Rock Mechanics and Rock Engineering

Digital 3D Rocks: a collaborative benchmark for learning rocks recognition

--Manuscript Draft--

Manuscript Number:	RMRE-D-18-01065R1
Full Title:	Digital 3D Rocks: a collaborative benchmark for learning rocks recognition
Article Type:	Technical Note
Keywords:	Geology; Remote Sensing; Computer Graphics
Corresponding Author:	Adrian Riquelme, Ph.D. University of Alicante Alicante, SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Alicante
Corresponding Author's Secondary Institution:	
First Author:	Adrian Riquelme, Ph.D.
First Author Secondary Information:	
Order of Authors:	Adrian Riquelme, Ph.D.
	Miguel Cano, Professor
	Roberto Tomás, Full Professor
	Luis Jordá
	José Luis Pastor, Assistant Professor
	David Benavente, Professor
Order of Authors Secondary Information:	
Funding Information:	Consejo Superior de Investigaciones Científicas (TIN2014-55413-C2-2-P) — Dr. Adrian Riquelme
	Consejo Superior de Investigaciones Científicas (TEC2017-85244-C2-1-P) — Dr. Adrian Riquelme
Abstract:	Naked eye rock recognition is an essential activity for professionals and students of geosciences, architecture and engineering. Through a hand holding rock specimen, they usually require not only to identify the rock but to recognise their texture and understand its expected properties mechanical and petrophysical properties. Although a wide choice of books, websites and apps are available in the literature and on the Internet, their contents are two-dimensional (2D) and static. Nowadays, the application of remote sensing techniques such as Light Detection and Ranging (LiDAR) or Structure from Motion (SfM) enable the generation of three-dimensional (3D) interactive models, which are here presented as a novel perspective of learning and practising rocks recognition. Despite limitations of the technique, 3D digital models of rocks permit their virtual visualisation and manipulation to reveal parts of the specimens that are hidden in the 2D photograph, and details of the rock specimen's texture such as grain and minerals size, distribution and organisation along with the possibility of identifying petrological features, foliation, mineral orientations and others. This provides a novel perspective of learning and practising rocks identification. A benchmark of digital rocks collected all around the world and generated using SfM technique is presented. The rocks are organised using a straightforward classification system based on the texture jointly with a detailed description to aid the specimen recognition. A behavioural geomechanical classification is then applied. A linked data sheet shows the engineering classification, the weathering degree, the guide physical and mechanical properties (general, and specific when available), the engineering

uses and others. The information is organised on an open-access website hosted by the University of Alicante (https://web.ua.es/digitalrocks). This initiative also aims to encourage students and professionals to generate their own models and to provide the description to enlarge the repository.

Response to Reviewers:

1Reviewer #1

Q1: The virtual hand samples are interesting to view online, and the 3D images generally provide a better non-contact impression of hand specimen characteristics, as compared to traditional 2D images. However, 2D GigaPan based imagery of hand specimens provide unparalled resolution and perspective, and perhaps this would be good to mention and make a comparison to.

R1: This type of photos is quite interesting, and we will be glad to use the SfM technique with such data when available. However, since we had to reduce the manuscript to adapt to the technical note requirements, we could not include a detailed discussion and comparison with these images. According to the reviewer's suggestion, we have included several references to GigaPan images:

L34: "Those 2D resources cover a wide range such as high-quality photos captured using GigaPan mediums (Benton 2014)."

L48: "Gigapixel images have also been used for 3D reconstruction (Lato et al. 2012; Lee et al. 2017)."

Q2: The online image quality is quite variable, and in several cases, the images become blurry as the viewer zooms in (obscuring important textural and mineralogical details).

R2: The Reviewer is right. Images become blurry when zooming in because of the (1) texture reconstruction process and (2) the photo resolution. For instance, quality will be always different when using a professional camera or using a smartphone. However, we tried that the generated models have enough quality to enable the rock recognition. From the first submission, we have generated various additional rock specimens. Please, for example check this calcarenite model (https://bit.ly/2DY20El) and its quality observing a small fossil of coral (note that the size of the letter of the reference target is approximately 5 mm, Figure 1).

Q3: Most of the online samples are simply images and no additional relevant information (including geomechanical parameters) is provided. Simply having a collection of 3D images is not considered very useful.

R: We described all the rocks to train students in rock identification. We included additional information (the data sheet) of previous rocks when available, and systematically for all new rocks. Furthermore, some specific and relevant characteristics of the rock samples (e.g. mineral grains, fossils, stylolites, etc.) have been pointed out on the 3D samples to improve the interactive interpretation of the main characteristics of some rocks specimens.

Q4: When physical parameters are presented, some are pertinent to the specimen scale and others to the rock mass scale, but this is not very clear.

R4: All presented physical parameters are concerned to intact rock. However, we also included the weathering grade of the outcrop, since sometimes the values of the physical properties of the intact rock are lower than the general ranges due to this alteration. But in fact, you are right and to avoid misunderstandings we have changed the document in the file:

Weathering grade of sampling outcrop (ISRM,1981)

Q5: There is little discussion or justification for using the classification schemes adopted, and these schemes are not always consistent with how the online samples are catalogued and described.

R5: In the manuscript (L136-164) we refer to the most accepted classifications (i.e., Dunham (1962) and Streckeisen (2002)) for sedimentary and igneous rocks, respectively. These classifications consider the genesis of the clasts and the rock minerals. Since the origin and nature of the particles or the mineralogy of the sample cannot be extracted from the 3D sample, we employed a classification system based on the texture and organoleptic properties of the rock described in the book 'Earth Sciences' (2015). In the manuscript we included the following sentence (L140) to clarify this point: "This rock classification uses textural (e.g. size of the grains or foliation) and organoleptic (e.g. mafic rocks are darker than lighter) properties that students can perceive by the sense of sight."

Q6: The online portal is a work-in-progress and appears to be in a nascent phase.

R6: The Reviewer is right. Actually, the repository will always be a work-in-progress. Since we initially submitted this manuscript, we have included five additional samples. Besides, we are planning to include medium-scale rocky outcrops to enable the identification of lithologies. It is worth noting that this webpage intends to become a collaborative repository in which other researchers can share their models and rock information. Therefore, we look forward to an active participation of other researchers to grow, complete and improve this database when published.

Q7: The paper spends a disproportionate amount of time covering the SfM workflow, which is now so common that it might be referred to in passing.
R7: As Reviewer #2 points, we seem to be very excited with the application of this technique, but this section was over-represented. As the Editor suggested, we resubmit this work as a technical note, so we dramatically reduced the size of this manuscript. Precisely, the SfM workflow section has been significantly reduced.

Q8: The conclusions are very general and, in some cases, have to be accepted on faith, as some statements do not seem to be based on verifiable results (e.g. how is it known that these online 3D images are aiding in rock recognition...has there been an objective assessment/comparison of the ability of students to recognize different rocks?).
R8: Since we started this project, we have been testing these models with students of early courses of the Civil Engineering degree in the University of Alicante (Spain). This repository is a virtual rock laboratory that students can access whenever they want. Our students have been testing the repository. Their feedback shows high satisfaction degree. Moreover, we used these 3D models in our Geology lectures, showing them in the projector screens (Riquelme et al. 2016). We have checked that it is an excellent aid to explain, for instance, what is a conglomerate or a fossil: while the lecturer interacts with the model in the screen, the students can also load this 3D model in their laptops, tablets or smartphones. We are planning to perform further educational experiences with this information in other degrees.

Q9: This is an interesting contribution that focuses on qualitative aspects of hand specimen identification. The vision of having an extensive online database of high-resolution 3D images is commendable.
R9: We deeply appreciate the reviewer words. We strongly believe other Universities and Institutions all around the world will join this project.

2Reviewer #2
Q1: I was very excited upon reading this contribution. I guess something very useful for the rock mechanics and geology community, practically and educationally, may emerge. The paper describes the establishment of an online rock type repository including rock properties tables and 3D images of rock samples.
In general, the paper is well structured and readable.
R1: Thanks for your kind words. In this version, the reviewers will find new improvements and substantial modifications according to your suggestions.

Some minor recommendations:
Q2: Review the English text (or let it review) - there are some order of words issues.
R2: We have reviewed all the text and corrected it. Besides that, a native speaker (Mrs Sophie Krzesniak) has revised the text.

Q3: Reviewer thinks that the section about the application of the structure from motion method is overrepresented in the manuscript (it seems the authors are quite excited about the method as well). Nonetheless, the focus should be placed on the online repository rather than the use of structure from motion applications. I am quite sure the softwares come along with instructions how to use it. (The section takes 6 of 14 pages of pure text)
R3: We understand your concerns. According to your suggestion, we have significantly reduced the section regarding SfM method.

Q4: Maybe the authors consider it publishing it as a technical note rather than an original paper?
R4: According to Reviewer #2 and the Editor’s suggestion, we have reduced the text and the number of figures of the manuscript to resubmit it as a technical note. We

	appreciate your words and suggestions. References Benton J (2014) The ”magic” al growth of an online gigapan repository for geoscience education. In: 2014 GSA Annual Meeting in Vancouver, British Columbia Dunham RJ (1962) Classification of Carbonate Rocks According to Depositional Textures. In: Classification of Carbonate Rocks--A Symposium. pp 108–121 Lato MJ, Bevan G, Fergusson M (2012) Gigapixel imaging and photogrammetry: Development of a new long range remote imaging technique. Remote Sens 4:3006–3021 . doi: 10.3390/rs4103006 Lee H, Mostegel C, Fraundorfer F, Kieffer DS (2017) GigaPan Image-Based 3D Reconstruction for Engineering Geological Investigation Maitre RWL (2002) Igneous Rocks: a Classification and Glossary of Terms. Cambridge University Press Riquelme A, Cano M, Tomás R, Jordá L, Santamarta Cerezal J (2016) Petrología 3D. In: XIV Jornadas de Redes de Investigación en Docencia Universitaria. Investigación, innovación y enseñanza universitaria: enfoques pluridisciplinares. Vicerrectorado de Calidad e Innovación Educativa, Universidad de Alicante, Alicante, Spain, pp 799–812 Tarbuck E, Lutgens F (2015) Earth Science, 14th Edition, 14th edn. Pearson

Dear Editor,

We are very thankful for the consideration of the Editor as it gave us an opportunity to improve tremendously the quality of our manuscript. Despite required heavy edits on writing and structural modifications, we have significantly changed our manuscript respecting the positive comments of the reviewers in the first review round. Following the Editor requirement, a native English speaker checked and corrected the draft. Besides, we resubmitted the manuscript as a technical note following the Editor and Reviewer #2 suggestion. We summarised the changes in the following document and outlined in the word file.

We would like to thank the Editor and the Reviewers and express our sincere appreciation for the thorough revision made. It allowed us to improve the original version of our work. We hope that the modifications and corrections can satisfy the Editor and the Reviewers.

Yours sincerely,

Adrián Riquelme, PhD

Corresponding Author on behalf of all the co-authors.

1 Reviewer #1

Q1: The virtual hand samples are interesting to view online, and the 3D images generally provide a better non-contact impression of hand specimen characteristics, as compared to traditional 2D images. However, 2D GigaPan based imagery of hand specimens provide unparalled resolution and perspective, and perhaps this would be good to mention and make a comparison to.

R1: This type of photos is quite interesting, and we will be glad to use the SfM technique with such data when available. However, since we had to reduce the manuscript to adapt to the technical note requirements, we could not include a detailed discussion and comparison with these images. According to the reviewer's suggestion, we have included several references to GigaPan images:

L34: "Those 2D resources cover a wide range such as high-quality photos captured using GigaPan mediums (Benton 2014)."

L48: "Gigapixel images have also been used for 3D reconstruction (Lato et al. 2012; Lee et al. 2017)."

Q2: The online image quality is quite variable, and in several cases, the images become blurry as the viewer zooms in (obscuring important textural and mineralogical details).

R2: The Reviewer is right. Images become blurry when zooming in because of the (1) texture reconstruction process and (2) the photo resolution. For instance, quality will be always different when using a professional camera or using a smartphone. However, we tried that the generated models have enough quality to enable the rock recognition.

From the first submission, we have generated various additional rock specimens. Please, for example check this calcarenite model (https://bit.ly/2DY20El) and its quality observing a small fossil of coral (note that the size of the letter of the reference target is approximately 5 mm, Figure 1).

Q3: Most of the online samples are simply images and no additional relevant information (including geomechanical parameters) is provided. Simply having a collection of 3D images is not considered very useful.

R: We described all the rocks to train students in rock identification. We included additional information (the data sheet) of previous rocks when available, and systematically for all new rocks. Furthermore, some specific and relevant characteristics of the rock samples (e.g. mineral grains, fossils, stylolites, etc.) have been pointed out on the 3D samples to improve the interactive interpretation of the main characteristics of some rocks specimens.

Figure 1. Example of the level of detail of the reconstructed samples.

Q4: When physical parameters are presented, some are pertinent to the specimen scale and others to the rock mass scale, but this is not very clear.

R4: All presented physical parameters are concerned to intact rock. However, we also included the weathering grade of the outcrop, since sometimes the values of the physical properties of the intact rock are lower than the general ranges due to this alteration. But in fact, you are right and to avoid misunderstandings we have changed the document in the file:

Weathering grade of sampling outcrop (ISRM,1981)

Q5: There is little discussion or justification for using the classification schemes adopted, and these schemes are not always consistent with how the online samples are catalogued and described.

R5: In the manuscript (L136-164) we refer to the most accepted classifications (i.e., Dunham (1962) and Streckeisen (2002)) for sedimentary and igneous rocks, respectively. These classifications consider the genesis of the clasts and the rock minerals. Since the origin and nature of the particles or the mineralogy of the sample cannot be extracted from the 3D sample, we employed a classification system based on the texture and organoleptic properties of the rock described in the book 'Earth Sciences' (2015). In the manuscript we included the following sentence (L140) to clarify this point: "This rock classification uses textural (e.g. size of the grains or foliation) and organoleptic (e.g. mafic rocks are darker than lighter) properties that students can perceive by the sense of sight."

Q6: The online portal is a work-in-progress and appears to be in a nascent phase.

R6: The Reviewer is right. Actually, the repository will always be a work-in-progress. Since we initially submitted this manuscript, we have included five additional samples. Besides, we are planning to include medium-scale rocky outcrops to enable the identification of lithologies. It is worth noting that this webpage intends to become a collaborative repository in which other researchers can share their models and rock information. Therefore, we look forward to an active participation of other researchers to grow, complete and improve this database when published.

Q7: The paper spends a disproportionate amount of time covering the SfM workflow, which is now so common that it might be referred to in passing.

