3D fabric analysis in mining geology

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Key words: *properties block modelling, 3D modelling, form surfaces, apparent dip analysis*

3D geological models are a critical tool in mining geology and aims to produce well-constrained representations of the subsurface. However, surfaces and volumes are often viewed by non-geology disciplines without due consideration, or understanding, of the underlying data used to generate the 3D reconstructions or viewed in 2D sections that reduces the visible data in the modelling software. Here we present two methods to view underlying data in the form of a properties block model and form surfaces, which can be used in downstream applications such as geohazard mapping, including confidence thereof.

A properties block model is a regular grid onto which desired properties, or parameters are assigned. Two properties are presented here (Figure 1): 1) data confidence in fault modelling for a complexly deformed underground mine; and 2) natural neighbour interpolation of a dominant, gneissic fabric in an open pit mine.

Data confidence property (Figure 1a) is a combination of distance to data and its type/source, which translates into the confidence/uncertainty of e.g. a structural model. The confidence of the data type is defined as a priority, with higher priority data assigned to the block centroid. Generally, data acquired via traditional methods (e.g. face mapping, structural logging) should be given higher priority over automated methods (e.g. photogrammetry, core scanning, interval logging). In this manner, confidence for a structural model can be communicated to various stakeholders (Figure 1a).

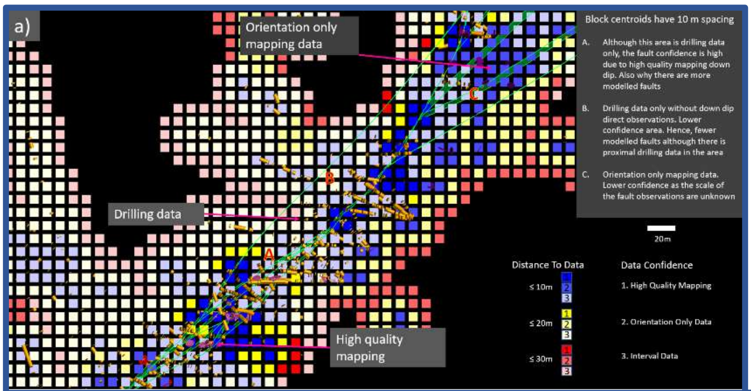


Figure 1: Properties block model generated in Python. a) Data confidence for fault modelling using a 10 m spacing. 10 m thick section. b) Natural-neighbour interpolation onto a 25 m grid closely matches form surfaces generated in Figure 2b. Note form surfaces are generated using numerous explicit controls, whereas block modelling is unconstrained and significantly quicker. 100 m thick section.

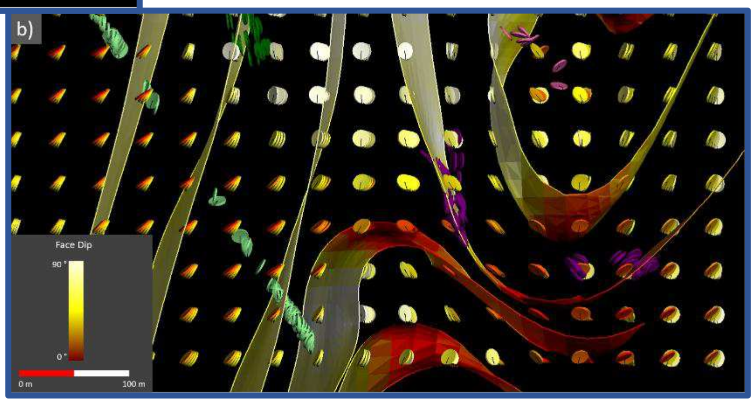


Figure 1b is a block model interpolation of the main plane of anisotropy (here dip and dip direction of gneissic foliation). Interpolation using natural-neighbour creates orientated centroids that blend where data are dense and averages towards a "global" mean where sparse. The interpolated block model provides a robust visualisation of the orientation of the desired fabric within a volume of interest. Notably, block model interpolation using natural-neighbour is not computationally intensive and can serve as a quick method to view fabric orientation.

In complexly deformed deposits, form surfaces provide a novel way to view scattered orientation data as discrete surfaces and are an excellent method to visualise dominant fabric in 3D. Pre-processing of structural data is recommended to avoid lengthy processing times and "outlier" orientation points (small-scale folding). Form surfaces with structural data can be used in downstream applications such as geotechnical engineering analysis for open pit slope design and risk management. For instance, apparent dip heat map (Figure 2b) is a method to show the angular relationship between a dominant fabric and a design surface (e.g. BASSON *et al.*, 2016, CREUS *et al.,* 2019), which has significant safety and economic benefits as it allows for quick identification of potential geohazards in a pit slope. Furthermore, it allows for rapid mine design optimisation.

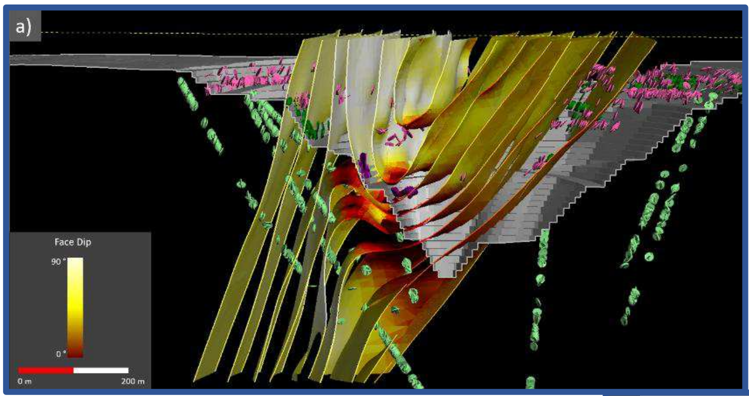
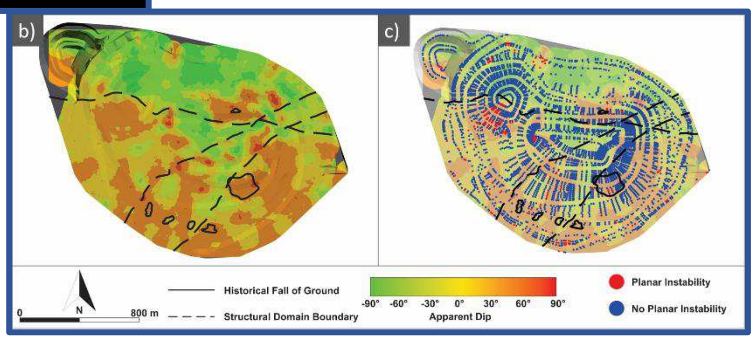


Figure 2: 3D fabric analysis. a) Form surfaces generated from scattered orientation data. Form surfaces require numerous explicit controls where geology is complex. b) Apparent dip heat maps help identify geohazards and can be analysed for planar instability (c).



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Active faulting and seismic event recurrences: tools for automatic quantitative analysis from DEM and DOM

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Key words: *Active fault, palaeoseismic event, morphotectonic*

Lidar and photogrammetry techniques have proven very valuable to acquire high- resolution (HR) topographic data sets for novel application in quantitative geomorphology (Zielke et al. 2011, Godard et al. 2019). At regional scales, these datasets are often still represented as Digital Elevation Models (DEM), but at decametre to kilometre scales, HR and often multivalued outcrop surfaces are represented as Digital Outcrop Model (DOM, Bellian et al. 2005) using textured Triangulated Irregular Networks (TIN) or coloured point clouds. Palaeo-seismic events occurrence and magnitude can be studied at both scales. In this work, two numerical approaches are proposed to facilitate this quantitative analysis at, respectively, regional and local scales. Both approaches are implemented in a plug-in of the open-source CloudCompare software.

At the scale of an active fault system, topographic profiles across the fault trace exhibit changes in slopes corresponding to fault displacements, hence to cumulative displacement associated with successive palaeo-seismic events (Tucker et al. 2011, Tesson et al. 2020). The fault displacement varies spatially along the fault and a current challenge in earthquake hazards is to better understand the link between the fault throw profile and other structural factors. Recently, some studies (e.g. Puliti et al., 2020 and references there in) have suggested that cumulative fault throw variability could be related to the presence of inherited tectonic structures acting as permanent barriers to rupture propagation. Such studies require the determination of throw profile along the fault length, generally manually acquired with a series of profiles. A semi-automatic approach (SPARTA - Hodge et al., 2019) has been proposed recently to facilitate these successive computations but still requires manual steps.

