in its current state after imaging and sampling. (b) The digital twin of the meteorite rendered as a 3D model. (c) Hosting in online environment, here Sketchfab.com, to allow users to inspect and rotate the model or access annotations with more information. The collection can be shared and accessed via the convenient short link www.DelftMeteoriteLab.nl.

collection for the Delft Meteorite Lab, where the digital models are made accessible in an online environment. The virtual collection is hosted online via SketchFab[1], following the approach by (Andrews et al., 2020) and others. Models are divided into sub-collections that include meteorites, meteorWrongs (objects sharing some resemblance to meteorites, but either of terrestrial or anthropogenic origins), impact rocks and an unlabeled teaching collection. These interactive models can be viewed from all directions, with annotations in clickable pop-ups providing additional information. This approach is analogous to the role of a teacher during a rock practicum, directing users to key features or relevant backstories. Readers are referred to the forthcoming article by de Vet & Cazaux (*forthcoming*) for more technical details on the 3D workflow.

4 Examples of applications

Education

The 3D models in our collection are used to familiarise novice learners with basic properties of meteorites that they can relate to specific processes, such as fusion crusts from ablation during atmospheric entry, compositional differences between differentiated and undifferentiated parent bodies, and processes atypical for common meteorite materials (e.g., vesicles, melts, slags etc.). We also created a guided activity where students follow the basic workflow of (Guedes et al., 2010). Several objects are assessed with some of them being meteorites and other being meteorWrongs. For the 2022 and 2023 cohorts in our BSc (n=92) and MSc (n=270) courses on planetary science we found that the large majority was able to classify the various objects correctly. Readers are referred to the research article by de Vet & Cazaux (*forthcoming*) for more details and evaluation of the educational applications.

Research

The ability of 3D models to capture the morphometry of an object also fosters new applications to quantify physical properties and various applications come tome mind. In (Langbroek et al., 2019) we used a 3D model to find the volume of the Diepenveen meteorite, and subsequently its density of 2.12 gcm3. Non-destructive quantification of physical properties can help study and classify meteorites as noted by (de Vet, 2016) and explored in more detail by (Harvey et al., 2023). (El-Naghy, 2021) proposed using point clouds of 3D models to match and pair meteorite fragments. We are currently using the Broek in Waterland (L6) meteorite (Langbroek & Kriegsman, 2019) as a case study to explore new applications of 3D models in meteoritics. Aduru & de Vet (*this issue*), discuss the use of 3D printed models in wind tunnel studies to determine aerodynamic properties during dark flight. Veithen & de Vet (*this issue*), highlight a novel approach to determine properties of regmaglypts to explore a framework for

[1] www.delftmeteoritelab.nl

Figure 2 – Screen grab of the online lecture by the author for the *Universiteit van Nederland*, a popular outreach medium with professionally created online lectures by scientists from Dutch universities. Shown here are animated models of the Diepenveen (CM2-an, just outside the field of view), Broek in Waterland (L6) and Ellemeet (DIO) meteorites. *Credit: Universiteit van Nederland.*

testing if the fracture surfaces were formed during the same fragmentation event during the luminous phase. While these applications for 3D models are still in an exploratory stage, they show interesting potential for various user cases.

Outreach

The availability of 3D models has inspired new formats for science outreach activities. During the past years, the use of 3D models in several outreach activities has been explored. During and online lecture for the popular '*Universiteit van Nederland*', for which scientists from Dutch universities give free lectures on the internet, we used the 3D models to animate several Dutch meteorites in a professional chroma key ('green screen') environment to help discuss properties of meteorites, their taxonomy and implications for planet formation (Figure 2). The online lecture has accumulated more than 14.085 views in 2 years. In addition to virtual renders, 3D models are also very suited to create hands-on, true-size models of meteorites akin to the test articles for the aforementioned wind tunnel studies. In collaboration with the Space Expo museum in Noordwijk, the Netherlands we created 3D prints of the *Utrecht* ('Loevenhoutje' fragment) and *Broek in Waterland* meteorites for their 'Mysterious meteorites & cooking comets' science shows. Over two weeks' time during the 2022 Christmas holiday some 10,172 visitors attend these shows and learned more about these meteorites. The use of 3D printing is perhaps the easiest way to disseminate 3D models for various hands-on outreach applications. On 27 October 2023 a special celebration was observed for the 150-year anniversary of the *Diepenveen* meteorite fall, which coincided with several other anniversaries in the Diepenveen community in 2023. To mark the occasion, a 6:1 scaled model was created for a monument based on the 3D model of Diepenveen and revealed on the day of the impact anniversary in the town's centre.

5 Future outlook

The use of 3D models to help make meteorite collections accessible to a broader audience has not gone unnoticed. In addition to coverage in local and national media, new collaborations have also been set-up. One of them is with Utrecht University's graduate school of Geosciences to help create the 'Utrecht Meteorite Lab' based on their meteorite collection, which is managed by Prof. I. L. ten Kate[2]. The next step that we consider will be the creation of the 'Dutch Meteorite Lab' that aims to make knowledge of meteorite collections more accessible to researchers active in various planetary science networks in the Netherlands, and the public at large. It too will be set-up as a virtual collection and the included models will collectively cover the meteorite taxonomy as complete as possible. A stratified data approach will help researchers explore the rich insights that these meteorites collectively have to offer, by linking to various the other data formats and measurement types. It will build upon the experiences that we are currently gaining with the Delft Meteorite Lab (photogrammetry workflow development, educational applications) and the Utrecht Meteorite Lab (linking to data from various material characterisation methods) and it aspires to become a national hub to explore meteorites in study collections found across the Netherlands.

6 Conclusions

The use of 3D scanning methods enables the rendering of photo-realistic models of meteorites and meteorWrongs. These 'digital twins' can be used for a variety of educational purposes, outreach and even in science applications. By bringing 3D models together as a collection in a web-based environment allowed various educational and scientific users to interact with them in one central location. In doing so, this digital approach to collection management increases the accessibility of collections and support the scientific storytelling of astrogeological science heritage through a variety of outreach formats. Future developments of the virtual collection concept, diversification of the collection to cover the meteorite taxonomy and exploration of scientific applications will further help increase the scientific and societal impact of this concept.

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