R7: As Reviewer #2 points, we seem to be very excited with the application of this technique, but this section was over-represented. As the Editor suggested, we resubmit this work as a technical note, so we dramatically reduced the size of this manuscript. Precisely, the SfM workflow section has been significantly reduced.

Q8: The conclusions are very general and, in some cases, have to be accepted on faith, as some statements do not seem to be based on verifiable results (e.g. how is it known that these online 3D images are aiding in rock recognition...has there been an objective assessment/comparison of the ability of students to recognize different rocks?).

R8: Since we started this project, we have been testing these models with students of early courses of the Civil Engineering degree in the University of Alicante (Spain). This repository is a virtual rock laboratory that students can access whenever they want. Our students have been testing the repository. Their feedback shows high satisfaction degree. Moreover, we used these 3D models in our Geology lectures, showing them in the projector screens (Riquelme et al. 2016). We have checked that it is an excellent aid to explain, for instance, what is a conglomerate or a fossil: while the lecturer interacts with the model in the screen, the students can also load this 3D model in their laptops, tablets or smartphones. We are planning to perform further educational experiences with this information in other degrees.

Q9: This is an interesting contribution that focuses on qualitative aspects of hand specimen identification. The vision of having an extensive online database of high-resolution 3D images is commendable.

R9: We deeply appreciate the reviewer words. We strongly believe other Universities and Institutions all around the world will join this project.

2 Reviewer #2

Q1: I was very excited upon reading this contribution. I guess something very useful for the rock mechanics and geology community, practically and educationally, may emerge. The paper describes the establishment of an online rock type repository including rock properties tables and 3D images of rock samples.

In general, the paper is well structured and readable.

R1: Thanks for your kind words. In this version, the reviewers will find new improvements and substantial modifications according to your suggestions.

Some minor recommendations:

Q2: Review the English text (or let it review) - there are some order of words issues.

R2: We have reviewed all the text and corrected it. Besides that, a native speaker (Mrs Sophie Krzesniak) has revised the text.

Q3: Reviewer thinks that the section about the application of the structure from motion method is overrepresented in the manuscript (it seems the authors are quite excited about the method as well). Nonetheless, the focus should be placed on the online repository rather than the use of structure from motion applications. I am quite sure the softwares come along with instructions how to use it. (The section takes 6 of 14 pages of pure text)

R3: We understand your concerns. According to your suggestion, we have significantly reduced the section regarding SfM method.

Q4: Maybe the authors consider it publishing it as a technical note rather than an original paper?

R4: According to Reviewer #2 and the Editor's suggestion, we have reduced the text and the number of figures of the manuscript to resubmit it as a technical note. We appreciate your words and suggestions.

References

Benton J (2014) The ”magic” al growth of an online gigapan repository for geoscience education. In: 2014 GSA Annual Meeting in Vancouver, British Columbia

Dunham RJ (1962) Classification of Carbonate Rocks According to Depositional Textures. In: Classification of Carbonate Rocks--A Symposium. pp 108–121

Lato MJ, Bevan G, Fergusson M (2012) Gigapixel imaging and photogrammetry: Development of a new long range remote imaging technique. Remote Sens 4:3006–3021 . doi: 10.3390/rs4103006

Lee H, Mostegel C, Fraundorfer F, Kieffer DS (2017) GigaPan Image-Based 3D Reconstruction for Engineering Geological Investigation

Maitre RWL (2002) Igneous Rocks : a Classification and Glossary of Terms. Cambridge University Press

Riquelme A, Cano M, Tomás R, Jordá L, Santamarta Cerezal J (2016) Petrología 3D. In: XIV Jornadas de Redes de Investigación en Docencia Universitaria. Investigación, innovación y enseñanza universitaria: enfoques pluridisciplinares. Vicerrectorado de Calidad e Innovación Educativa, Universidad de Alicante, Alicante, Spain, pp 799–812

Tarbuck E, Lutgens F (2015) Earth Science, 14th Edition, 14th edn. Pearson

Digital 3D Rocks: a collaborative benchmark for learning rocks recognition[1]

Adrián Riquelme [a*], Miguel Cano [a], Roberto Tomás [a], Luis Jordá [b], José Luis Pastor [a], David Benavente [c]

a Departamento de Ingeniería Civil, Universidad de Alicante. P.O. Box 99, E-03080 Alicante, Spain.

b Instituto Geológico y Minero de España, Calle de Ríos Rosas, 23, 28003 Madrid, Spain.

c Departamento de Ciencias de la Tierra y del Medio Ambiente, Universidad de Alicante, San Vicente del Raspeig, Spain.

*Corresponding author: Adrián Riquelme (ariquelme@ua.es), Phone: +34 96 590 3707

Keywords: Geology; Remote Sensing; Computer Graphics

Highlights

- A 3D interactive rocks open repository generated using SfM is presented.
- Rocks are organised using a classification system based on their texture.

[1] Dr Adrián Riquelme scanned most of the rocks, programmed the website and wrote and supervised the manuscript. Dr Roberto Tomás described part of the rock specimens, wrote and revised the manuscript along with the website. Dr Miguel Cano described part of the rock specimens, wrote and revised the manuscript along with the website and created the behavioural datasheet and collected most of the mechanical values of the rock samples. Dr Luis Jordá scanned part of the rock specimens and described them, wrote and revised the manuscript along with the website. Dr David Benavente revised all the definitions of the rocks, wrote and revised the manuscript. Dr José Luis Pastor described part of the rock specimens, wrote and revised the manuscript along with the website.

- Rocks are classified following a behavioural classification.
- General and specific values of their mechanical properties are provided.
- A description of the rock is provided to aid the naked eye recognition.

1 Introduction

Civil, petroleum, mining and geological engineers, scientists such as geologists, geophysicist and environmentalist, architects and professionals require knowing the main properties or rocks Although field and laboratory tests provide these properties, in some occasions, it is needed, in terms of economy and time, a faster and prior classification. The sense of sight allows us to learn about the surrounding environment, permitting the assimilation of information from the surroundings, and makes up about 70% of objects perception (Schroeder, 1996). Therefore, the simple naked eye recognition of rocks allows their classification, providing precious information about them. Naked eye recognition of rocks is a mandatory part in civil engineering and architecture professional practice, at least in the preliminary stages of a construction project.

Many authors have published a considerable amount of articles and books on the field of naked eye recognition of rocks (Goodman, 1989; Tarbuck and Lutgens, 2015; The United States. Federal Highway Administration, 1991). Many websites offer the identification, classification and description of rocks (Hudson Institute of Mineralogy, 1993; Imperial College London, 2013; Michna, 1995), being aided by digital pictures or even videos. Those 2D resources cover a wide range such as high-quality photos captured using GigaPan mediums (Benton, 2014). The resources that use videos offer a better comprehension of the recognition process. However, a major problem is that they cannot exploit the interactive information of hand holding a rock (for example, roughness, the existence of voids or characteristic features). The object motion (rotation and translation) provides valuable information because we perceive most of the features by moving through their three-dimensional structure. Therefore, the use of 3D models makes up a better alternative than 2D static images for the description of a rock. Fortunately, the generation of 3D models is possible thanks to the development of several novel techniques.

Since the early 2000s remote sensing techniques, such as LiDAR (Light Detection and Ranging) or SfM (Structure from Motion), have been applied in many fields to capture 3D scenes. While LiDAR instruments are expensive, SfM technique can be applied using conventional cameras. LiDAR-derived data characteristics depend on, among others, the instrument type, range and environmental conditions. Contrarily, SfM-derived data depend on the software and on used photos, and consequently of the lens, capture strategy, environment and so on. Gigapixel images have also been used for 3D reconstruction (Lato et al., 2012; Lee et al., 2017).

Digital data acquired through remote sensing techniques enables the interactive visualisation of solid surfaces using specific software packages. Therefore, its application to the field of petrology offers a new perspective for naked eye recognition of rocks and improves the study of rocks through the visualisation of their real colours, textures, sizes and shapes (Riquelme et al., 2016). However, this information could be insufficient for the naked eye recognition and classification of rocks. Therefore, a geological description of each rock must be provided along with each digital model.

The present work aims to satisfy two principal objectives: (1) to provide students of engineering, architecture and sciences, who are required to take subjects of geology, with an almost organoleptic 3D system that enables and aids the recognition of the major rock groups; and (2) to provide users a rock classification system that considers their geomechanical behaviour. The authors initially designed this work for students of civil, geological and mining engineering, but it is also useful for other students and professionals thanks to the novelty of the first aim. To satisfy these objectives, we present the full establishment of an open online repository. The open online repository contains 3D digital models and detailed descriptions of the rocks, including their rock classification, texture description, a basic link between their petrological and geomechanical/petrophysical properties, collection place and potential uses in everyday life. The present paper will allow researchers and students to generate their own 3D models along with the proposed data sheet and to upload them to the repository. To encourage users to generate and to upload their models, we describe and detail the full generation process of the 3D models.

It is not the aim of this work to include all rocks, as reference books on petrography mention over one thousand types of rocks (Goodman, 1989), but to upload some main rocks classified in an accepted classification system. Educational framework

Engineering studies must provide solid knowledge to students who will be further employed in the design, building and supervision of different constructions. Students must overcome theoretical concepts and apply these concepts through practice. Traditionally, geology subjects are part of the syllabus of geosciences and engineering degrees. In these subjects, general concepts of geology are provided, and part of the practical study comprises the application of these contents to the naked eye recognition of rocks and minerals. This process can be performed in the field or in the laboratory where the explanations are supported by physical rocks. However, students rarely have those rocks when studying at home. Using digital models provides complementary information to aid the study process to strengthen skills in rock recognition. This open online repository provides an exceptional framework for students for studying rock collection before, during and after the practical lessons.

Besides geology, rock mechanics is an important part of the syllabus of civil, mining and geological engineers. Rock mechanic subjects aim to analyse the behaviour of rocks and rock masses. Hence, it is a major necessity to understand the rocks through its genesis and its expected behaviour. We propose a simplified description in which students and professionals can find significant values of relevant details, providing an order of magnitude of parameters of those rocks when available.

2 Workflow process of the 3D reconstruction.

The 3D reconstruction of the rocks uses the SfM-MVS technique. The Figure 1 presents the workflow process. In the first stage, the scene is prepared along with metric information. The second stage comprises the photo capture. Finally, the third stage processes the photos and generates the specimen 3D model.

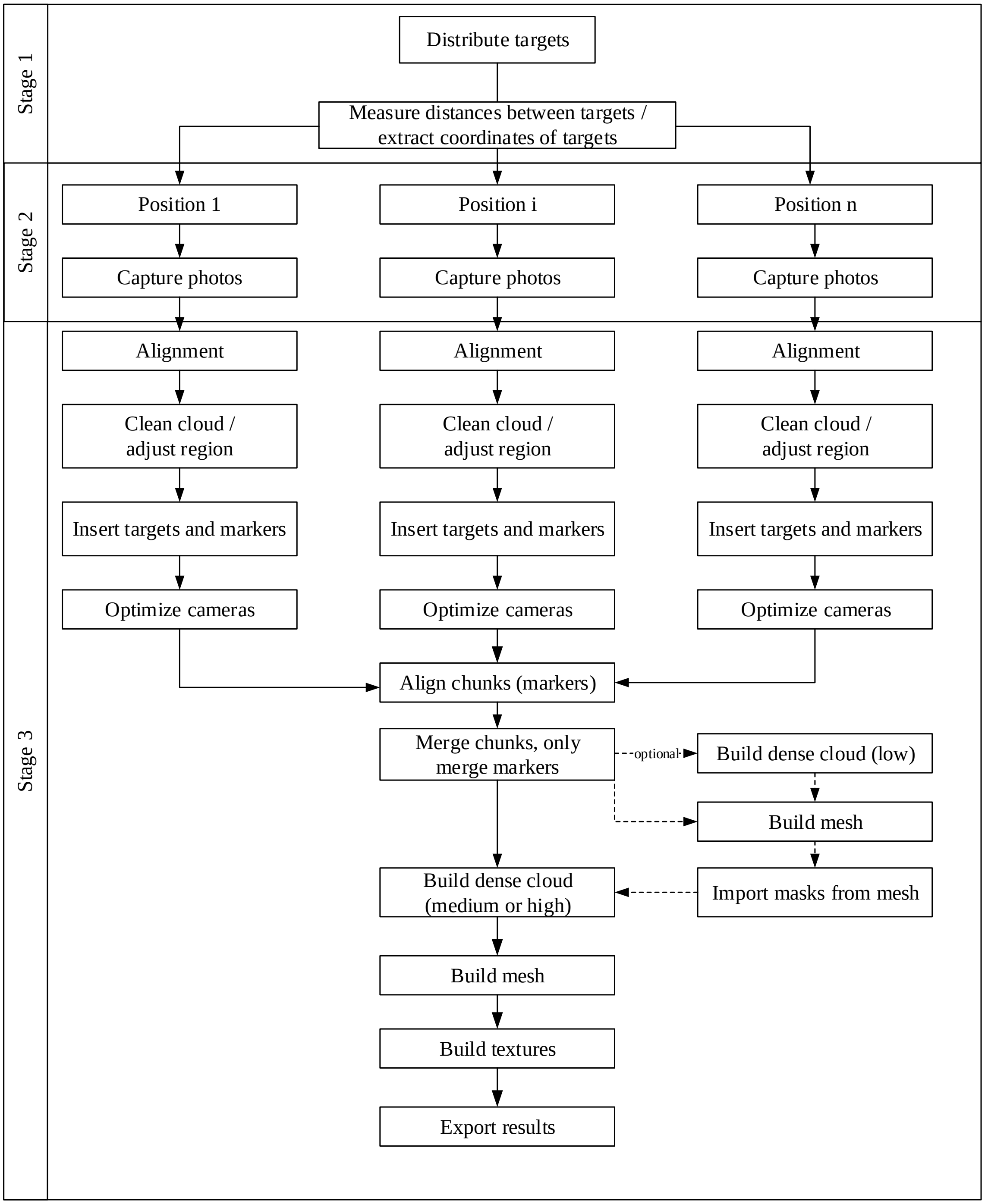


Figure 1. Workflow of the process to generate a full rock.