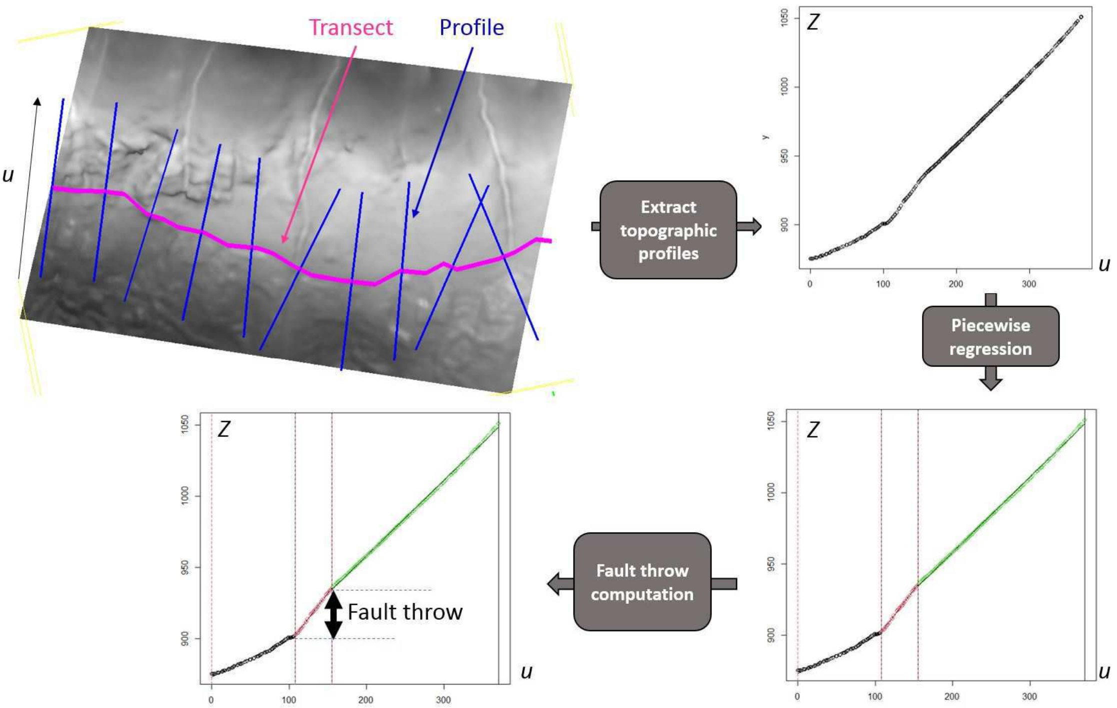

Figure 1: Workflow for the automatic computing of individual and cumulative fault throw along a given transect. A series of topographic profiles are evenly extracted. A piecewise approach is applied onto the (u,Z) plot in order to show different slope parts. Using this segmentation, the fault throw can be estimated, as done in Puliti et al., (2020).

In this work, an automatic tool is proposed for: (i) automatically extracting a regular series of topographic profiles along a user-defined transect; (ii) dividing each profile into successive segments depending on slope changes; (iii) extracting fault scarps and computing fault throw. First, the even extraction of profiles along transects relies on an available functionalities of CloudCompare. Second, we propose to segment the topographic profiles using piecewise linear regression. Indeed, piecewise linear regressions aims at approximating a 2D plot by successive, continuous or not, linear trends. Many algorithms have been proposed in the literature (LEMIRE, 2007; MUGGEO et. al., 2008). In this work, the approach proposed by LEMIRE, (2007) has been chosen, as it only requires a user-defined parameter controlling segment merging or not. Finally, the comparison of segment slopes may be achieved in order to extract fault scarp segments and to compute fault throw using trigonometric relationships, as presented in (PULITI et al., 2020).

At the scale of an outcrop, on an exposed fault scarp, a challenge is to unravel the successive portions that have been exhumed by palaeo-seismic events using surface roughness analysis. Bedrock surfaces indeed changes in texture and roughness with the exposure time due to meteoric processes (e.g., weathering, erosion, dissolutions). Many roughness criteria have been proposed in the literature (HE et al., 2016; GHAFOURI et al. 2017; ZOU et al., 2020) for describing surface variability in many application domains. HE et al. (2016) have proposed an approach to delimit the different seismic event onto rectangular pieces of fault scarps. This approach relies on the computation of a fractal dimension based on the fitting of a power variogram model. Furthermore, TANKAM et al. (2012) have shown that the power variogram model is not the only model describing areal patterns. Different variogram models may characterize different patterns.

In this work, an approach based on the approach proposed by HE et al. (2016) is implemented, but different variogram models are tested. Moreover, other variogram parameters are extracted in order to scrutinize their variability in function of the seismic event boundaries.

Both proposed approaches are applied on active fault located in the Apennines range in Italy (host of the 2016 seismic sequence, 5 shocks Mw5 to 6.5 over 9 months) because it provides one of the most appropriate places worldwide to study long-term morphological build-up from the addition of single earthquakes. High-resolution DEMs and DOMs have been acquired using photogrammetry and allows such approaches to be used for quantitative analysis. The different results are discussed and compared with previous works.

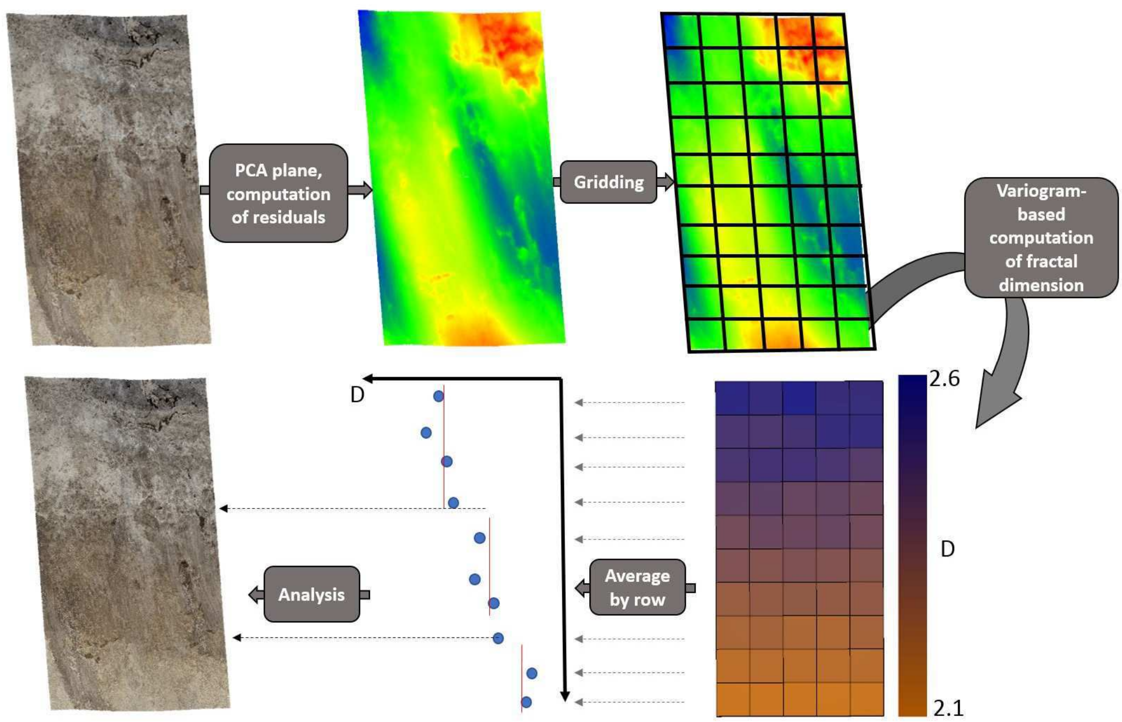

*Figure 2.Workflow for detecting palaeo-earthquake events along fault scarps using fractal dimension D. From the defined areas of the fault scarp, the fractal dimension is computed using a variogram computation and fitting. Variability in fractal dimension have been shown to be potentially associated with surface roughness variability, hence different earthquale events (*HE et al., 2016; S et al., 2020).

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Rockfall activity identification by means of Terrestrial Laser Scanner and Machine Learning. Case study at Montserrat Massif (Catalonia, Spain)

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Key words: *terrestrial laser scanner, machine learning, rockfall.*

Rockfall monitoring with remote sensing techniques has been an accepted technique by the scientific community from years. The digital capture of a rock cliff in a point cloud can be done with photogrammetric or LIDAR (LIght Detection And Ranging) techniques. The requirements of temporal and spatial resolutions, as well as the precision, budget, logistics and dilatory processes, condition the selection of technique and device. The digital capture must be complemented by an efficient methodology for the identification and classification of the changes in the point cloud due to rockfall activity.

The methodology presented here is implemented in a computer solution that tries to minimize user intervention. Monitoring with high temporal resolution can be an advantage to create a machine learning system. The developed algorithms identify clusters of points with different values of position, taking a threshold value as a reference with respect to a previous point cloud. The algorithms also characterize these clusters through seventeen geometric and textural parameters statistically analyzed to classify the different process occurred on the cliff, such as a) rockfall, b) small rock movements on the cliff as rock displacement prior to a rockfall and c) non-interest clusters of vegetation or noise like edge effects.

Machine learning techniques are applied to classify clusters characterized by rockfalls or small movements events (ZOUMPEKAS, 2021). For this reason, the system builds a mathematical model or "training data" based on clusters previously classified by the user. With this learning, the system can classify automatically clusters from new point clouds. Machine learning strategy has been tested to achieve an optimal solution and adapted to each scenario.