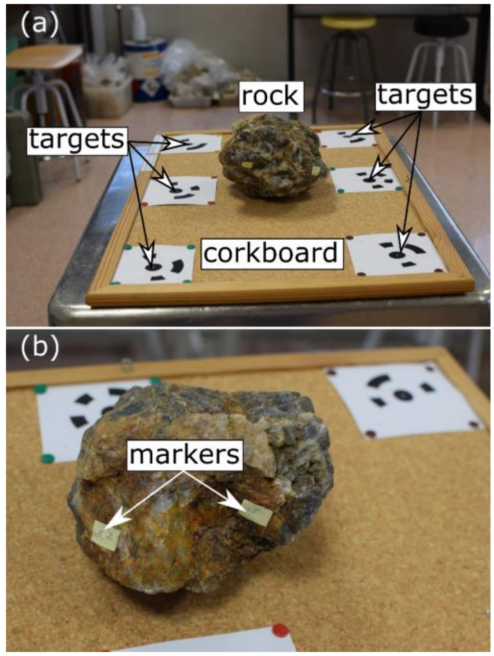


Figure 2. Preparation of the scene: (a) a flat surface, in this case, a corkboard, is placed on a horizontal surface, targets are fixed to the corkboard and the rock specimen is placed in the centre; (b) several markers are attached to the rock when the rock is captured in various positions.

The first stage comprises the scene preparation. Figure 2 shows an example where a corkboard has been utilised due to its flat non-regular textured surface. Targets were fixed to the surface and the distances between their centres were accurately measured. Second stage comprises the photos capture. In this work, several users reconstruct rocks using their own cameras: Coolpix S2800, Sony DSC W330 (14.1 Mpx) and Nikon D5500, using a fixed lens model Nikkor 50 mm f/1.8G, or domestic smartphone cameras: OnePlus X and Huawei P20 Lite. SfM strategy englobes capturing the specimens by different photos from distinct positions and orientations. The capture of the images must be enough to overlap between neighbouring photos. A good strategy, to guarantee overlap, is to capture photos following an imaginary circumference centred over the rock specimen and pointing the camera to the rock. Figure 3 depicts an example of the described approach where Figure 3 (a) shows the location of the captured photos of a rock specimen.

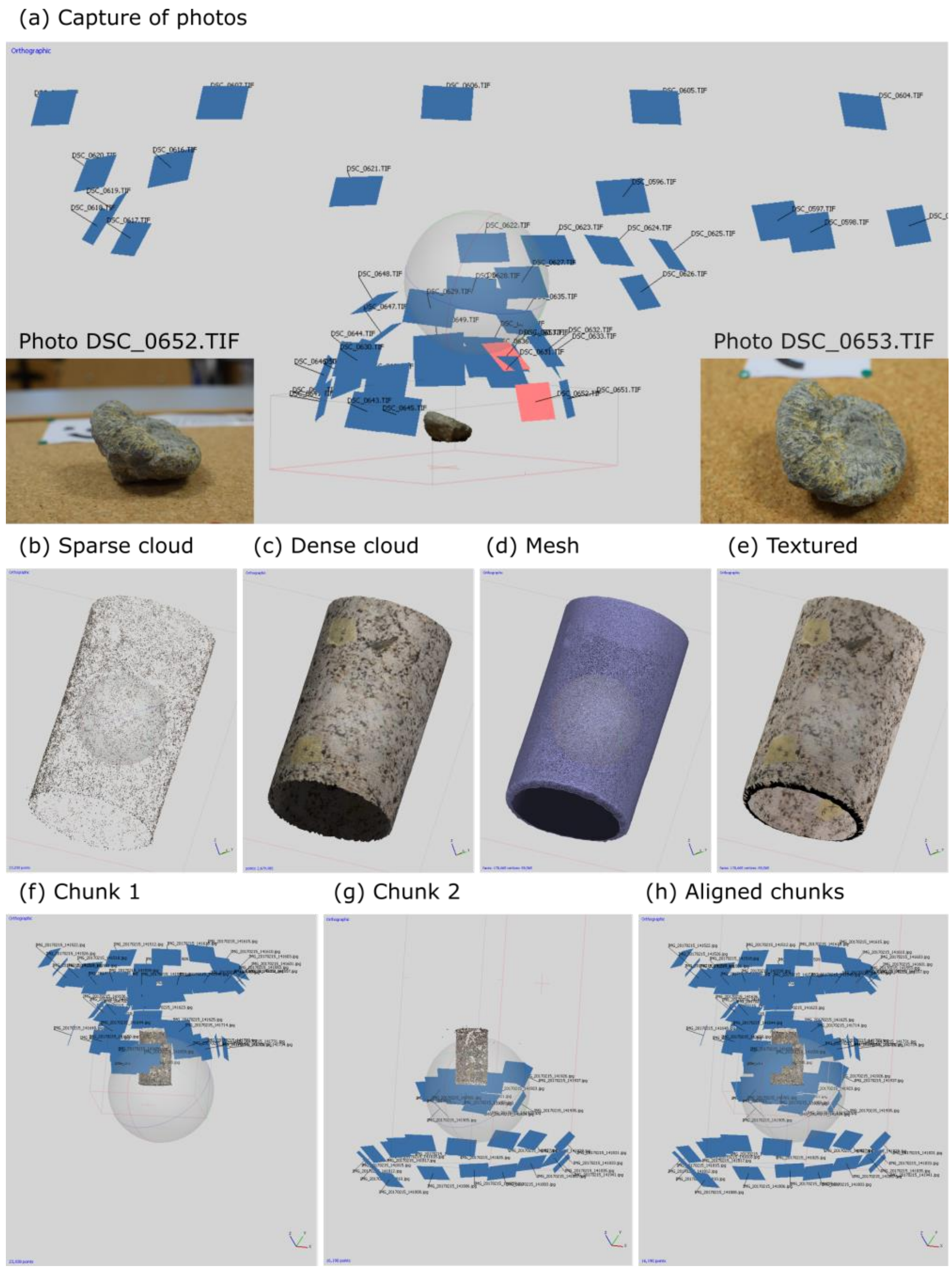


Figure 3. (a) Location and direction (black lines) of the capture of photos (blue rectangles); different processing stages: (b) sparse cloud obtained after alignment; (c) dense cloud obtained after building dense cloud; (d) mesh obtained after building mesh and (e) textured mesh, after building texture; alignment of chunks: (f) chunk 1; (g) chunk 2 and (h) chunks 1 and 2 aligned and merged.

Third stage comprises six steps: (1) alignment of photos; (2) insertion of Ground Control Points (GCP); (3) optimisation of the calibration parameters of the camera; (4) dense cloud reconstruction; (5) mesh reconstruction; and (6) build of textures.

If the specimen is fully modelled, for each position of the specimen the three first steps are applied. Otherwise, these steps are applied only once. First, the alignment process estimates internal and external camera orientation parameters in a local reference system. This process generates a sparse cloud (Figure 3a). Second, metric information is provided to the model which allows conducting a transformation and optimisation process. In this step, the markers are inserted in the scenario and captured along with the rock. Third, camera positions and internal parameters are optimised. When generating a full model, all positions are aligned using the joint markers (Figure 2b) and then merged (Figure 3f-h). Fourthly, the dense cloud is reconstructed (Figure 3c). Fifthly, a mesh is reconstructed to represent the surface of the object (Figure 3d) from the existing dense cloud. Finally, the textures are applied to the previous mesh (Figure 3e).

Different formats are available to export and share results. We used an online platform to share the models.

3 Classification of rocks

The uploaded rocks used a genetic classification into the major rock groups: igneous, sedimentary and metamorphic. In this study, we have considered and adapted the basic rock classification in one of the most common geology reference books (Tarbuck and Lutgens, 2015; Tucker et al., 2009). This classification is based on textural (e.g. size of the grains or foliation) and organoleptic (e.g. mafic rocks are darker than lighter) properties. Although we avoided the use of more specific and complex classifications, such as the proposed by Dunham (1962) for carbonate sedimentary rocks or the International Union of

Geological Sciences (IUGS) systematics of igneous rocks (Streckeisen, 1974), we complementarily include and extend the rock description in some complex rocks with the specific classifications. For instance, in the repository, the available sample #7 (Guimaraes granite) is as a porphyritic coarse-grained biotite granite, but it is also termed as monzogranite because of its mineralogical composition IUGS's classification. The repository presents the use classification system (https://web.ua.es/es/digitalrocks/system-of-classification.html), that defines the organisation of the samples.

Igneous rocks are commonly classified by the Streckeisen classification (Le Bas and Streckeisen, 1991; Le Maitre et al., 2002). However, as we focused on rock specimens inspected through 3D models, we used a simple classification based on the rock texture and its composition (Tarbuck and Lutgens, 2015). This classification is not as accurate and robust as the previously suggested but offers an easier way to classify the most common types of rocks to students and non-experts. First, the classification is based on the texture and secondly on the mineral composition and optionally on the rock size, showing the name of the corresponding common rock.

Despite the most accepted classification system for sedimentary rocks proposed by Folk (1980), we used a simpler classification (and less robust) (Tarbuck and Lutgens, 2015). The scientific community widely accepts that sedimentary rocks are classified into two groups: (1) detrital and (2) chemical and organic or non-detrital sedimentary rocks. Depending on the texture of metamorphic rocks, the common classification uses two big groups: foliated and non-foliated.

Instead of a genetic point of view, engineers may be more interested in a behavioural classification system such as the one proposed by Goodman (1989), which we applied along with the genetic classification.

4 Information, data portal design and implementation

The repository is defined by two main parts: the database and a website that organises and offers all the virtual contents. The database organisation follows a logical order to classify and describe a rock specimen from the point of view of civil, geological and mining engineers. However, it is noteworthy that users interested in geosciences will also find this work of interest.

To catalogue and describe the specimens, we designed a datasheet which is fulfilled when data are available (Online Resource 1). All rocks must have, at least, two fields: identification number and the name of the rock. Despite the fact that the name of the rock can be identical for several specimens in the database, its number (id) must be unique. All fields are organised in four sections: (1) geological classification; (2) geomechanical classification (behavioural classification according to Goodman (1989)); (3) description of the local sample and (4) engineering classification of intact rocks (general classification according to Deere and Miller (1966)).

The first section classifies the specimen using the genetic classification. This section requires three blocks: introductory definition, petrologist's definition and commercial definition. The first field is the introductory definition, which is a simple definition that enables readers to identify common rocks based upon a visual inspection following a genetic classification (naked eye). This definition describes the original digitised rock, and it is supported by the digital rock available in the portal. The second field is the petrological definition, which describes the composition and texture of the rock. The last field is the commercial definition if exists. In the second section, the specimen is classified based on the behavioural classification of Goodman (1989). Third section describes the local sample in four fields: (1) local sample description from a geological point of view; (2) additional information about the outcrop; (3) weathering grade of the rock, following the ISRM criterion and (4) location where the rock sample was collected.

All rocks and information are available in the following URL: https://web.ua.es/digitalrocks. This portal is organised on a landing page and the rock repository (Figure 4**Error! Reference source not found.**).

In the site, the users can inspect the rock specimens through an embedded visualisation window, provided by the Internet site Sketchfab© (https://sketchfab.com/). Besides the online visualisation, the web shows a brief description of the rock and its corresponding geological and geotechnical information. The visualisation of a 3D model allows zooming, translating, rotating and inspecting the specimen's texture in an interactive way. Moreover, the inserted annotations of clasts, minerals, fossils and other features enhance this experience (Figure 4**Error! Reference source not found.**). Details of the texture, grain size and shape, colours, organisation and other geometric properties of the rock surface can be determined by the user. The web also provides a report of the generation of the 3D model. Finally, the data sheet details the collected data of the sample.

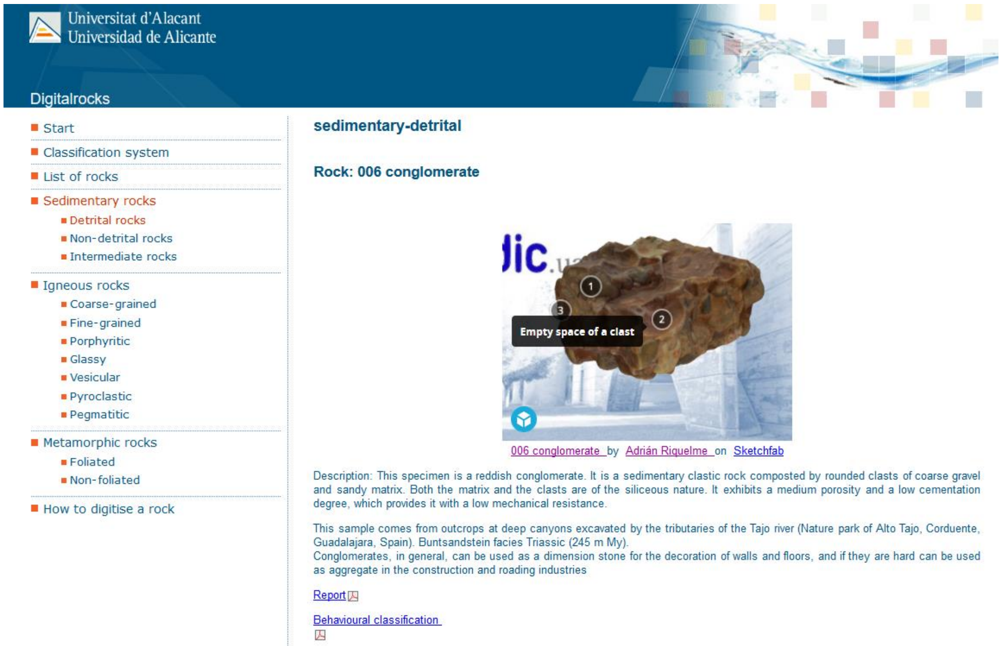


Figure 4. Capture of the portal.

5 Conclusions

An open online repository that stores 3D models of rock samples is presented. The main aim of this repository is to be a complementary tool to support the training process on rock recognition, traditionally performed using 2D static images or videos. The specimens are organised following a genetic classification and are presented along with a short description and a datasheet that contains valuable geological and geomechanical information, what will be of interest to geology and rock mechanic professionals. These 3D models provide the opportunity to virtually visualize in three dimensions and in a realistic way rocks specimens as well as to highlight remarkable details of interest for the students as the constituent minerals of the rock and other properties.

At the moment of this work submission, more than 50 common rocks (sedimentary, igneous and metamorphic) were generated using common cameras, and even smartphones, through the SfM-MVS technique. The methodology to generate scaled rocks is described. This process can be performed by non-experts that will increase their abilities as they practise with the generation of 3D models.

The present work successfully satisfies the following objectives: (1) to provide engineering and geosciences students, who are required to study geology, with an 'almost organoleptic 3D' system that enables and aids the rocks recognition and complements the available resources for this process; and (2) to provide users (students and professionals) with a rock classification that considers their geomechanical behaviour. In early stages of this repository, pilot studies were conducted for the students of Geology applied to Civil Engineering in the University of Alicante (Spain). The student's acceptance and the obtained results demonstrated its potential for geology practices (Riquelme et al., 2016).