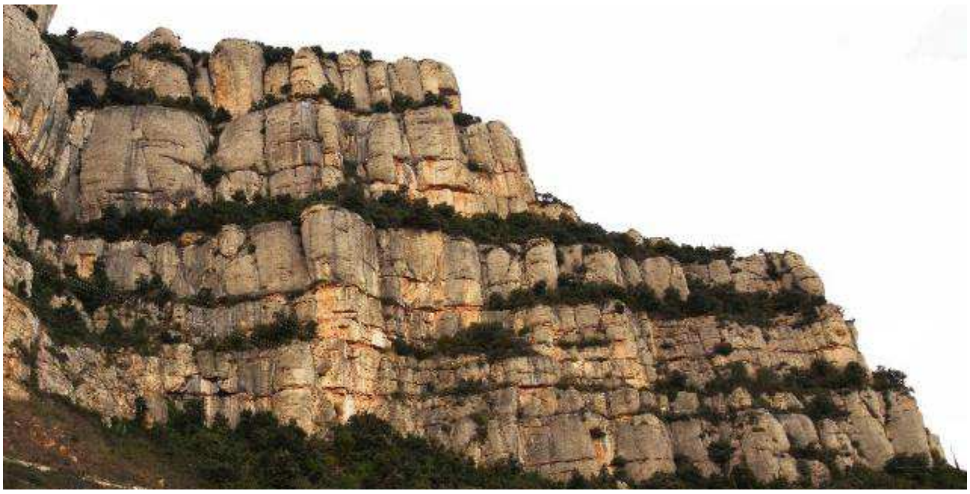

Figure 1: Left. Landscape of the Montserrat Massif outcrop selected for testing the methodology.

The proposed methodology has been tested in the Montserrat Massif (Barcelona, NE Spain), a fractured conglomerate outcrop (150 m height and 190 m length) with a long history of rockfalls and a high presence of visitors (JANERAS *et al.*, 2016).

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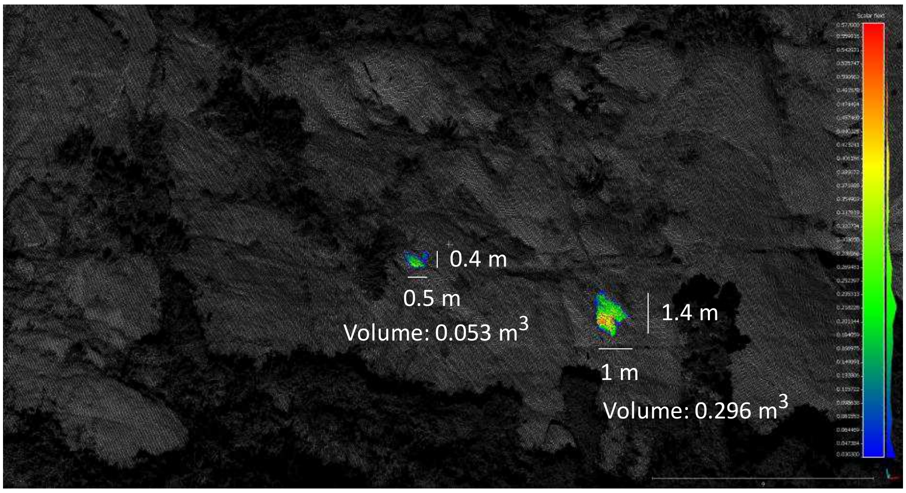

Figure 2: Two examples of cluster classified as rockfall coloured with the distance parameter calculated perpendicularly to the Montserrat cliff surface. Monitoring dates: Decembre 2017 - July 2018

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Automated processing of SfM-MVS in underground mining geology using Agisoft Metashape

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Key words: *SfM-MVS, digital photogrammetry, Python, underground mining*

The use of structure-from-motion, multi-view stereo (SfM-MVS) in the mining industry is well-established for capturing digital data. In underground mining, development faces are typically blasted within a day, thus SfM-MVS allows faces to be viewed and mapped in the form of a virtual outcrop.

When using SfM-MVS in underground mining, it is possible to have several captures that need to be processed per day. These captures require several, user-interacted steps during processing and can take several hours per day. Here we present a methodology to automate processing using Agisoft Metashape Professional v1.6. The method requires minor modification during capture of a development face and uses a custom Python script to process the development. The script utilises a loop to iterate through captures without the need for user interaction.

At the development face, coded targets from Metashape are surveyed to georeference the capture in a local mine grid so that the virtual outcrop can be used in 3D modelling software. The coded targets also allow for automated marker detection in images during processing. An additional 4 points are captured in a specific order to be used in region modifying during automated processing. Notably, these points do not have an associated coded target and therefore not used in georeferencing.

The first 3 points (captured at the unsupported ground line; Fig. 1) form a triangle, orthogonal to the development direction (Fig. 2). The 4th point is captured on the face and forms the lower elevation of the region (Fig.1). Together, the 4 points are used to calculate a rigid transformation matrix (see CREUS *et al.*, 2021), which is applied to the region so that the 3D reconstruction can be trimmed of unnecessary parts and artefacts (Fig. 1).

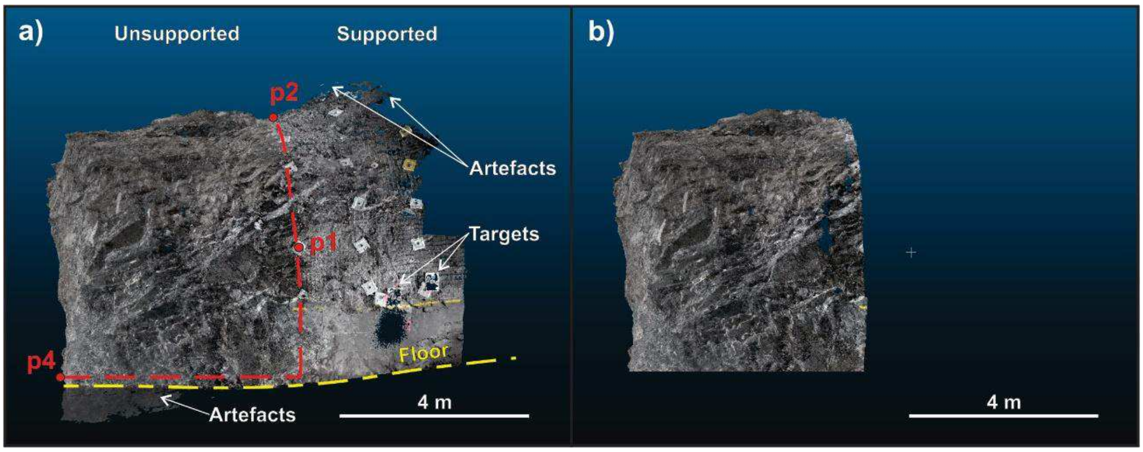

Figure 1: Sideview of a development face. a) Untrimmed mesh, which includes artefacts. The red dashed line delineates the region shown in (b). b) Trimming the data excludes the ground support mesh and the floor of the development.

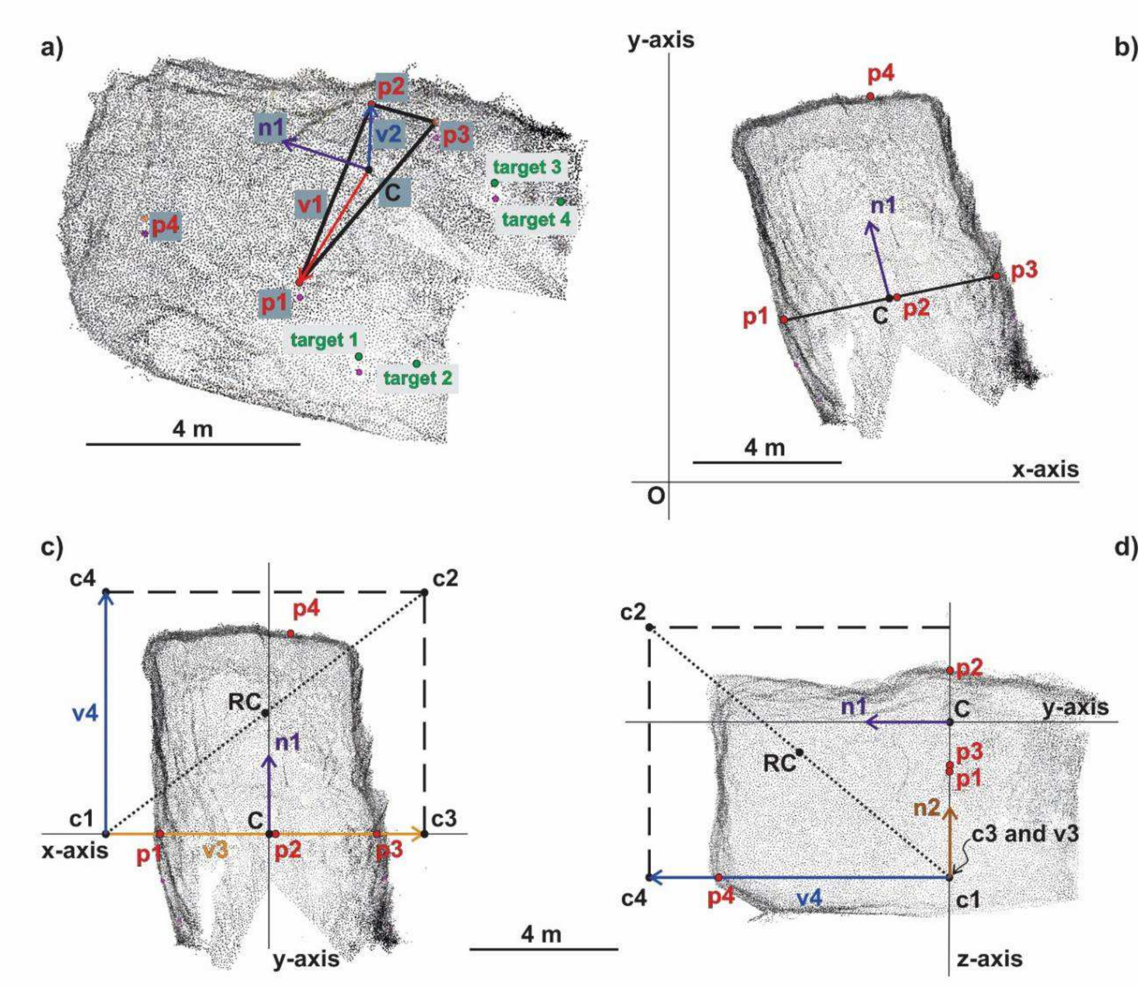

Figure 2: Steps involved in modifying the region of the capture. a) The centroid of triangle (p1 – p3) forms the origin of a coordinate system translation (C). c) Using geometry and a transformation matrix, the capture is translated and rotated, so that the normal (n1) of triangle (p1 – p3) is parallel to the y-axis and its direction used to determine which side of the x-axis to keep. d) The box defined by the dashed black line is the part of the capture that is kept.

Acknowledgements: MMG- Dugald River are thanked for providing funding and access to data for this project. Agisoft are thanked for providing an academic license for Metashape Professional.

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Flood risk assessment at the plot scale, from DEM and hydraulic modelling

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Key words: *Flood hazard, streamflow, digital elevation model (DEM), hydraulic model*

The flood hazard is addressed by the Risk Prevention Plan (PPR) in France, which is a regulatory tool in land use planning. Nearly 17 million French people are exposed to flood risks such as the rivers overflow, marine submersion, groundwater rise, runoff during rainy events and runoff in urban areas. For mapping flood risks at the plot scale, it is necessary to have the spatial extension using a Digital Elevation Model (DEM) and to model the streamflow with a hydraulic model.

In France, there are open-access flood risks maps, but they are generally created with the IGN BD-Alti (25, 75 meters) database. Now, the RGE Alti (1 or 5 meters) is also available but at the plot scale, this DEM is not adapted. Moreover it is built

. So, coupling the photogrammetry and the 3D-scan is the solution to have a DEM with a high resolution (centimetric). With this methodology, we have a high-resolution 3D-model showing streams of small width and shallow depth (<20 cm for example) in vegetated and urbanised areas.

At the plot scale, we want to compare flood risk according to the 10-year, 50-year and 100-year flood. Two hydraulic models, based on the finite volume method, are realised according to our high-resolution DEM (Figure 1) and to the open-access 1 meter resolution DEM.

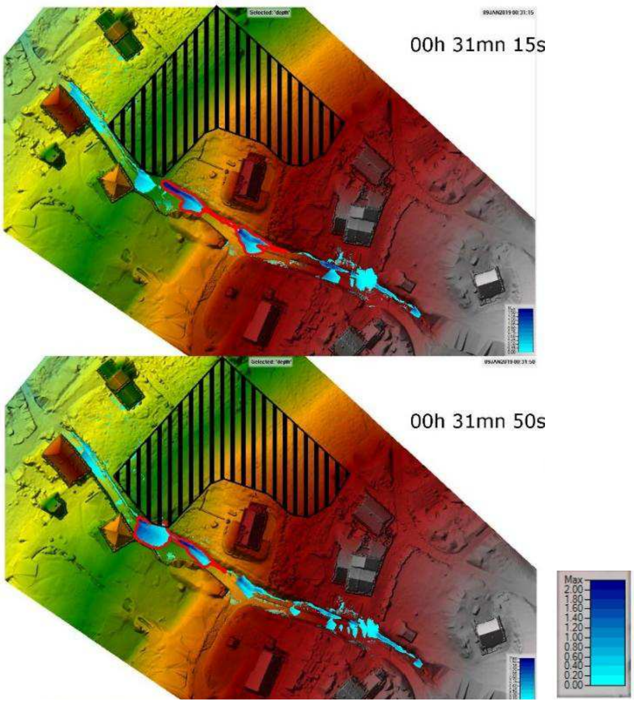

Figure 1 Result of the 2D non-permanent flow modelling with high-resolution DEM

The Rim-Nat platform, developed by Geolithe Innov, presents a 3D visualisation that visualise the flood wave (Figure 2).

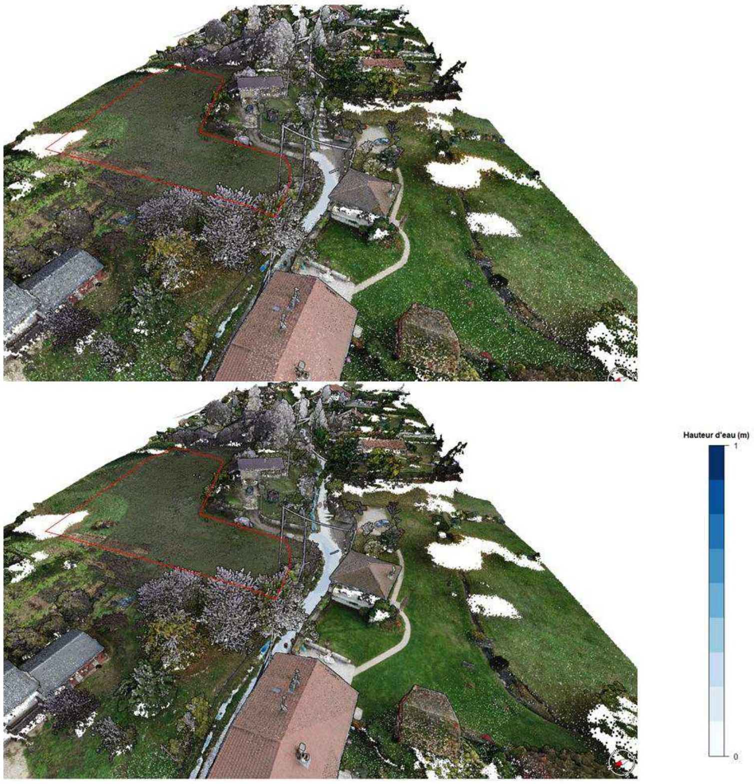

Figure 2 Representation in 3D, with the Rim-Nat platform, of the flood wave with high resolution DEM. In red line, the study area limits. At the middle of the figure, white and blue areas are the water depth

A high-resolution DEM with hydraulic models is a necessary combination tools to limit uncertainties, as wooded and urbanized areas or small surface stream, in order to better manage building areas by public organisations or by private individual.

High-resolution Digital Outcrop Modelling of terrestrial analogues for education on Planetary Geology.

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Key words: *Digital Outcrop Model, Virtual Reality, Photogrammetry, Virtual field-trip, Sedimentology, Planetary Geology.*

Teaching in Planetary Geology relies both on remote data gathered by various probes exploring the solar system (orbiters, landers and rovers), and on the study of terrestrial analogues sites. Usually, a field-trip on selected outcrops is the most widely used approach. However, this cannot always be possible for various reasons, such as a far distance of the site, safety or accessibility issues, cost, etc.

To overcome these problematics, a complementary solution is progressively emerging thanks to 3D reconstruction and Virtual Reality (VR) techniques. Virtual field-trips can be organized using high-resolution 3D recreations of outcrops providing relevant analogues for Planetary Geology. Here, we specifically focus on the "Goldmine Beach" outcrop in western France (Pénestin, Morbihan), that displays a suite of fluvial siliciclastic sedimentary rocks and structures (VAN VLIET-LANOË *et al.*, 1997; BRAULT *et al.*, 2001) used as an analogue to Martian fluvial valley systems. Our objectives are to: 1) Produce a highly-resolved 3D photogrammetric model of the outcrop, 2) Evaluate the accuracy of the 3D model reconstruction process by comparing it with ground-truth measurements, and in particular by evaluating the accuracy of the reconstruction computed with limited conditions similar to the ones available from Martian rovers; and 3) Integrate the model within a VR system to allow our students to roam over and characterize at real scale the entire outcrop.