It is the purpose of the authors to continue with this line of investigation and to encourage students and professionals to actively collaborate with this repository providing their own 3D models and descriptions of rock specimens from all round the world, offering an accessible reference of 3D geological information.

Acknowledgements

This work was partially funded by the University of Alicante (vigrob-157 Project, GRE14-4, GRE15-19 and GRE17-011 Projects), the Spanish Ministry of Economy and Competitiveness (MINECO) and EU FEDER under Projects TIN2014-55413-C2-2-P and TEC2017-85244-C2-1-P. Authors thank Ignacio Pérez-Rey and Leandro Alejano for the

description of some samples. Finally, we acknowledge Mrs. Sophie Krzesniak for the English language revision and correction of this manuscript.

References

Benton, J., 2014. The ”magic” al growth of an online gigapan repository for geoscience education, in: 2014 GSA Annual Meeting in Vancouver, British Columbia.

Deere, D.U., Miller, R.P., 1966. Engineering classification and index properties for intact rock, Technical report No. AFWL-TR-65-116.

Dunham, R.J., 1962. Classification of Carbonate Rocks According to Depositional Textures, in: Classification of Carbonate Rocks--A Symposium. pp. 108–121. https://doi.org/10.1306/M1357

Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hemphill Publishing Company, Austin, Texas, USA, Texas, USA.

Goodman, R.E., 1989. Introduction to rock mechanics, 2nd ed, John Willey & Sons, New York, USA. Wiley New York.

Hudson Institute of Mineralogy, 1993. Mineralogy Database - mineral collecting, localities, mineral photos and data.

Imperial College London, 2013. Imperial College Rock Library [WWW Document]. URL https://wwwf.imperial.ac.uk/earthscienceandengineering/rocklibrary/glossary.php (accessed 1.11.17).

Lato, M.J., Bevan, G., Fergusson, M., 2012. Gigapixel imaging and photogrammetry: Development of a new long range remote imaging technique. Remote Sens. 4, 3006–3021. https://doi.org/10.3390/rs4103006

Le Bas, M.J., Streckeisen, A.L., 1991. The IUGS systematics of igneous rocks. J. Geol. Soc. London. 148, 825–833. https://doi.org/10.1144/gsjgs.148.5.0825

Le Maitre, R.W., Streckeisen, A.L., Zanettin, B., Le Bas, M.J., Bonin, B., Bateman, P., Bellieni, G., Dudek, A., Efremova, S., Keller, J., Lameyre, J., Sabine, P.A., Schmid, R., Sorensen, H., Woolley, A.R., 2002. Igneous Rocks: a Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks, 2nd ed. Cambridge University Press, Cambridge.

Lee, H., Mostegel, C., Fraundorfer, F., Kieffer, D.S., 2017. GigaPan Image-Based 3D Reconstruction for Engineering Geological Investigation.

Michna, P., 1995. Earth Science Australia [WWW Document]. URL http://www.earthsci.org/index.html

Riquelme, A., Cano, M., Tomás, R., Jordá, L., Santamarta Cerezal, J., 2016. Petrología 3D, in: XIV Jornadas de Redes de Investigación En Docencia Universitaria. Investigación, Innovación y Enseñanza Universitaria: Enfoques Pluridisciplinares. Vicerrectorado de Calidad e Innovación Educativa, Universidad de Alicante, Alicante, Spain, pp. 799–812.

Schroeder, R., 1996. Possible Worlds: The Social Dynamic of Virtual Reality Technology. Westview Press, Inc., Boulder, CO, USA.

Streckeisen, A., 1974. Classification and nomenclature of plutonic rocks recommendations of the IUGS Subcommission on the systematics of Igneous Rocks. Geol. Rundschau 63, 773–786. https://doi.org/10.1007/BF01820841

Tarbuck, E., Lutgens, F., 2015. Earth Science, 14th Edition, 14th ed. Pearson.

The United States. Federal Highway Administration, 1991. Rock and mineral identification for engineers. U.S. Dept. of Transportation, Federal Highway Administration.

Tucker, M.E., Wright, V.P., Dickson, J.A.D., 2009. Carbonate Sedimentology, Carbonate Sedimentology. Blackwell Science Ltd. https://doi.org/10.1002/9781444314175

Digital 3D Rocks: a collaborative benchmark for learning rocks recognition[1]

Adrián Riquelme [a*], Miguel Cano [a], Roberto Tomás [a], Luis Jordá [b], José Luis Pastor [a], David Benavente [c]

Formatted: English (United Kingdom)

a Departamento de Ingeniería Civil, Universidad de Alicante. P.O. Box 99, E-03080 Alicante, Spain.

b Instituto Geológico y Minero de España, Calle de Ríos Rosas, 23, 28003 Madrid, Spain.

c Departamento de Ciencias de la Tierra y del Medio Ambiente, Universidad de Alicante, San Vicente del Raspeig, Spain.

*Corresponding author: Adrián Riquelme (ariquelme@ua.es), Phone: +34 96 590 3707

Field Code Changed

~~Abstract:~~

~~Naked eye rock recognition is an essential activity for professionals and students of geosciences, architecture and engineering. Through a hand holding rock specimen, it is usually required not only to identify the type of rock but recognize their texture and understand its expected properties mechanical and petrophysical properties. Although a wide choice of books, websites and apps are available in the literature and on the Internet,~~

[1] Dr Adrián Riquelme scanned most of the rocks, programmed the website and wrote and supervised the manuscript. Dr Roberto Tomás described part of the rock specimens, wrote and revised the manuscript along with the website. Dr Miguel Cano described part of the rock specimens, wrote and revised the manuscript along with the website and created the behavioural datasheet and collected most of the mechanical values of the rock samples. Dr Luis Jordá scanned part of the rock specimens and described them, wrote and revised the manuscript along with the website. Dr David Benavente revised all the definitions of the rocks, wrote and revised the manuscript. Dr José Luis Pastor described part of the rock specimens, wrote and revised the manuscript along with the website.

their contents are two-dimensional (2D) and static. Nowadays, the application of remote sensing techniques such as Light Detection and Ranging (LiDAR) or Structure from Motion (SfM) enable the generation of three-dimensional (3D) interactive models, which are here presented as a novel perspective of learning and practising rocks recognition. Despite limitations of the technique, 3D digital models of rocks permit their virtual visualization and manipulation to reveal parts of the specimens that are hidden in the 2D photograph, as well as details of the rock specimen's texture such as grain and minerals size, distribution and organization along with the possibility of identifying petrological features, foliation, mineral orientations and others. This provides a novel perspective of learning and practising rocks identification. Herein, a benchmark of digital rocks collected all around the world and generated using SfM technique is presented. The rocks are organised using a straightforward classification system based on the texture jointly with a detailed description to aid the specimen recognition. A behavioural geomechanical classification is then applied. Moreover, a linked datasheet shows the engineering classification, the weathering degree, the guide physical and mechanical properties (general, and specific when available), the engineering uses and others. The information is organised on an open-access website hosted by the University of Alicante (://web.ua.es/digitalrocks). This initiative also aims to encourage students and professionals to generate their own models and to provide the description to enlarge the repository.

Keywords: Geology; Remote Sensing; Computer Graphics

Highlights

- A~~n~~ 3D interactive rocks open repository generated using SfM is presented.
- Rocks are organised using a classification system based on their texture.
- Rocks are classified following a behavioural classification.
- General and specific values of their mechanical properties are provided.
- A description of the rock is provided to aid the naked eye recognition.

1 Introduction

Civil, petroleum, mining and geological engineers, scientists ~~-as~~such as geologists, geophysicist and environmentalist, architects and professionals require knowing the main properties or rocks Although field and laboratory tests provide these properties, in some occasions, it is needed, in terms of economy and time, a faster and prior classification. ~~.~~ ~~Although the field and laboratory tests provide these properties, they need in terms of economy and time a fast-prior classification.Properties of rocks are requested to be known by engineers as civil, petroleum, mining and geological, scientists as geologists, geophysicist and environmentalist, architects and professionals. A wide variety of professionals request to know certain properties of rocks for their daily work. These professionals range from engineers as civil, petroleum, mining and geological, sciences as geologists, geophysicist and environmentalist and architects, to professional related to these activities such as consultants, contract manufacturer and salespersons. Although these properties can be obtained through the available field and laboratory tests, a fast-prior classification is needed~~

~~in terms of economy and time. Indeed, if a rock specimen is classified, its main characteristics, as well as its expected behaviour, are reasonably known.~~

The sense of sight allows us to learn about the surrounding environment, permitting the assimilation of information from the surroundings, and ~~constitutes~~ makes up about 70% of objects perception (Schroeder, 1996). Therefore, the simple naked eye recognition ~~and classification~~ of rocks ~~by visual inspection can allow~~ allows their classification, providing ~~very valuable~~precious information about them. ~~Moreover, the age of the rock may be correlated with its hardness, strength, durability and other properties, despite this information is not infallibly (Goodman, 1989). That is the reason why a basic recognition by means of visual analysis is commonly performed. Consequently, the n~~Naked eye recognition of rocks is a mandatory part in civil engineering and architecture professional ~~practise~~practice, at least in the preliminary stages of a construction project~~s~~.

Many authors have published ~~A~~a considerable amount of articles and books ~~literature has been published~~ on the field of naked eye recognition of rocks ~~(i.e.,~~ (Goodman, 1989; Tarbuck and Lutgens, 2015; The United States. Federal Highway Administration, 1991)~~)~~. ~~Traditionally, existing works were published in printed form. Since the Internet became a common channel of communication, new multimedia contents can be used to describe rocks. Therefore, m Additionally, m~~Many websites offer the identification, classification and description of rocks ~~(i.e.,~~ (Hudson Institute of Mineralogy, 1993; Imperial College London, 2013; Michna, 1995)~~)~~, being aided by digital pictures or even videos. ~~Those resources, which usually use 2D photos, can cover a wide range of quality(~~“Those 2D resources cover a wide range such as high-quality photos captured using GigaPan mediums

Formatted: No underline, Underline color: Auto, Pattern: Clear

Field Code Changed

Formatted: Check spelling and grammar

Field Code Changed

Formatted: No underline, Underline color: Auto, Pattern: Clear

Field Code Changed

(Benton, 2014)~~")~~. The resources that ~~, and those which~~ use ~~digital~~ videos offer a better comprehension of the recognition process. However, a major problem ~~with these digital contents~~ is that they cannot exploit the ~~real 3D~~ interactive information ~~that brings the observation~~ of ~~a~~ hand holding a rock (for example, roughness, the existence of voids or ~~the presence of~~ characteristic features). ~~Even though holding in hands a rock is a unique experience in which we use the five senses. Very valuable~~ The object motion (rotation and translation) provides valuable information because we perceive most of the features by moving through their three-dimensional structure. ~~information can also be provided when the object is observed while it is translated and rotated, because we perceive most of the information about the objects by moving through their three-dimensional structure.~~ Therefore, the use of 3D models~~, which can be zoomed in and out, rotated and oriented by the user,~~ makes up ~~constitutes~~ a better alternative than 2D static images for the description of a rock. Fortunately, the generation of 3D models is ~~currently~~ possible thanks to the development of several novel techniques.

Since the early 2000s remote sensing techniques, such as LiDAR (Light Detection and Ranging) or SfM (Structure from Motion), have been applied in many fields to capture 3D scenes. While LiDAR instruments are ~~currently~~ expensive, SfM technique can be applied using ~~common,~~ conventional cameras. ~~The~~ LiDAR-derived data characteristics depend on, among others, the instrument type, range and environmental conditions. Contrarily, ~~the~~ SfM-derived data depend on the software and on used photos, and consequently of the lens, capture strategy, environment and so on. ~~Interestingly,~~ Gigapixel images have also been used for 3D reconstruction (Lato et al., 2012; Lee et al., 2017).

Field Code Changed

Formatted: Not Highlight

Formatted: No underline, Underline color: Auto, Pattern: Clear

Field Code Changed

~~Indeed, the number of publications in the database Web of Sciences that contain the terms “LiDAR” or “laser scan” is dramatically increasing since the 90s (Abellán et al., 2016). Moreover, the publications containing the term “Structure from Motion” appeared in 2010, and its number is sharply increasing (Abellán et al., 2016).~~

~~On the one hand, LiDAR instruments, also known as 3D laser scanners, provide precise and accurate 3D point clouds, but at a high cost of acquisition. On the other hand, SfM provides precise 3D models generated from 2D images acquired by means of common instruments such as photo cameras. In general terms, those models generated with SfM have lower accuracy than those generated with LiDAR instruments, although its quality can be reasonably good. Moreover, many researchers have applied this technique to archaeology (Van Damme, 2015), cultural heritage (Kwiatek and Tokarczyk, 2015), ecology (Cunliffe et al., 2016), forensic (Urbanová et al., 2015), oceans (Kwasnitschka et al., 2016) and topography and mapping (Purdie et al., 2016).~~

Digital data acquired through remote sensing techniques enables the interactive ~~visualization~~ visualisation of solid surfaces using specific software packages. Therefore, its application to the field of petrology offers a new perspective ~~to the~~ for naked eye recognition of rocks and improves ~~. This fact can dramatically improve the experience of studying~~ the study of rocks through the ~~visualization~~ visualisation of their real colours, textures, sizes and shapes (Riquelme et al., 2016). However, this information could be insufficient for the naked eye recognition and classification of rocks. Therefore, a geological description of each rock must be provided along with each digital model.

Formatted: No underline, Underline color: Auto, Pattern: Clear

Field Code Changed

~~1.1 The aim of this paper~~

The present work aims to satisfy two principal objectives: (1) to provide students of engineering, architecture and sciences, who are required to take subjects of geology, with an ~~'~~almost organoleptic 3D~~'~~ system that enables and aids the recognition of the major rock groups ~~(i.e., igneous, sedimentary and metamorphic, and their most common forms)~~; and (2) to provide users a rock classification system that considers their geomechanical behaviour. The authors initially ~~This work was initially~~ designed this work for students of civil, geological and mining engineering, but it is also useful for other students and professionals thanks ~~because of due~~ to the novelty of the first ~~objective~~aim.