We made two Digital Outcrop Models (DOMs) of the "Goldmine Beach" outcrop using Structure-from-Motion photogrammetry. The first model was obtained using a set of photos taken following the usual procedure for photogrammetric reconstruction (fixed optical parameters, homogeneous lighting, maximum overlapping and coverage). It provides the maximum accuracy to allow our students a close mm-scale inspection of the outcrop and its structures. The second model was made using a "degraded" set of photos, analogue to the photos taken by the Mars Science Laboratory *Curiosity* rover (varying optical parameters – focal length, frame resolution –, heterogenous lighting, lower overlapping, non-optimal coverage). This second model has a good accuracy despite the degraded observing conditions (Fig. 1) and thus validate the creation of Martian DOMs produced from *Curiosity* data (e.g., CARAVACA *et al.*, 2020) in a controlled case.

The DOM was subsequently integrated within a VR environment (Fig. 2), using either SteamVR, Sketchfab online platform, or a game engine. In the VR environment, several students and a teacher can interact using real-time networked telepresence to observe, characterize and interpret the structures of the outcrop (Fig. 2a), including the most remote parts that are not accessible on the real outcrop (e.g., top of the cliff; Fig. 2b). Additionally, it is possible to "come back" to the virtual place at any time for further observations and get familiar with taught structures taking advantage of the online availability of the model on the Sketchfab platform (model available at: https://skfb.ly/6WJrW. VR has the potential to become a major part of our Geoscience lessons in the coming years for both remote planetary outcrops (Moon, Mars, etc.) and their terrestrial analogues.

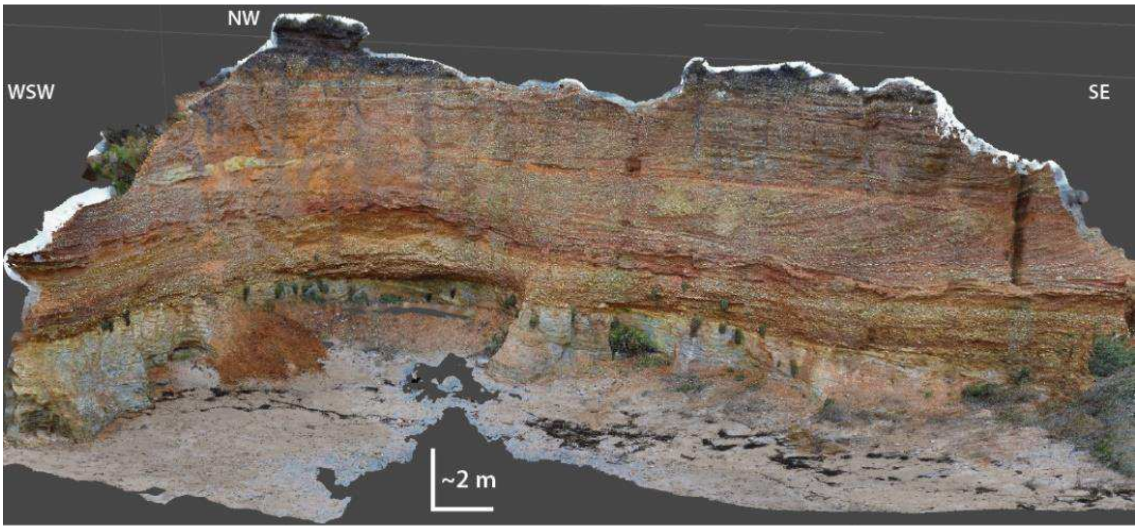

*Figure 1: Preview of the Goldmine Beach outcrop high-resolution DOM produced under Agisoft Metashape photogrammetry software and using an MSL/*Curiosity*-analogue photoset. The reconstruction includes the well-expressed fluvial sedimentary pattern on the upper part of the outcrop. DOM available on Sketchfab at: https://skfb.ly/6WJrW.*

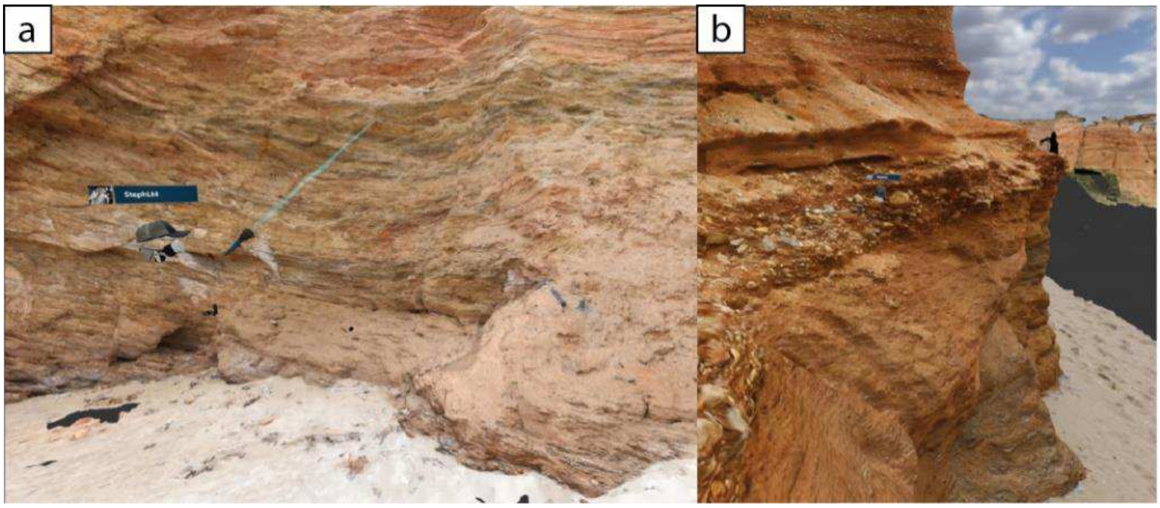

Figure 1: Screen capture of the Virtual Reality environment featuring the Goldmine Beach outcrop; a) VR avatar of a teacher pointing a structure of interest on the DOM. The hammer is modelled for scaling; b) Same VR teacher avatar pointing another structure from a remote place on top of the cliff, where access is prevented on the real outcrop.

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Method to Estimate the Initial Landslide failure Surface and Volumes using Grid Points and Spline Curves

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Keywords: *Spline curves, Contour limits, Landslide failure surface, Right and Left profiles, Dip-Strikes*

Here we present a new method to estimate the Landslide failure surface and volume using the grid points and spline curves based on a tangent of the failure surface. The Model requires fundamental data inputs, which are readily available online. The challenge in landslide hazard assessment is to estimate the volume involved in slope movements before carrying out a detailed field survey. The volumes are usually only defined once the instability is detected. Digital Elevation Models (DEM) 's increasing availability enables us to estimate the volumes involved in slope movements, thus limiting expensive field investigations*(Jaboyedoff, M. et al., 2004)*. This Model requires a DEM of the study area and a KML file of contour limits of the landslide as an input. The calculation procedure is simple-using DEM; we have made grid points for each cell (Fig1.b). The cross-section for each point has been drawn perpendicular to the slope line joining the Highest elevation point and lowest one within the contour limits. A cubic spline curve requires four parameters, which can be taken from each cross-section endpoint*(Michel Jaboyedoff et al.,2020*) (Coordinates of two endpoints and first derivative at these points).

The Z value has been calculated at each grid point using these parameters, and finally, a 3D failure surface has been generated. And volume can be calculated using the elevation difference of failure surface and original surface multiplying by the cell size of each grid point. Approximately 1100 line Matlab code has been written to execute this process automatically. We have proposed three methods for variation of the angles between the failure surface and the cross-section lines.

In Method-1, we have assumed the angles are constant for each cross-section. In the 2nd Method, the weights for the Angle variation have been given based on the distance of endpoints from the elevation line joining the highest and lowest points. Here the Dip and strike angles are varying non-linearly and inversely proportional to the distance.

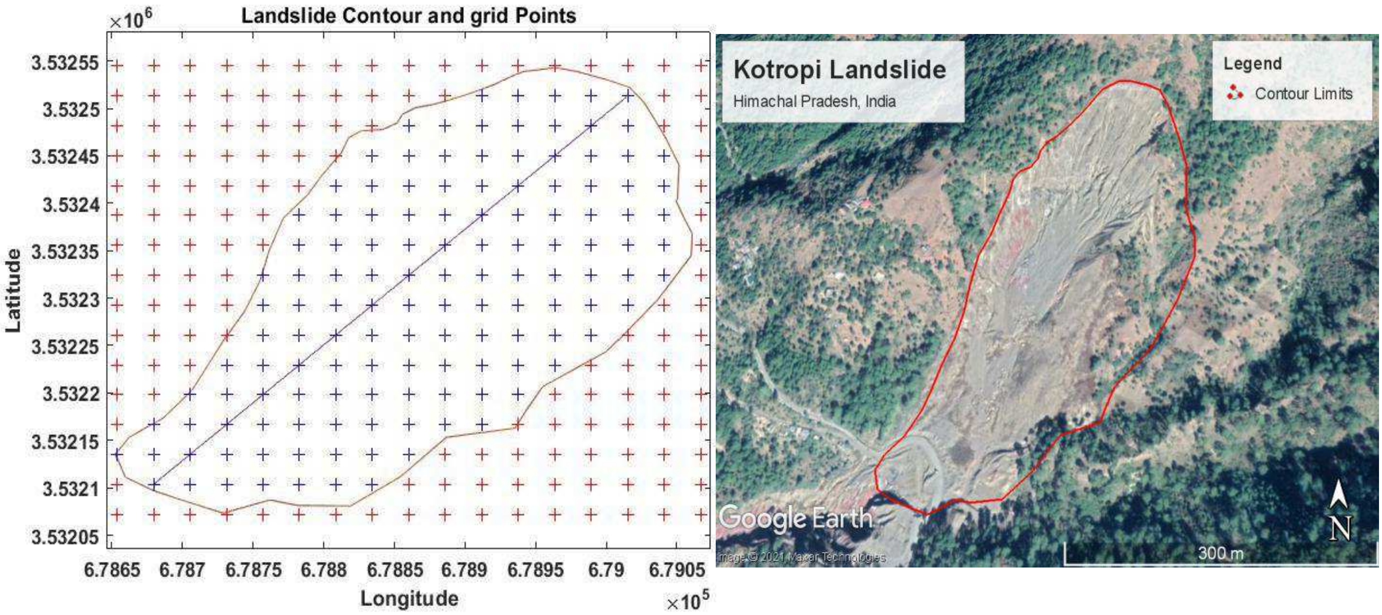

Figure 1:Location of the landslide(Right side) and the gride points and elevation line passing through the highest and lowest elevation points(Left side). The Z value for each point will be calculated using a spline curve.

In the 3rd Method, it has been assumed that the Left and Right profiles of the failure surfaces are part of a big arc, and the Dip and Strike angles are varying linearly.

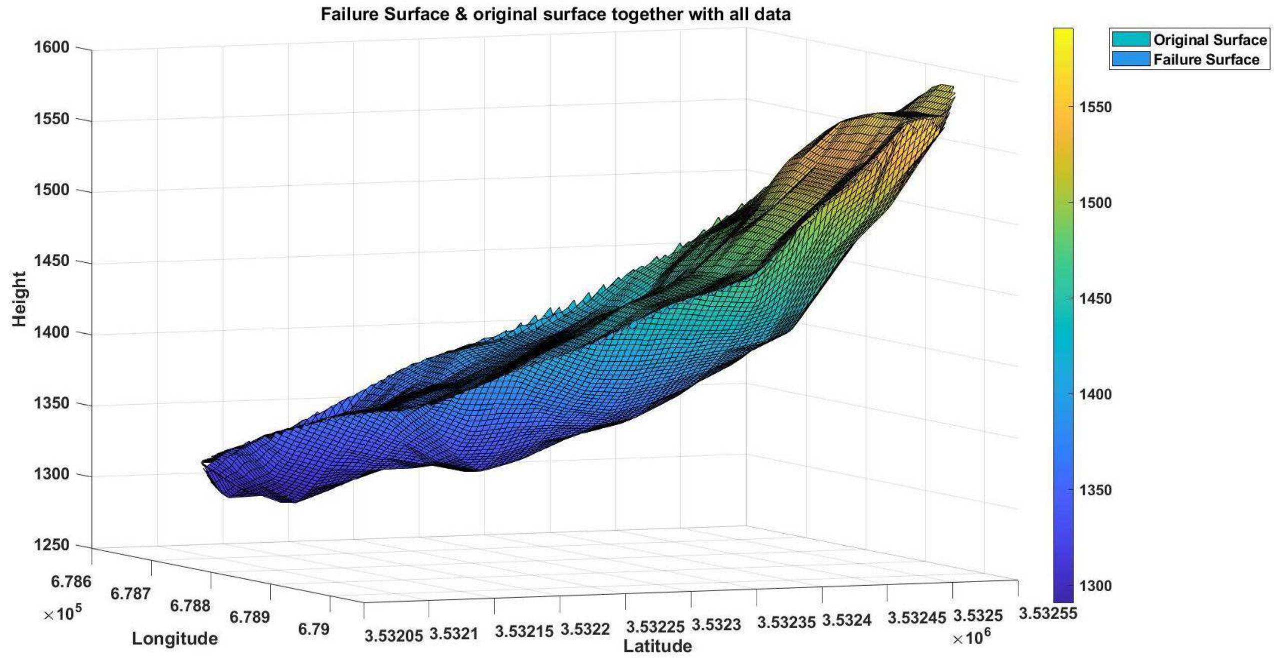

Figure 2. 3D-View Kotropi Landslide with Failure surface and original surface together. Posted after refining the gride

We have tested the Model on the Kotropi landslide of August 2017, Himachal Pradesh, India *(Sharma, P. et al.,2019)* and The La Frasse landslide in the Canton of Vaud (Switzerland). The Kotropi landslide (Fig 1.a) is found at N31° 54′ 39.4″ and E76° 53′ 27.4 on the Indian toposheet Number, 53A/13. A large scrap of the slope has been washed away along with the vast Volume of debris and other properties like two-state government busses and few other vehicles *(Pradhan, S.P. et al., 2017)*. Government reports suggest that there have been at least 46 deaths caused by this disastrous event which buried nearly half a kilometre of the highway, disrupting state transportation very severely. Here in Fig-2, we have shown the 3-D Model of the calculated failure surface and the original surface. Here method-1 has been used with-(Right profile constant Dip=42^0 and Left profile constant Dip=59º. The Volume has been calculated, and it is approximately 5.9 million m^3.

The implication of this model is straightforward. We can easily get the required data with very little fieldwork, and the processing will hardly take a few minutes to produce the result. Its advantages are that it allows the use of data sources available all over the globe can be used based using DEM and images such as Tiff files, ASC files, KML and other standard data inputs. There are so many parameters; we can manipulate accordingly to get better results. We can enrich the real scenario by making more constraints on the variation of the cross-section angle based on field measurement. This model is also helpful in predicting the area that can be affected by the mass of the failure surface, and we can make a predefined risk zone to avoid any casualties in future.

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Multi-disciplinary approach for stability analyses in discontinuous rock masses by means of conventional geostructural-geomechanical surveys and remote sensing techniques

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Key words: *remote sensing, discontinuities, rock mass characterization, 2D quantitative analyses, modeling*

In the last two decades, the application of remote sensing techniques in Earth Sciences has become mainstream. As regards the characterization of rock masses, several methods for the semi-automatic and /or automatic extraction of discontinuity sets and their properties, from raw point clouds or processed surfaces, were introduced in the literature. However, when dealing with low-relief outcrops or man-made excavations, extracting discontinuities from point clouds can be challenging because of the lack of exposed surfaces, thus leading to not realistic rock mass characterization. In these circumstances, 2D quantitative analyses on discontinuities mapped in orthophotos seem to have higher reliability. In addition, numerical stability analyses on rock masses often require the simplification of the model to avoid time-consuming computations and non-convergence issues, which results in partly disregarding the remote sensing data.

Aiming at a full exploitation of the potential of remote sensing techniques in the framework of rock stability analyses, we developed a multi-disciplinary approach which combines conventional geostructural-geomechanical surveys and remote sensing technologies. We carried out Unmanned Aerial Vehicle (UAV) surveys on a 20 m high cliff and on an adjacent low-relief area. Successively, we applied Structure from Motion technique to obtain a mesh of the cliff and a high-resolution orthophoto of the flat area. We compiled a specific Matlab routine to semi-automatically identify and characterize the discontinuity sets from the joint traces on the orthophoto. Conventional geostructural-geomechanical surveys were performed to validate the results of 2D quantitative analysis of the discontinuities and to assess the non-geometrical parameters (i.e. roughness, wall strength, aperture). Furthermore, we collected representative rock samples for the physical and mechanical characterization. The different lithofacies were mapped on the mesh of the cliff with the help of UAV-acquired photographs.

We then used the above data to perform a 3D Finite Element Analysis, using a software that allows to implement ubiquitous joints. The geometric model was created by importing the Digital Terrain Model (2 m resolution) of a wider zone and merging the high-resolution mesh of the case study. The lithofacies were created by dividing the 3D model with planes generated along the previously mapped interfaces. The physical and mechanical properties of the rock materials, as well as the strength criteria, were defined according to the outcomes of the geotechnical characterization. Moreover, 3 discontinuity sets were added using the 2D quantitative analysis results. To derive the initial tensional state, we created an additional volume which was eroded during the middle-Pleistocene sea-level regression. After assigning the restraints to the model, an appropriate mesh was created. The transition from shallow-water carbonate platform to the current morphology was simulated by means of successive excavations during the computation.

Despite the presence of the weak Plio-Pleistocene transgressive deposits at the top of the cliff, local instabilities were detected along overhanging blocks and karst caves in the jointed limestones and dolostones. The failure mechanisms are compatible with the results of on-site geomechanical investigations.