Commented [MC1]: And also Geological Engineering, que son els nostres

To satisfy ~~the presented~~ these objectives, we present ~~,~~ the full establishment of an open online repository ~~is presented~~. The open online repository contains 3D digital models and detailed descriptions of the rocks, including their rock classification, texture description, a basic link between their petrological and geomechanical/petrophysical properties, collection place and potential uses in everyday life. ~~Moreover, t~~The present paper will allow researchers and students to generate their own 3D models along with the proposed data sheet and to upload them to the repository. To encourage users to generate and to upload their models, we describe and detail the full generation process of the 3D models ~~is described in detail in the present work~~.

Formatted: No underline, Underline color: Auto, Pattern: Clear

It is not the aim of this work to include all ~~the types of~~ rocks, as reference books on petrography mention over~~more than~~ one thousand types of rocks (Goodman, 1989), but to upload some ~~of the~~ main ~~types of~~ rocks classified in an ~~generally~~ accepted classification

Field Code Changed

system. ~~Despite good reference books on petrography mention more than one thousand types of rocks (Goodman, 1989), it is not the aim of this work to include them all. The basic education of civil and geological engineers request to become familiar with around 40 rocks (Goodman, 1989). Accordingly, the introduced repository tries to offer a reasonable number of varied rocks to aid students and professionals with the naked eye recognition process. Additionally, those rocks uploaded to the repository are classified in generally accepted classification systems.~~

~~2~~ Educational framework

Formatted: Normal

Engineering studies must provide solid knowledge to students who will be further employed in the design, ~~construction~~ building and supervision of different ~~types of~~ constructions. ~~While these studies are conducted, s~~Students must overcome theoretical concepts and apply these concepts through practice. Traditionally, geology subjects are part of the syllabus of geosciences~~, architecture~~ and engineering degrees. In these subjects, general concepts of geology are provided~~ to students~~, and part of the practical study ~~consists of~~comprises the application of these contents to the naked eye recognition of rocks and minerals. This process can be performed in the field or in the laboratory~~,~~ where the explanations ~~can be~~are supported by ~~means of p~~physical rocks. However, students rarely ~~do not usually~~ have those rocks when studying at home~~the home study process is conducted~~. Using~~The use of~~ digital models provides ~~very useful~~ complementary information to aid the study process to strengthen skills in rock recognition. ~~Additionally, t~~This open online repository provides an exceptional framework for~~to~~ students for studying rock collection before, during and after the practical lessons.

~~In addition to~~Besides geology, rock mechanics is an important part of the syllabus of civil, mining and geological engineers. Rock mechanic~~s~~ subjects aim to analyse the behaviour of rocks and rock masses. Hence, it is a major necessity to understand the rocks through its genesis~~, which has been previously studied in the geology subjects,~~ and its expected behaviour. We ~~This work~~ propose~~s~~ a simplified description in which students and professionals can find significant values of relevant details~~parameters~~, providing an order of magnitude of parameters of those rocks when available.

~~3~~2 Workflow process of the 3D reconstruction.

The ~~SfM-MVS technique is used in the process of the~~ 3D reconstruction of the rocks uses the SfM-MVS technique. The ~~The workflow process is shown in The used workflow uses the SfM-MVS technique and is presented in~~ Figure 1 presents the workflow process. In the first~~SfM is a technique that generates 3D models from unorganised digital photos captured from different locations. Although this technique can be applied by non-experts, certain rules should be followed in order to produce rock models with good quality. In this section, we focus on the application of the technique to the rocks reconstruction under laboratory and field conditions. Figure 2 shows the proposed workflow, considering that the rock is generated from a single position (Figure 1).~~ stage, the scene is prepared along with metric information. The second stage comprises ~~consists of t~~the photo capture. Finally, the third stage processes the photos and generates the specimen 3D model.

Formatted: English (United Kingdom)

Field Code Changed

Formatted: English (United Kingdom)

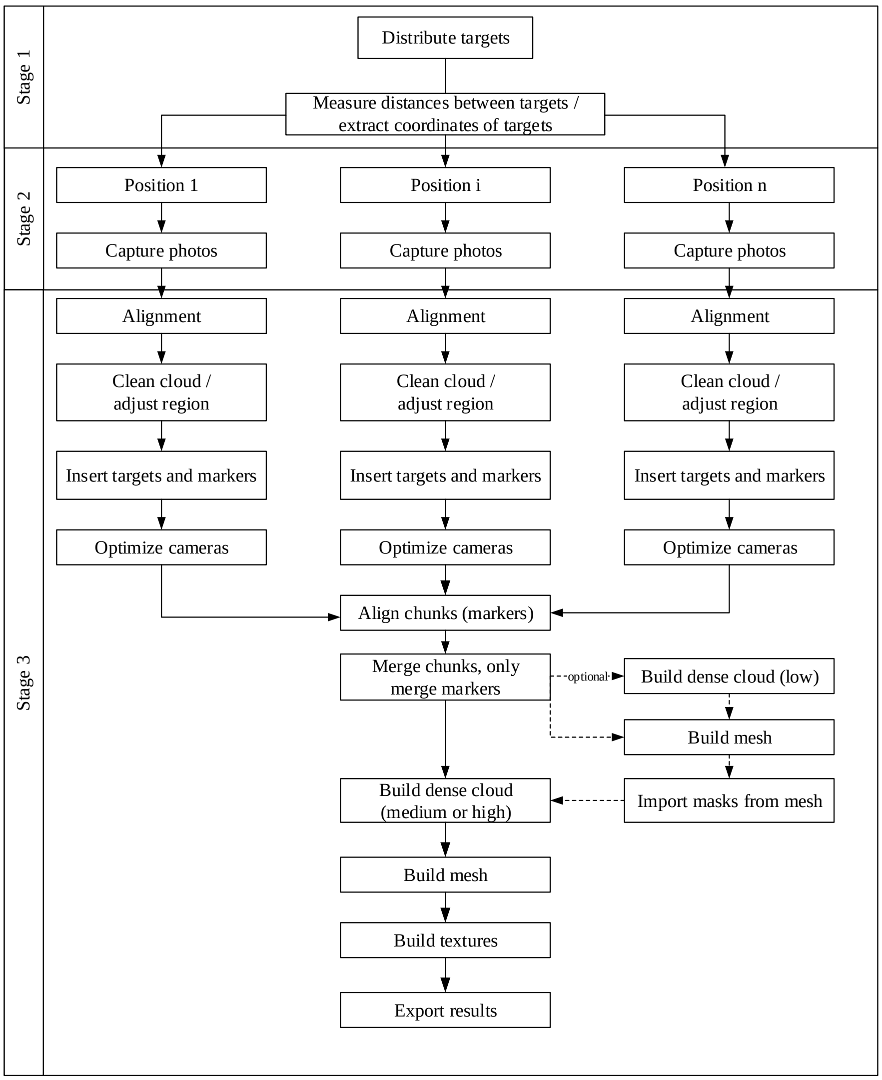


Figure 1. Workflow of the process to generate a full rock.

Field Code Changed

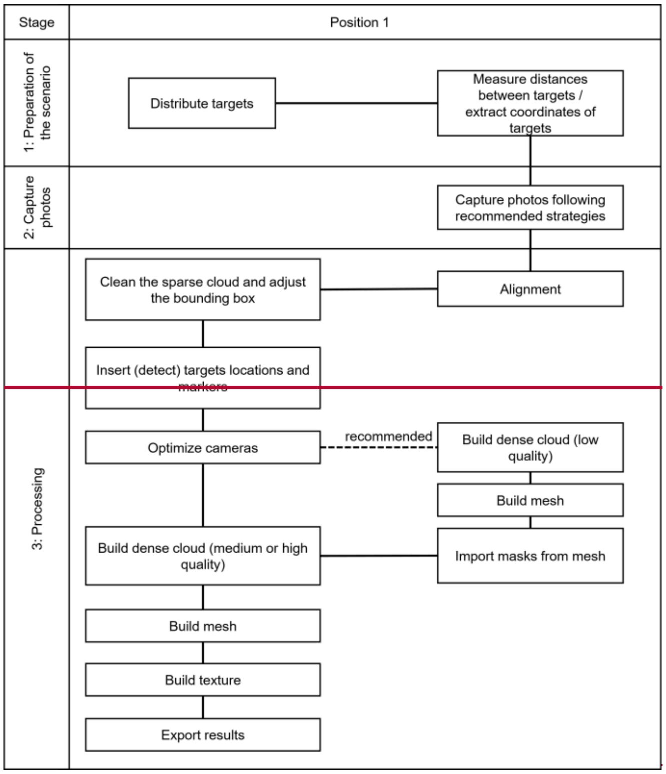


Figure 2. Proposed workflow for the generation of a model from a single position.

3.1 Scene preparation

Firstly, the scene must be prepared in order to proceed to the following stages in optimum conditions. To capture the photos from any point of view, the object should be isolated in a relatively wide area. Additionally, we strongly recommend working under homogeneous lightning conditions of the specimen, therefore shadows do not affect to the scene.

The insertion of reference information can be conducted in three different ways. The first one consists of the insertion of the coordinates of the cameras positions, and the other two require the insertion of the position of some markers and scale bar distances. In this study, we insert markers, which are printed coded targets that have previously been located and fixed on a flat surface. The used software allows the generation of these coded targets, and this process presents an interesting benefit: its centres are automatically detected by the software.

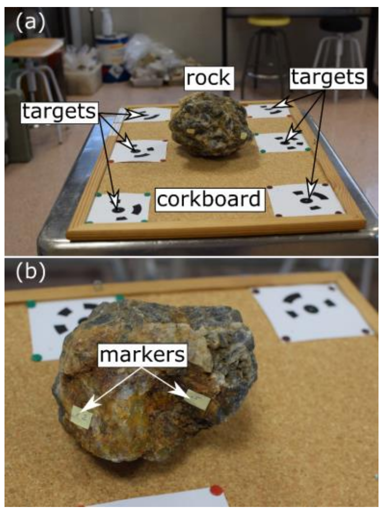


Figure 2. Preparation of the scene: (a) a flat surface, in this case, a corkboard, is placed on a horizontal surface, targets are fixed to the corkboard and the rock specimen is placed in the centre; (b) several markers are attached to the rock when the rock is captured in various positions.

Field Code Changed

The first stage consists ofcomprises the scene preparation, which is designed according to the specimen rock. In Figure 2 an example is sshowns an example, shows an example of the preparation of the scene. In this case,where a corkboard has been utilised due to becauseits flat non-regular textured surface. Targets were fixed to the surface and the distances between their centres were accurately measured. : (1) it is a flat surface, (2) it has an irregular texture (due to the nature of the cork) and (3) it allows fixing targets using

Field Code Changed

Formatted: Check spelling and grammar pins. This figure also highlights six targets evenly distributed and fixed on the corkboard. The used targets were generated with the software Agisoft Photoscan Professional (Agisoft LLC, 2016a), although others can be used. Additionally, subfigure (b) displays several markers which are attached to the rock. These markers permit the identification of fixed points of the rock when it is generated in various positions, as it will be further detailed.

3.2 Yo pondría: "... due to..."Equipment

Second stage comprises the photos capture. In this work, several users reconstruct rocks using their own cameras: Coolpix S2800, Sony DSC W330 (14.1 Mpx) and Nikon D5500, using a fixed lens model Nikkor 50 mm f/1.8G, or domestic smartphone cameras: OnePlus X and Huawei P20 Lite. Second stage consists of the photos capture. Different types of cameras can be used to apply the SfM technique: metric and non-metric cameras. The utilization of professional cameras is not mandatory for this purpose and digital consumer-level cameras have shown excellent results (Agisoft LLC, 2016b). For example, in this work some rocks are digitised using a smartphone with good quality. However, the reconstruction quality of the model strongly depends on the photos quality, and therefore on the equipment. Although photos should be captured employing at least 5 Mpx resolution cameras, it is better to opt for 12 Mpx or higher (Agisoft LLC, 2016b). Additionally, a fixed lens is preferred. Finally, we use a tripod in order to avoid undesired movements in the photos and, therefore, blurring in the images.

Formatted: Check spelling and grammar

Formatted: Font color: Dark Blue

Formatted: Normal

In this work, rocks are reconstructed by different users who used their own cameras: Coolpix S2800, Sony DSC W330 (14.1 Mpx) and Nikon D5500, using a fixed lens model Nikkor 50 mm f/1.8G. Additionally, some models were generated by means of a smartphone model OnePlus X and Huawei P20 Lite.

3.3 Capture of photos

SfM strategy englobes consists ofcomprises capturing the specimens by different photos from distinct positionslocations and orientations. In other words, itThe capture of the images must be enough to overlap between neighbouring photos. A good strategy, to guarantee overlap, is to capture photos following an imaginary circumferenceIt must be guaranteed enough image overlap between neighbouring photos. A good strategy consists ofcomprises capturing photos along with an imaginary circumference, centred over the rock specimen and pointing the camera to the rock. Each photo should overlap as high as possible to the precedent and subsequent. Figure 3 displays depicts an example of the described approach, where Figure 3Figure 3 ((a)) shows the location of the captured photos of a rock specimen. Figures 34 (b) and (c) show two consecutive photos with wide overlap, which are marked in a red square in (a). The circumferences should be described at different elevation and radius..