Sonification of very low frequency signals:
Listening to seafloor pressure and meteorological time series

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Key words: *Sonification, Auditory display, Time series, Sea waves, Tsunami, Oceanography, Meteorology*

As part of a tsunami modelling project, pressure recorders were placed at the bottom of the Sea of Marmara (Turkey) in 800 to 1200 m water depth in order to detect seiche phenomena and measure their periods and amplitudes (HENRY *et al*., 2021). Seiches are resonant oscillations of the surface of a closed sea or lake that can be triggered by earthquakes or meteorological events. Seiches in Sea of Marmara have a period of 10 to 120 minutes (YALCINER & PELINOVKY, 2007) and the strongly accelerated reading of the waveform, similar to a sound wave, makes them audible (audification). The oscillation modes are governed by a non-dispersive wave propagation equation, making the sea surface analogous to an irregularly shaped drum membrane. In fact, the sound obtained evokes a chaotic rolling. The objective of this work is to combine signal processing and listening tests to clarify the relationships between meteorological events and observed resonant phenomena (seiche), via the analysis of their representations as sound (PATÉ *et al.*, 2017). Several approaches are tried: (1) the perceptual categorization of sound events and its relation to their physical attributes (frequency content, envelope, etc.), (2) the search for temporal correlations between seiche and meteorological events by comparing the pressure signal recorded with synthetic signals generated from meteorological recordings (all these signals potentially being transposed into the audible domain for auditory analysis), (3) the development of an acoustic zoom based on time-stretching methods or granular synthesis to more detailed listening of the signals.

The seafloor pressure records sampled at 5 seconds or 300 seconds depending on the deployment may be considered as waveforms and, at least for a first approach, can be made audible with simple acceleration. This is not possible for the available meteorological time series, which are hourly reanalysed datasets. We experiment various combinations of frequency or amplitude modulation and filtering to generate sounds from wind velocity data to convey information on its physical parameters through hearing (velocity, direction, rate of change). Vector based or distance-based amplitude panning (VBAP and DBAP; PULKKI, 1997; LOSSIUS *et al*., 2009) are used for spatializing the sound source as a function of wind direction or change of direction. The sounds generated from the seafloor pressure time series and the wind time series can then be listened simultaneously, the aim being to understand whether hypotheses on the mechanisms triggering pressure oscillations at the seafloor can be tested through sonification. We request an interactive presentation slot in order to demonstrate the sonification methods and gain feedback from attendees on their perceptions.

Acknowledgements: Financial support for the acquisition of the seafloor time series was provided by the bilateral ANR/TÜBITAK collaborative research project MAREGAMI (ANR-16-CE03-0010-02 and Tübitak Project 116Y371) and by CNRS-INSU through the European Multidisciplinary Sea Observatory (EMSO) Research Infrastructure program.

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Developing Virtual Field Trips using Geocognition Principles

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Key words: *Virtual Reality, Panorama High Definition, Geocognition, Blended Learning*

While acknowledging that exposure to real fieldwork is indispensable, the ability for virtual reality to immerse the user into an alternate environment has been greatly improved in recent years and the educational abilities for virtual reality have been seen to be very beneficial in aiding and enhancing traditional methods of teaching (Hurst, 1998; Spicer & Stratford, 2001),. This allows some relief for institutional resources as ever-increasing health and safety regulations, combined with growing class sizes have caused curtailment of field excursions (Hurst, 1998; Spicer & Stratford, 2001). It also makes it possible for students with mobility restrictions to participate in a safe environment without leaving the university grounds (Stanfield, et al., 2000). The advancements in digital photo processing and image development have allowed for the integration of high-definition panorama photographs with virtual reality systems to create virtual reality tours of geological outcrops. These can be used as pre-study material to familiarize students with outcrops before going into the field to do field observations and study outcrops. In our study, High-Definition images were taken of outcrops used in the Department of Earth Sciences' first-year service course field trips and then developed to produce a virtual and interactive tour followed by an assessment to gauge the learning gain made by students' interaction with the tour. This tour was developed in conjunction with geo-cognition principles that are based on the use of annotations, overlays and suggestive questions (Libarkin & Brick, 2002; Petcovic & Libarkin, 2007). This was done to guide the student to fuse individual features and definitions into an understanding of a geological concept that comes with the natural progression from novice to expert (Benner, 1982; Petcovic & Libarkin, 2007). The first year class' scores were analyzed in 2 groups; a group that attended the tour orientation and a group that didn't attend the orientation. The group that attended the tour orientation scored a significantly higher average than the group that didn't.

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VR2Planets, virtual reality for geosciences and education

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Key words: *virtual reality, orbital imagery, photogrammetric model, assessments, measurement tools*

VR2Planets is a spin of from the CNRS created by the will of two researchers LPGNantes, at the Nantes University, in order to improve the scientific knowledge diffusion and the visualisation of imagery data acquired by the space exploration probes. The new technology of virtual reality offers a fantastic tool to work on the complex available data. Therefore, users can visualize in three dimensions the studied lands and outcrops . These technologies make possible a great improvement of analysis and understanding of the information which become the basis for a new exchange quality with colleagues, students, and the public. The specificity of VR2Planets' software is the ability to create georeferenced virtual scenes from orbit to ground data (satellite, drone or in-situ images) at full scale in a fully surrounded universe (Fig. 1). VR2Planets has developed a network interface to let users the ability to be connected in the same virtual scene even from remote places.

Figure 1: A/ immersive experience in Gale crater (Curiosity landing site) in collaboration, with a teacher (red avatar in Nantes) and 4 students (orange avatar in Nantes, Paris, and Toulouse). B/ Each user can use its own tool menu to extract, share and export quantitative information from the virtual world in a standard format.

VR2planets develops tools for visualizing large amounts of data from: DTM/orthoimages, point clouds or photogrammetric models. To visualize large amounts of data in collaborative fluid virtual environments, it is necessary to control the graphic resources in a very precise way: a virtual reality headset must be able to display 90 frames per second in "full HD" quality in each eye. Based on the latest generation of consumer graphics cards, our software is specifically adapted to the display constraints of immersive tools. We have developed interaction tools to extract quantified information from virtual worlds to allow researchers, teachers, and students to obtain the necessary information for papers, courses, or learning (Fig. 1.B & 2).

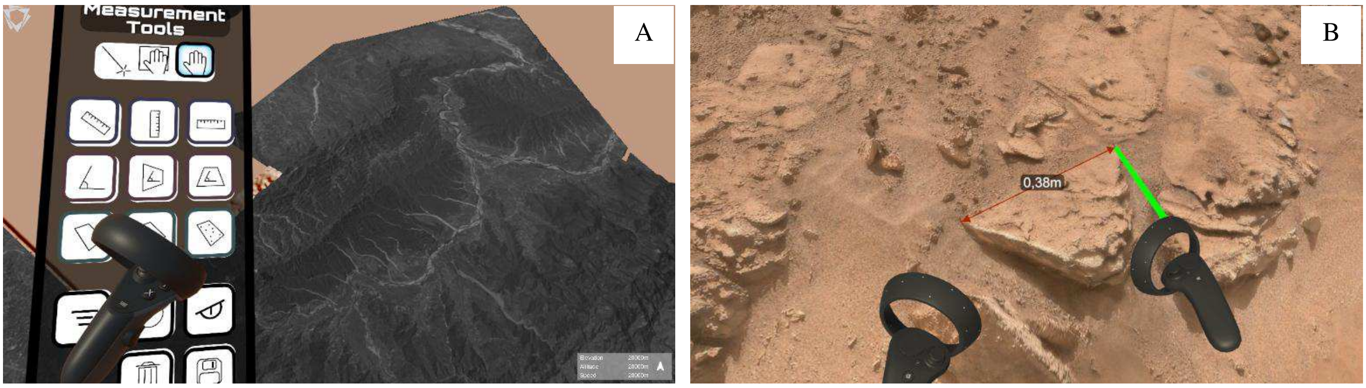

Figure 2. virtual tool menu to extract quantitative information from the virtual world: distances and angles (direct and their respective projection on horizontal and vertical planes), best fit planes, georeferenced position of points, and clinometer.

3D modelling of an avalanche experiment using multi-platform remote observations

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Key words: *Structure-from-Motion, photogrammetry, avalanche, UAS*

On April 11, 2021, a size 4 avalanche was released at the NGI test site Ryggfonn near Stryn, western Norway, one of two such large-scale experimental facilities in the world. In addition to permanently-installed instrumentation used to measure dynamic avalanche parameters (GAUER & KRISTENSEN, 2016), a suite of ground-based, airborne and satellite observation techniques were deployed to monitor the valley before, during and after the experiment. Among the observation methods used were 1) a pair of DLSR cameras with long lenses mounted in a fixed position atop the mountain opposite the avalanche path, 2) an Uncrewed Aircraft System (UAS) used to survey the lower portion of the 1.5-km long avalanche path, both before and after the experiment, and used as a hovering camera in the valley to record video during the event, and 3) high-resolution satellite imagery of the valley that was tasked shortly after the event. The various imaging techniques were used to estimate and map the volume and distribution of the mobilized snow, while also being used to reconstruct and visualize real-time information about the avalanche.