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Check spelling and grammar

Field Code Changed

Field Code Changed

Formatted: Default Paragraph Font

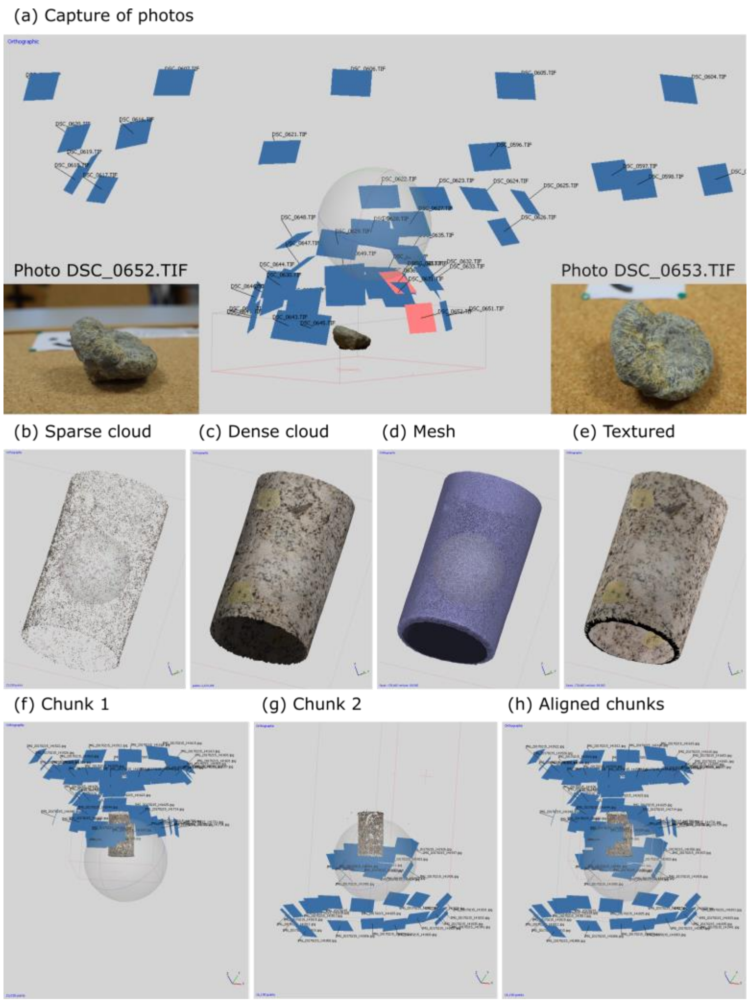


Figure 3. (a) Location and direction (black lines) of the capture of photos (blue rectangles);~~ (b) and (c) are two overlapping photos, marked as a red square in (a)~~ different processing stages: (b) sparse cloud obtained after alignment; (c) dense cloud obtained after building dense cloud; (d) mesh obtained after building mesh and (e) textured mesh, after building texture; alignment of chunks: (f) chunk 1; (g) chunk 2 and (h) chunks 1 and 2 aligned and merged.~~.~~

~~**3.4** Processing~~

Third stage ~~The processing consists of~~comprises six steps: (1) alignment of photos; (2) insertion of Ground Control Points (GCP); (3) ~~optimization~~ optimisation of the calibration

Field Code Changed

parameters of the camera; (4) dense cloud reconstruction; (5) mesh reconstruction; and (6) build of textures.

If the specimen is fully modelled, for each position of the specimen the three first steps are applied. Otherwise, these steps are applied only once. First~~ly~~, the alignment process estimates internal and external camera orientation parameters in a local reference system. This process generates ~~In this process,~~ a sparse cloud ~~is generated~~ (Figure 3~~Figure 4~~a). ~~In this process, a sparse point cloud is reconstructed (Figure 5 a) and linearly transformed by using a rigid transformation matrix. In this step, we recommended to increase the default key point limit to 40,000 in order to obtain better results in subsequent steps. The sparse cloud will produce undesired points, which should be removed manually.~~

Second~~ly~~, ~~,~~ metric information is provided to the model~~,~~ which allows conducting a transformation and ~~optimization~~ optimisation process. In this step, the markers are inserted in the scenario and captured along with the rock.

Third, ~~ly,~~ ~~the information inserted in the previous stage is used.~~ In this process, camera positions and internal parameters are optimi~~z~~sed. When generating a full model, all positions are aligned using the joint markers (Figure 2b) and then merged (Figure 3f-h).

Fourthly, the dense cloud is reconstructed ~~There are two ways of utilizing the reference information. The first one consists of the application of a rigid transformation matrix, in which only rotation, translation and scale are applied to the point cloud. The relative positions of cameras markers and tie points do not change, and the parameters of the interior camera orientation are also kept. As this is a rigid transformation, it does not~~

Field Code Changed

Field Code Changed

Field Code Changed

~~affect subsequent stages, and therefore, it can be performed at any step. The second one consists of the optimization of the positions and orientations of the cameras. Because of this, not only previous transformations are applied but non-linear deformations are corrected. This process is carried out using the inserted coordinates of markers or inserting distances between the centres of the markers (i.e. scale bars). As this optimization affects the relative position of the cameras, it must be performed before subsequent steps. Selected parameters of the cameras are optimized, and the model is transformed.~~

~~The following step consists of the reconstruction of the dense point cloud~~ (Figure 3~~Figure 4Figure 5~~ ~~b~~c). Fifthly, a mesh is reconstructed~~This is the longest process and the most time-consuming step. Better results can be obtained in terms of timing if a subprocess is conducted at this stage. A mesh can be built from existing sparse point cloud or from a dense cloud generated using low quality. In both cases, all points that do not belong to the rock should be previously removed from the point cloud. Although this mesh does not accurately represent the rock, it is enough to be projected on all captured photos and then generate a mask for every single photo. It is noteworthy that although this process can take a few minutes, it significantly reduces the processing time for the subsequent high-quality building of the dense cloud.~~

Field Code Changed

~~The fifth stage is the mesh reconstruction. In this step, a TIN (triangular irregular network) is reconstructed~~ to represent the surface of the object (Figure 3~~Figure 4Figure 5~~ ~~c~~d)~~.~~ ~~The mesh can be built using two methods: Delaunay or Poisson (Lai et al., 2014). Delaunay reconstruction should be used when reconstructing maps, as it assigns an elevation value for each point in a plane, also known as 2.5D models. Poisson method~~

Field Code Changed

reconstructs the model in 3D, so it is the adequate option for the purposes of this work. Poisson reconstruction is usually configured setting the surface type to arbitrary, instead of the height field option for Delaunay triangulation. This mesh is generated from the existing dense cloud.

Finally, the sixth and final step is the application ofthe -textures are applied to the previous mesh (Figure 3Figure 4Figure 5 -de). Contrarily to the existing dense cloud, in which colours were assigned to each point, this model presents a textured surface. Because of this, the textured mesh provides a more enhanced representation of the reality than the dense cloud.

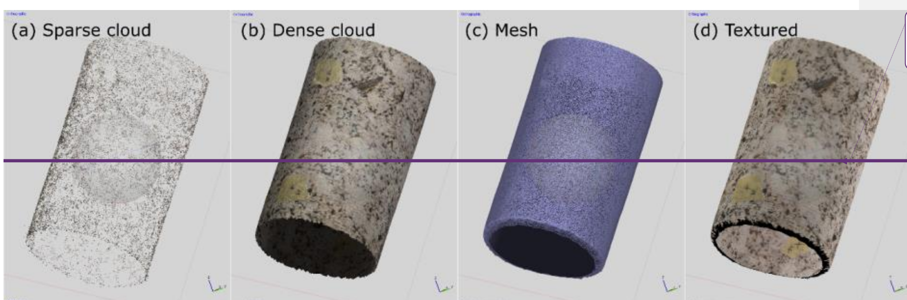


Figure 45. Different processing stages: (a) sparse cloud obtained after alignment; (b) dense cloud obtained after building dense cloud; (c) mesh obtained after building mesh and (d) textured mesh, after building texture.

Field Code Changed

Formatted: Indent: First line: 0.49", Don't keep with next

Formatted: Normal

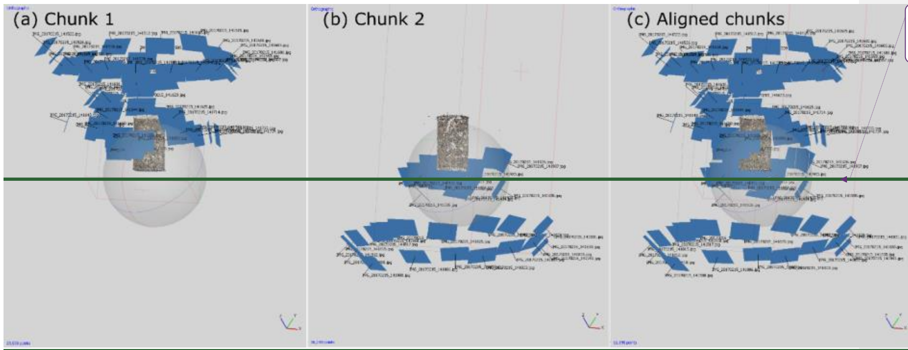


Figure 57. Alignment of chunks: (a) chunk 1; (b) chunk 2 and (c) chunks 1 and 2 aligned and merged.

Formatted: Indent: First line: 0.49", Don't keep with next

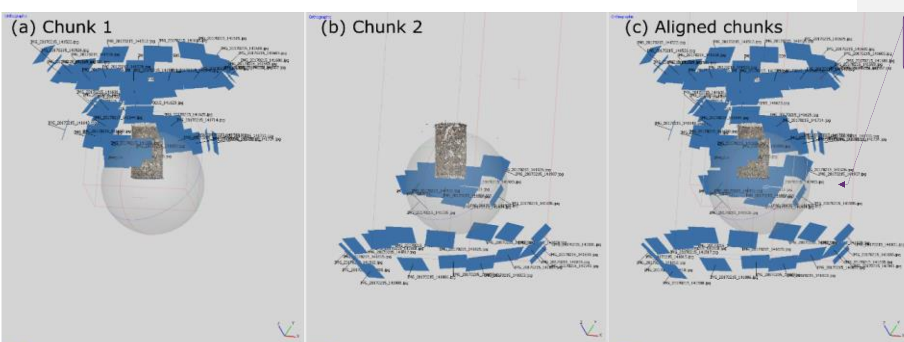
Formatted: Normal

3.5 Complete generation of a rock

If the previous process is conducted, only visible parts of the rock specimen are reconstructed. Therefore, the base of the rock specimen cannot be generated (Figure 5) because photos of this part cannot be taken. However, it is possible to adapt the previous process to generate the entire rock surface. Figure 6 shows the process for generating a full 3D model of the specimen, which is an adaptation of the previous workflow (Figure 2).

Firstly, for each position *i-th* the rock is located on the corkboard and all photos are captured. Then, the rock is turned, and the process is performed again, therefore all its surface is captured. Photos are loaded into the software in separate chunks, and the alignment of each chunk is performed separately, as it was detailed in the previous subsection. At this point for each chunk, a sparse cloud is obtained, and photos are oriented in different reference systems. All points that do not belong to the rock should be removed from the sparse cloud. For each chunk, new markers are inserted (Figure 3 - b). Optionally, some features of the rock such as small marks or singular colours can be detected, and markers can be inserted. Those markers are inserted in all chunks as accurate as possible, being labelled using the same name. Then, all chunks are aligned in the same reference system using previously inserted markers which are common in all chunks. Next step is to merge all chunks in a single chunk. Figure 7 presents an example of this process. Subfigures (a) and (b) displays two different chunks, which are aligned in the same reference system. Merging both chunks generates another one in which all cameras are oriented in the same system of reference (Figure 7 - c).

If after the alignment process the sparse clouds have been cleaned, the resulting merged cloud can generate a mesh that allows importing masks to all photos. However, it is also possible to generate a dense cloud using low-quality setting and then generate the mesh to import masks. This last option requires that the dense cloud is cleaned because part of the corkboard could be reconstructed simultaneously with the rock. Finally, the process normally continues with the merged chunk.



Formatted: Indent: First line: 0.49", Don't keep with next

Figure 7. Alignment of chunks: (a) chunk 1; (b) chunk 2 and (c) chunks 1 and 2 aligned and merged.

3.6 Exportation and visualization

Different formats are available to export and share results. This workWe used Currently, different software packages to manage point clouds and meshes are available, such as CloudCompare (Girardeau-Montaut, 2016) or Meshlab. However, it is possible to export the results in Universal 3D (U3D) format, which is a compressed file format standard for 3D computer graphics data, and it is natively supported by the PDF format. It has been verified that the software packages Acrobat Reader © and Foxit Reader © (enabling a 3D plugin) can open this format.

4 In this work an online platform was used to share the models. study, the repository is available online. Therefore, several alternatives have been considered and it was decided to use the Sketchfab© platform. In this platform, all generated models can be upload and an HTML code is provided, so it can be inserted in almost any website.

53 Classification of rocks

The Uuploaded rocks are classified used a genetic classification into the major rock groups: igneous, sedimentary and metamorphic, and their most common forms. In this study, we have considered and adapted the basic rock classificationFor clarity purposes, we

Formatted: Normal

Formatted: Highlight

Formatted: Normal

Formatted: Highlight

~~considered and adapted basic rock classifications~~ ~~that they are included~~ in one of the most common geology reference books (Tarbuck and Lutgens, 2015; Tucker et al., 2009). This classification is based on textural (e.g. size of the grains or foliation) and organoleptic (e.g. mafic rocks are darker than lighter) properties. ~~-~~Although we avoided the use of more specific and complex classifications~~, but~~ , ~~classifications~~ such as the proposed by Dunham ~~classification system~~ (1962) for carbonate sedimentary rocks or the International Union of Geological Sciences (IUGS) systematics of igneous rocks (Streckeisen, 1974), we ~~complementary~~complementarily include and extend the rock description in some complex rocks with the specific classifications. For instance, in the repository, the available sample #7 (Guimaraes granite) is ~~classified~~ as a porphyritic coarse-grained biotite granite, but it is also termed as monzogranite because of ~~due to~~ its mineralogical composition IUGS's classification. The repository presents the use classification system (https://web.ua.es/es/digitalrocks/system-of-classification.html), that defines the organisation of the samples.

~~We avoided the use of more specific, although more complex, classifications such as Dunham classification system (Dunham, 1962) for carbonate sedimentary rocks or the International Union of Geological Sciences (IUGS) systematics of igneous rocks (Streckeisen, 1974).~~

~~**5.1 Igneous rocks**~~

Igneous rocks are commonly classified by ~~though~~ the Streckeisen classification (Le Bas and Streckeisen, 1991; Le Maitre et al., 2002). However, as we ~~this work is~~ focused on

Field Code Changed

Formatted: Not Highlight

Field Code Changed

Field Code Changed

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

Field Code Changed

Formatted: Hidden

Formatted: Font color: Dark Blue

Formatted: List Paragraph, Bulleted + Level: 1 + Aligned at: 0.49" + Indent at: 0.74"

Field Code Changed

rock specimens inspected through 3D models, we used a simple classification ~~is used~~ based on the rock texture and its composition (Tarbuck and Lutgens, 2015). This classification is not as accurate and robust as the previously ~~suggested, but~~suggested but offers an easier way to classify the most common types of rocks to students and non-experts. First, ~~Table 1 shows t~~the classification is ~~of igneous rocks adopted in this work, which is~~ based~~d~~sd on ~~firstly on~~ the texture~~,~~ and secondly on the mineral composition and optionally on the rock size, ~~indicating~~ showing the name of the corresponding common rock.

~~Table 1. Classification of igneous rocks. Modified from *(Tarbuck and Lutgens, 2015)*.~~

		~~Mineral composition~~			
~~Texture~~		~~Granitic (Felsic)~~	~~Andesitic (Intermediate)~~	~~Basaltic (Mafic)~~	~~Ultramafic~~
~~Coarse-grained (Phaneritic)~~		~~Granite~~	~~Diorite~~	~~Gabbro~~	~~Peridotite~~
~~Fine-grained (Aphanitic)~~		~~Rhyolite~~	~~Andesite~~	~~Basalt~~	~~Komatiite (rare)~~
~~Porphyric~~		~~Granite porphyry~~	~~Andesite porphyry~~	~~Basalt porphyry~~	~~Uncommon~~
~~Glassy~~		~~Obsidian~~	~~Less common~~	~~Less common~~	~~Uncommon~~
~~Vesicular~~		~~Pumice~~		~~Scoria~~	~~Uncommon~~
~~Pyroclastic Fragmental~~	~~> 64 mm~~	~~Blocks (angular) - Bombs (rounded)~~			
	~~2 - 64 mm~~	~~Lapilli~~			
	~~1/16 - 2 mm~~	~~Thick ash~~			
	~~< 1/16 mm~~	~~Fine ash (dust)~~			
~~Pegmatitic~~		~~Pegmatitic granite~~			~~Uncommon~~

~~5.2~~ Despite the ~~Sedimentary rocks~~

~~The~~ most accepted classification system for sedimentary rocks ~~was~~ proposed by Folk (1980), we used ~~. However,~~ a simpler classification (and less robust) ~~is used in this work~~ (Tarbuck and Lutgens, 2015). ~~It is widely accepted by t~~The scientific community widely accepts that sedimentary rocks are classified into two groups: (1) detrital and (2) chemical and organic or non-detrital sedimentary rocks.

Field Code Changed

Formatted: Not Highlight

Formatted: Normal

Formatted: Indent: First line: 0.49"

Field Code Changed

Field Code Changed

Table 2 shows the classification system of sedimentary detrital rocks, and Table 3 shows the corresponding to sedimentary non-detrital rocks used in this work.

Field Code Changed
Field Code Changed

Table 2. The classification system of detrital sedimentary rocks. Modified from (Tarbuck and Lutgens, 2015).

Formatted: Indent: First line: 0.49"
Field Code Changed
Field Code Changed

Clastic texture (particle size)	Sediment name	Rock name	
Coarse (> 2 mm)	Gravel (rounded particles)	Conglomerate	
	Gravel (angular particles)	Breccia	
Medium (1/16 - 2 mm)	Sand	Sandstone	
Fine (1/256 to 1/16)	Silt	Lutite	Siltstone
Very fine (<1/256 mm)	Clay		Shale or mudstone

Table 3. *The classification system of sedimentary non-detrital rocks. Modified from* (Tarbuck and Lutgens, 2015).

Composition	Texture		Rock name
Calcite $CaCO_3$	Nonclastic	Fine to coarse crystalline	Crystalline limestone
		Microcrystaline calcite	Microcrystalline limestone
		Fine to coarse crystalline	Travertine
	Clastic	Visible shells and shell fragments loosely cemented	Coquina
		Various size shells and shell fragments cemented with calcite cement	Fossiliferous limestone
		Microscopic shells and clay	Chalk
Quartz SiO_2	Nonclastic	Very fine crystalline	Chert (light coloured)
Gypsum $CaSO_4 \cdot 2H_2O$	Nonclastic	Fine to coarse crystalline	Rock gypsum
Halite NaCl	Nonclastic	Fine to coarse crystalline	Rock salt
Altered plant fragments (organic)	Nonclastic	Fine-grained organic matter	Bituminous coal

5.3 Metamorphic rocks

Formatted: Normal

Depending on the texture of Metamorphic metamorphic rocks, the common classification uses they are commonly classified into two big groups: foliated and non-foliated. In addition to its texture, the parent rock of the metamorphic rock plays a key role in the classification system, as its determination and the degree of metamorphism leads to

Formatted: Indent: First line: 0.49"

the classification of the rock. Table 4 shows the adopted classification system of metamorphic rocks (Tarbuck and Lutgens, 2015).

Instead of a genetic point of view, engineers may be more interested in a behavioural classification system such as the one proposed by Goodman (1989), which we applied along with the genetic classification.

Table 4. The classification system of metamorphic rocks. Modified from (Tarbuck and Lutgens, 2015).

Grain size	Parent rock	Distinctive properties		Rock name
Foliated	Very Fine	Shale or siltstone	Excellent rock cleavage, smooth dull surfaces	Slate
	Fine	Shale, slate or siltstone	Breaks along wavy surfaces, glossy sheen	Phyllite
	Medium to coarse	Shale, slate, phyllite or siltstone	Micas dominate, breaks along scaly foliation	Schist
		Shale, schist, granite or volcanic rock	Compositional banding due to segregation of dark and light minerals	Gneiss
Non-foliated	Medium to coarse	Limestone, dolostone	Interlocking calcite or dolomite crystals nearly the same size, soft, reacts to HCl	Marble
		Quartz sandstone	Fused quartz grains, massive, very hard	Quartzite
	Coarse-grained	Quartz-rich conglomerate	Round or stretched pebbles that have a preferred orientation	Metaconglomerate
	Fine	Bituminous coal	Shiny black rock that may exhibit conchoidal fracture	Anthracite
		Any rock type	Usually, dark massive rock with a dull lustre	Hornfels
		Mafic or ultramafic rocks	Very fine grained, a typically dull with a greenish colour, may contain asbestos fibres	Serpentinite

Formatted: Indent: First line: 0.49"

Field Code Changed

Formatted Table

Formatted: Indent: First line: 0"

5.4 Geomechanical classification

Instead of a Previous classification systems aim to classify rocks from a genetic point of view, attending to their formation process and composition. However, engineers may be more interested in a behavioural classification system such as the one proposed by rather than a genetic one. That is the reason why Goodman proposed an alternative classification system, which divides rocks into classes and subclasses (Goodman, 1989). Table 5 shows this classification system, in which the rock is observed, and its texture is determined according to four groups: (1) crystalline texture; (2) clastic texture; (3) very fine-grained rocks and (4) organic rocks. Then, a second subclass is determined, for which more information must be provided. Some of them might be deduced from the visual inspection of the 3D models, and others might not when fine details were not generated.

In this work, this classification system is applied along with the genetic classification.

Table 5. Behavioural classification of Goodman (Goodman, 1989).

Texture	Classification	Examples
I. Crystalline texture	A. Soluble carbonates and salts	Limestone, dolomite, marble, rock salt, trona, gypsum
	B. Mica or other planar minerals without continuous mica sheets	Mica schist, chlorite, schists, graphite schist
	C. Banded silicate minerals	Gneiss
	D. Randomly oriented and distributed silicates minerals of uniform grain size.	Granite, diorite, gabbro, syenite

Formatted: Indent: Left: 0", First line: 0"

Formatted: Indent: First line: 0"

Field Code Changed

Formatted: Font: 9 pt, Italic, Font color: Text 2

Formatted: Normal, Don't keep with next

Field Code Changed

Formatted: Font: 9 pt, Italic, Font color: Text 2

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

	~~E. Randomly oriented and distributed silicates minerals in a background of very fine grain and with vugs~~	~~Basalt, rhyolite, other volcanic rocks~~
	~~F. Highly sheared rocks~~	~~Serpentinite, mylonite~~
~~II. Clastic texture~~	~~A. Stably cemented~~	~~Silica cemented sandstone and limonite sandstones~~
	~~B. With slightly soluble cement~~	~~Calcite-cemented sandstone and conglomerate~~
	~~C. With highly soluble cement~~	~~Gypsum-cemented sandstones and conglomerates~~
	~~D. Incompletely weakly cemented~~	~~Friable sandstones, tuff~~
	~~E. Uncemented~~	~~Clay-bound sandstones~~
~~III. Very fine-grained rocks~~	~~A. Isotropic, hard rocks~~	~~Hornfels, some basalts~~
	~~B. Anisotropic on a macro scale but microscopically isotropic hard rocks~~	~~Cemented shales, flagstones~~
	~~C. Microscopically anisotropic hard rocks~~	~~Slate, phyllite~~
	~~D. Soft, soil-like rocks~~	~~Compaction shale, chalk, marl~~
~~IV. Organic rocks~~	~~A. Soft coal~~	~~Lignite and bituminous coal~~
	~~B. Hard coal~~	
	~~C. "Oil shale"~~	
	~~D. Bituminous shale~~	
	~~E. Tar sand~~	

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

Formatted: Justified, Indent: First line: 0.49", Space After: 8 pt, Line spacing: Double

~~6~~4 Information, data portal design and implementation

The repository is defined by two main parts: the database and a website that organises and offers all the virtual contents. ~~The website can be created under a static or dynamic perspective. A dynamic perspective can allow users to upload their own work, sharing their work with the repository community almost immediately. This is the way in which many Internet portals currently work offering 3D models and point clouds, such as Sketchfab ("Sketchfab," 2016) or Pointbox (GeoBit Consulting S.L., n.d.), although they are focused on a different aim. However, a static perspective is chosen as it provides control to administrators to select and organise the repository.~~

~~6.1 Organization of the database~~

Formatted: Normal

The database ~~is~~ organis~~ed~~ation ~~following~~ follows a logical order to classify and describe a rock specimen from the point of view of civil, geological and mining engineers. However, it is noteworthy that users interested in geosciences will also find this work of interest.

To catalogue and describe the specimens, we designed a datasheet which ~~was~~is fulfilled when data are available (Online Resource 1). All rocks must have, at least, two fields: identification number and the name of the rock. Despite the fact that the name of the rock can be identical for several specimens in the database, ~~Despite the name of the rock can be identical for several rocks in the database,~~ its number (id) must be unique. All fields are organised in four sections: (1) geological classification; (2) geomechanical classification (behavioural classification according to Goodman (1989)); (3) description of

Formatted: Highlight

the local sample and (4) engineering classification of intact rocks (general classification according to Deere and Miller (1966)).

All rocks must have, at least, two fields: identification number and the name of the rock. Despite the name of the rock can be identical for several rocks in the database, its number (id) must be unique. All fields are organised in four sections: (1) geological classification; (2) geomechanical classification; (3) description of the sample and (4) engineering classification of intact rocks (general classification). All four sections are subsequently described, and an example is shown in Table 2.

Table 6. Descriptive datasheet of a rock specimen: a garnet amphibolite (id 48)

GARNET AMPHIBOLITE (ID: 48) GEOLOGICAL CLASSIFICATION (Genetic classification)	
Introductory definition (*naked eye*)	Garnet amphibolite is a dark coarse-medium grained banded metamorphic rock.
Petrologist's definition	The garnet amphibolite is a medium size grained (0.1 to 0.2 mm), compact, brownish to greenish grey, somewhat banded, metamorphic rock. This rock was formed through recrystallization under conditions of high viscosity and directed pressure. The metamorphism has considerably flattened and elongated the mineral grains to produce a banded texture, in between schistose and coarse grained. According to this, this specimen could also be considered as a gneiss. The minerals mostly present in this rock are amphiboles, which are dark silicates (relatively low in silica) rich in iron and/or magnesium. This provides this specimen with the dark colour. Additionally, the cleavage of amphiboles is two planes at 60º and 120º.
Commercial definition (if any)	

Formatted: Normal, Don't keep with next
Field Code Changed
Formatted: English (United Kingdom)
Formatted: Normal
Formatted: Normal
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: Normal
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: Normal
Formatted: English (United Kingdom)

GEOMECHANICAL CLASSIFICATION (Behavioural classification, Goodman, 1989)							
I. Crystalline texture	C. Banded silicate minerals.						
DESCRIPTION OF LOCAL SAMPLE							
A geological description of the local sample	The material was recovered in a former copper mine located some kilometres to the east of Santiago de Compostela (A Coruña, Spain).						
Other information about the outcrop	This Precambrian sample outcrop at copper mines in Touro, near Santiago de Compostela in Spain.						
Weathering grade (ISRM, 1981)	I						
Location	42° 53'N, 8° 20' W						
ENGINEERING CLASSIFICATION OF INTACT ROCKS (General classification)							
ISRM classification by strength (USC (MPa)) (ISRM, 1978, (Deere and Miller, 1966))	R0	R1	R2	R3	R4	R5	R6
	Extremely weak (0.25-1)	Very weak (1-5)	Weak (5-25)	Medium strong (25-50)	Strong (50-100)	Very strong (100-250)	Extremely strong (>250)

Formatted: Normal

Formatted: Normal

Formatted: English (United Kingdom)

Formatted: Normal

Formatted: Normal

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: Normal

Formatted: Normal

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: Normal

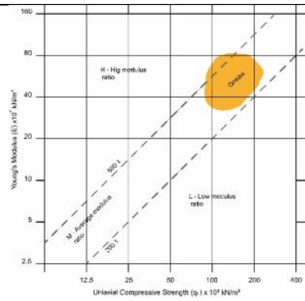
Formatted: Normal

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: Normal

Formatted: English (United Kingdom)

~~Deere and Miller classification by strength and deformation properties (Deere and Miller, 1966)~~			
~~Mechanical properties (unaltered)~~		~~General values~~	~~Particular (local) values (if any)~~
	~~Young's Modulus (E) Tangent modulus at 50% ultimate strength (GPa)~~	~~28.5-82.1 (AASHTO, 1989) – Gneiss~~ ~~13-92 (González Vallejo) – Amphibolite~~	~~30 GPa (Pérez-Rey 2014)~~
	~~Poisson's coefficient (v)~~	~~0.09-0.40 (AASHTO, 1989) – Gneiss~~	~~0.15 (Pérez-Rey 2014)~~
	~~Uniaxial compression strength (MPa)~~	~~24-310 (AASHTO, 1989) – Gneiss~~ ~~210-530 - Amphibolite~~	~~110 MPa (Pérez-Rey 2014)~~
	~~P wave velocity (m/s)~~	~~7200 (Fourmaintraux, 1976) – Amphibolite~~ ~~2500-550 (Schön, 1996) – Gneiss~~	
	~~m_i (Hoek and Brown criterion, 1980)~~	~~31 (Hoek et al, 1994) - Amphibolite~~ ~~28±5 (Hoek, 2003) - Gneiss~~	~~13.4 (Pérez-Rey 2014)~~
	~~Basic friction angle (Φ_b)~~	~~26–29 (Coulson, 1962) - Gneiss~~ ~~32 (Wallace et al, 1970) – Amphibolite~~	~~-~~
~~Physical properties (unaltered)~~	~~Dry unit weight (kN/m³)~~	~~29.8-32 (AFTES, 2003) – Amphibolite~~ ~~26–27.8 (Ramirez Oyanguren and Alejano, 2013) - Gneiss~~	~~28.2 (Pérez-Rey 2014)~~
	~~Porosity~~	~~1–5 (Ramirez Oyanguren and Alejano, 2013) - Gneiss~~	~~-~~

Formatted: Normal

Formatted: Normal, Left

Formatted: Normal

Formatted: English (United Kingdom)

Formatted: Normal

Engineering uses and others	This specimen has been exploited for aggregate, due to the irregular rock disjunction, its compacity and strength. If the aggregate is for concrete, special attention must be paid if the presence of sulphur is detected. This amphibolite has been widely used for masonry. In fact, almost all of Santiago's old town constructions (Spain) used this rock. The high compacity of this rock leads to low permeability. Additionally, the permeability of the discontinuities is not usually enough to enable water flow. Accordingly, in the Santiago region (Spain) there are not almost aquifers.

Formatted: Normal

Formatted: English (United Kingdom)

Firstly, the geological classification, which is a genetic classification, is determined. This first stage of the classification is composed of three fields. The first field is the introductory definition. Basically, rocks are divided into three groups: (1) igneous, (2) sedimentary and (3) metamorphic rocks. Igneous rocks are classified depending on its texture (grain size, porphyric, vesicular, glassy, pyroclastic and pegmatitic), and then depending on its composition (felsic to mafic or ultramafic). It is a simple definition that enables readers to easily identify common rocks based upon a visual inspection following a genetic classification. This definition is based on the original digitised rock and supported by the digital rock available in the portal. The second field is the petrologist's definition, which describes the composition and texture of the rock. The last field is the commercial definition if exists.

Formatted: Indent: First line: 0"

Formatted: English (United Kingdom)

Secondly, the geomechanical classification is based on the aforementioned behavioural classification of Goodman (Goodman, 1989), which is interested in behavioural rather than genetic attributes of rocks.

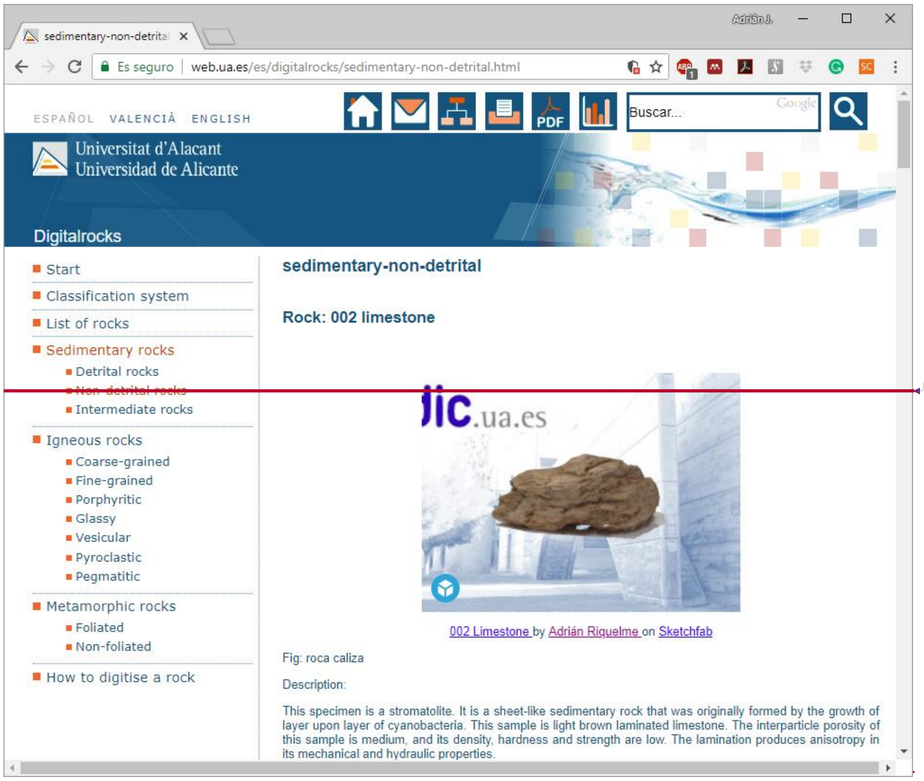
The fFirst section classifies the specimen using the genetic classification. This section requires three blocks: introductory definition, geomechanical classificationpetrologist's definition and ~~rock description~~commercial definition. The first field is the introductory definition, which is a simple definition that enables readers to identify common rocks based upon a visual inspection following a genetic classification (naked eye). This definition describes the original digitised rock, and it is supported by the digital rock available in the portal. The second field is the petrologi~~st's~~cal definition, which describes the composition and texture of the rock. The last field is the commercial definition if exists. In the second section, the specimen is classified based on the behavioural classification of Goodman (1989). Third section ~~Third,~~ describes the local sample ~~rock specimen is described in~~in four fields: (1) ~~. The first field describes the~~ local sample description from a geological point of view~~, ; and the second field provides~~(2) additional information about the outcrop; (3) ~~. The third field describes the~~ weathering grade of the rock ~~in the digitation moment~~, following the ISRM criterion and (4)~~. The last field is the~~ location where the rock sample was collected.

~~6.2 Data portal~~

All rocks and information are available in the following URL: https://web.ua.es/digitalrocks~~https://web.ua.es/en/digitalrocks/~~. This portal is organised on a landing page and the rock repository (Figure 4 ~~(~~).

Field Code Changed

Field Code Changed



~~*Figure 4. Capture of the portal.*~~

In the site, the users can inspect the rock specimens ~~The site offers a visual inspection of the models by means of an image capture~~ through an embedded ~~visualization~~ visualisation window, provided by the Internet site Sketchfab© (https://sketchfab.com/). ~~It allows the upload of generated models and its 3D visualization by means of an Internet browser. In addition to~~Besides the online ~~visualization~~visualisation, the web shows a brief description of the rock and its corresponding geological and geotechnical information ~~is shown~~. The ~~visualization~~ visualisation of a 3D model allows zooming, translating, rotating and inspecting the specimen's texture in an interactive way~~interactively~~. Moreover, the

Formatted: Centered

Field Code Changed

Field Code Changed

inserted annotations of clasts, minerals, fossils and other features enhance this experience (Figure 4). ~~Consequently, d~~Details of the texture, grain size and shape, colours, ~~organization~~ organisation and other geometric properties of the rock surface can be determined by the user. The web also provides ~~A~~a report of the generation of the 3D model ~~is also provided~~. Finally, ~~a pdf~~the data_sheet details the collected data of the sample.~~**provides the engineering classification, the ISRM weathering classification, mechanical values, physical properties, engineering uses and more information.**~~

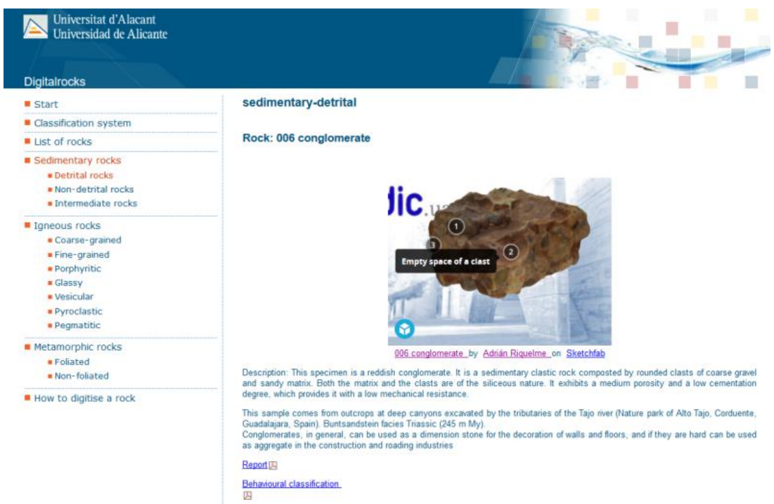


Figure 4. Capture of the portal.

Formatted: Font: Bold

Formatted: Font: Bold, Do not check spelling or grammar

Figure 9. Screen capture of the sandstone id 046. Retrieved from ~~(Riquelme, 2016)~~

Field Code Changed

Field Code Changed

~~7~~5 Conclusions

An open online repository that stores ~~of~~ 3D models of rock samples ~~has been created~~ ~~and~~is presented ~~in this work~~. The main aim of this repository is to be a complementary tool to support the training process o~~f~~n rock recognition ~~(students' homework or sciences, engineers or architects)~~, traditionally performed using 2D static images or videos. The specimens are organised following a genetic classification and are presented along with a short description and a datasheet that contains valuable geological and geomechanical information, what will be of interest to geology and rock mechanic professionals. These 3D models provide the opportunity to virtually visualize in three dimensions and in a realistic way rocks specimens as well as to highlight remarkable details of interest for the students as the constituent minerals of the rock and other properties.

Formatted: Not Highlight

At the moment of this work submission, –more than 50 common ~~A wide representative number of the most common and important~~ rocks (sedimentary, igneous and metamorphic) ~~has been~~were generated using common cameras, and even smartphones, through the SfM-MVS technique. The methodology to generate scaled rocks is described~~Applying the proposed and described methodology, rocks can easily be fully generated and scaled~~. ~~The experience has shown that: (1) quality depends on the used lens, the number of captured images and their quality~~T~~ and (2) t~~his process can be performed by non-experts that will increase their abilities as they practise ~~more and more~~ with the generation of 3D models. ~~This offers an interesting opportunity for students of civil and geological engineering as well as geosciences to study rocks recognition. A simplistic classification system was used in order to classify and organise the presented rock specimens. Additionally, a behavioural classification system is used along with a genetic classification system in order to provide information about the 3D rock to engineers when possible.~~

Formatted: Strikethrough

~~The presented online repository offers 3D models of common rocks that can be inspected online, offering a new point of view for the study of rocks, which are organised following a genetic classification and are presented along with a short description and a datasheet that contains valuable geological and geomechanical information. These 3D models provide the opportunity to virtually visualize in three dimensions and in a realistic~~

way rocks specimen as well as to highlight remarkable details of interest for the students as the constituent minerals of the rock and other properties.

The present work successfully satisfies the following these next objectives: (1) to provide civil and geological engineering and as well as geosciences students, who are required to study geology, with an 'almost organoleptic 3D' system that enables and aids the rocks recognition and complements the available resources for this process; and (2) to provide users (students and professionals) with a rock classification that considers their geomechanical behaviour. In early stages of this repository, pilot studies were conducted for the students of Geology applied to in the Civil Engineering Degree in the University of Alicante (Spain). The student's acceptance and the obtained results demonstrated its potential for geology practices (Riquelme et al., 2016).

It is the purpose of the authors to continue with this line of investigation this work and to encourage students and professionals to actively collaborate with this repository providing their own 3D models and descriptions of rock specimens from all round the world worldwide, offering an freely accessible reference of 3D geological information.

Field Code Changed

Formatted: Not Highlight

Formatted: Font color: Dark Blue

Acknowledgements

This work was partially funded by the University of Alicante (vigrob-157 Project, GRE14-4, GRE15-19 and GRE17-011 Projects), the Spanish Ministry of Economy and Competitiveness (MINECO) and EU FEDER under Projects TIN2014-55413-C2-2-P and TEC2017-85244-C2-1-P. Authors thank Ignacio Pérez-Rey and / Leandro Alejano for the description of some used samples. Finally, we acknowledge Mrs. Sophie Krzesniak for the English language revision and correction of this manuscript.

References

Formatted: English (United Kingdom)

Field Code Changed

Benton, J., 2014. The "magic" al growth of an online gigapan repository for geoscience education, in: 2014 GSA Annual Meeting in Vancouver, British Columbia.

Deere, D.U., Miller, R.P., 1966. Engineering classification and index properties for intact rock, Technical report No. AFWL-TR-65-116.

Dunham, R.J., 1962. Classification of Carbonate Rocks According to Depositional Textures, in: Classification of Carbonate Rocks--A Symposium. pp. 108–121. https://doi.org/10.1306/M1357

Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hemphill Publishing Company, Austin, Texas, USA, Texas, USA.

Goodman, R.E., 1989. Introduction to rock mechanics, 2nd ed, John Willey & Sons, New York, USA. Wiley New York.

Hudson Institute of Mineralogy, 1993. Mineralogy Database - mineral collecting, localities, mineral photos and data.

Imperial College London, 2013. Imperial College Rock Library [WWW Document]. URL https://wwwf.imperial.ac.uk/earthscienceandengineering/rocklibrary/glossary.php (accessed 1.11.17).

Lato, M.J., Bevan, G., Fergusson, M., 2012. Gigapixel imaging and photogrammetry: Development of a new long range remote imaging technique. Remote Sens. 4, 3006–3021. https://doi.org/10.3390/rs4103006

Le Bas, M.J., Streckeisen, A.L., 1991. The IUGS systematics of igneous rocks. J. Geol. Soc. London. 148, 825–833. https://doi.org/10.1144/gsjgs.148.5.0825

Le Maitre, R.W., Streckeisen, A.L., Zanettin, B., Le Bas, M.J., Bonin, B., Bateman, P., Bellieni, G., Dudek, A., Efremova, S., Keller, J., Lameyre, J., Sabine, P.A., Schmid, R., Sorensen, H., Woolley, A.R., 2002. Igneous Rocks: a Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks, 2nd ed. Cambridge University Press, Cambridge.

Lee, H., Mostegel, C., Fraundorfer, F., Kieffer, D.S., 2017. GigaPan Image-Based 3D Reconstruction for Engineering Geological Investigation.

Michna, P., 1995. Earth Science Australia [WWW Document]. URL http://www.earthsci.org/index.html

Riquelme, A., Cano, M., Tomás, R., Jordá, L., Santamarta Cerezal, J., 2016. Petrología 3D, in: XIV Jornadas de Redes de Investigación En Docencia Universitaria. Investigación, Innovación y Enseñanza Universitaria: Enfoques Pluridisciplinares. Vicerrectorado de Calidad e Innovación Educativa, Universidad de Alicante, Alicante, Spain, pp. 799–812.

Schroeder, R., 1996. Possible Worlds: The Social Dynamic of Virtual Reality Technology. Westview Press, Inc., Boulder, CO, USA.

Streckeisen, A., 1974. Classification and nomenclature of plutonic rocks recommendations of the IUGS Subcommission on the systematics of Igneous Rocks. Geol. Rundschau 63, 773–786. https://doi.org/10.1007/BF01820841

Tarbuck, E., Lutgens, F., 2015. Earth Science, 14th Edition, 14th ed. Pearson.

The United States. Federal Highway Administration, 1991. Rock and mineral identification for engineers. U.S. Dept. of Transportation, Federal Highway Administration.

Tucker, M.E., Wright, V.P., Dickson, J.A.D., 2009. Carbonate Sedimentology, Carbonate Sedimentology. Blackwell Science Ltd. https://doi.org/10.1002/9781444314175