Oblique frames of the avalanche event were exported from the ground-based video footage. The images were then georeferenced before visualisation and further analysis. A mono-photogrammetric (monoplotting) approach supported 3D reconstruction from oblique and unrectified imagery. The approach utilized a semi-automated calibration process for the camera, an editor for defining and measuring features of interest, and visualisation of one or more photographs of the target landscape, as depicted in Figure 1. The mono-photogrammetric reconstruction technique was highly dependent on the quality of the terrain model used in the analysis.

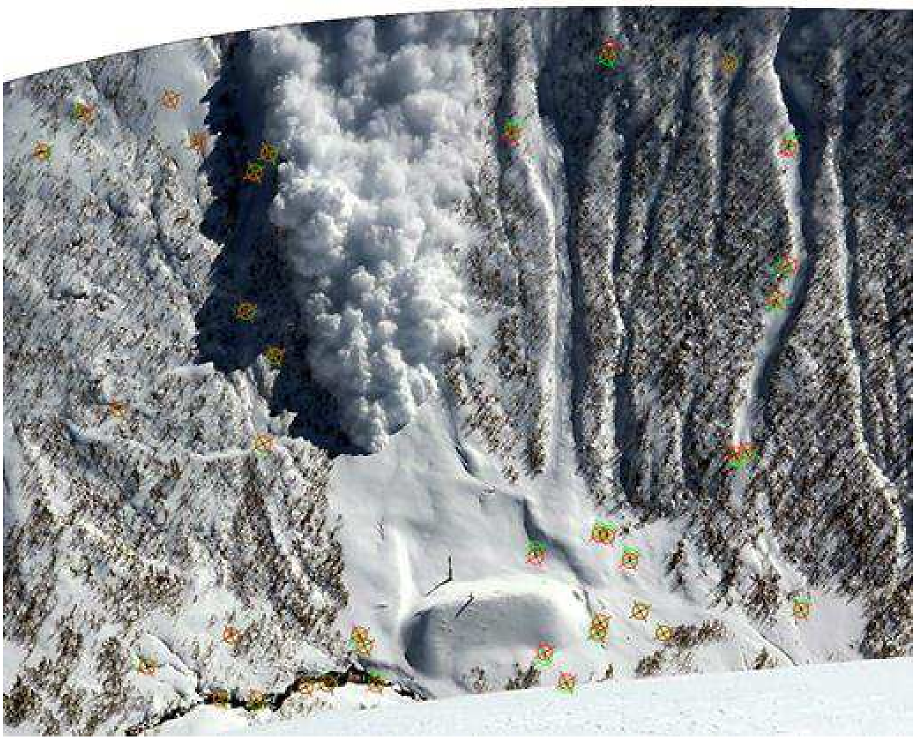

Figure 1: Oblique and unrectified image of the avalanche approaching the instrumented embankment dam; image used for mono-photogrammetric reconstruction and measurement of avalanche characteristics.

For the UAS-based observations, a directly georeferenced photogrammetric survey approach was utilized. The Structure-from-Motion Multi-View-Stereo (SFM-MVS) reconstruction of approximately 500 UAS images relied on a combination of real-time-kinematic (RTK) positioning and a limited number of ground control points, due to the inaccessibility of the area surrounding the avalanche path. Total mobilized snow volume was estimated from the difference between the pair of independently georeferenced surface models (before, after the event), while orthomosaics provided high-resolution overviews (7 cm x 7 cm spatial ground resolution) of the avalanche path (Figure 2). Additional UAS surveys were performed over the same area in a baseline condition, i.e. without any snow cover, to derive a snow cover map of the path and surrounding valley. Python-enabled GIS and statistical analyses were performed to assess the quality of the UAS-derived products and to provide comparison for coarser resolution Airborne Laser Scanning (ALS) data.

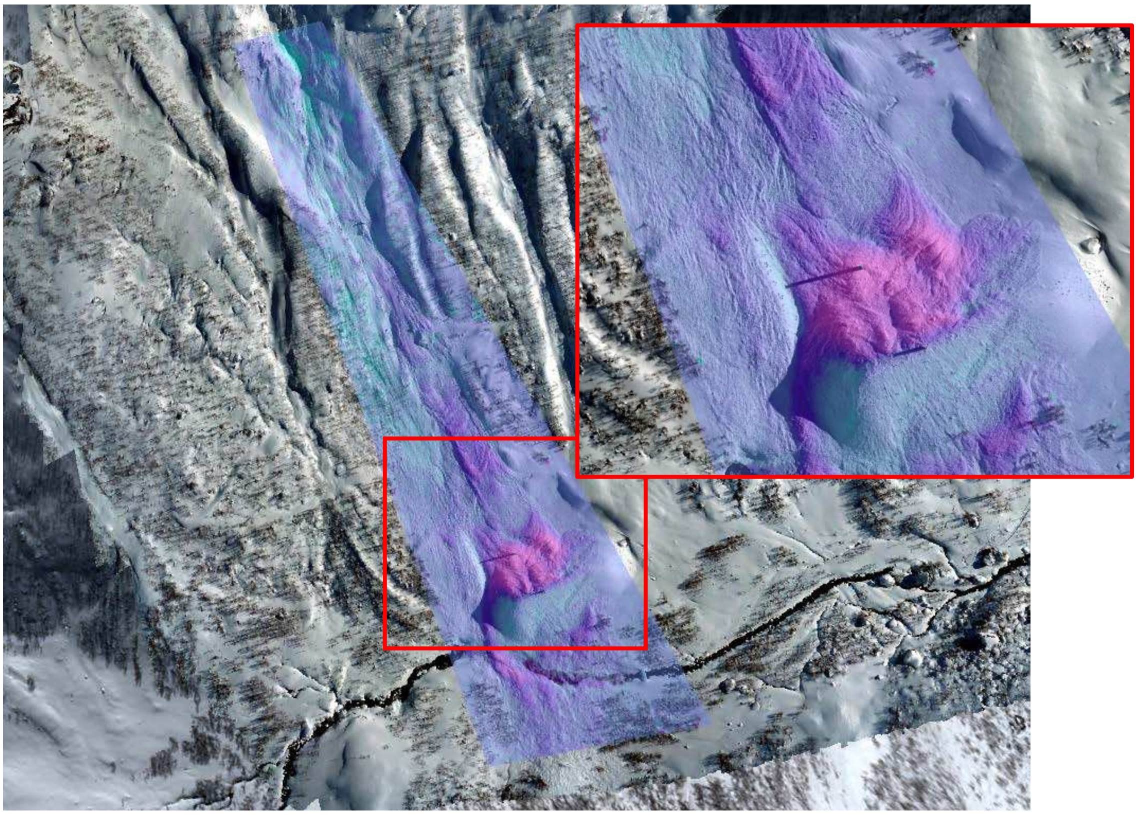

Figure 2. Difference of UAS-derived surface models generated before and after the avalanche experiment (warmer colours indicate snow accumulation, while cooler colours represent snow erosion); difference map displayed on top of UAS-derived orthomosaic and high-resolution satellite image.

In addition to ground-based and UAS surveying techniques, a Pléiades high-resolution optical satellite image (0.5 m x 0.5 m spatial ground resolution) was tasked over the area following the experiment. The image provides additional information on the path of the avalanche not covered by the drone surveys.

The multi-temporal, multi-platform suite of observation techniques, that were used to monitor the avalanche experiment, enable unique visualization and analysis opportunities. The techniques provide an estimate on the spatial distribution of the mass balance, which is an important parameter for avalanche dynamics.

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4D Virtual Outcrops for Natural Hazard Monitoring

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Key words: *4D, Timelapse, Virtual Outcrop, Landslide Monitoring, Catterline, Stromboli, Volcano, UAV*

Virtual outcrops first appeared at the turn of the century and have become mainstream tools in the geoscience tool box in the last 10 years, with the advent of UAVs and SfM. They have a wide variety of utilities from detailed outcrop characterization to virtual fieldtrips and with the advent of easy to use interpretation and manipulation software such as Lime (Buckley et al. 2019) and the easy, wide spread sharing of data with tools such as V3Geo (Buckley et al. this vol), they have become a standard part of the field geologists toolkit.

A logical progression of this work is the "time lapse" monitoring of areas of the Earth's surface that are in constant flux such as volcanos and unstable slopes. Here with the use of repeat surveys it is possible to quantify the rates of change and the volumes of material that are removed or added, often in areas that are otherwise inaccessible (e.g. Williams et al 2018).

Here we present two case studies that were undertaken to determine and monitor long term changes in an active volcano (Stromboli) and an actively degrading slope below the historic coastal village of Catterline in NE Scotland.

Stromboli is an active volcano in the Aeolian Islands, southern Italy. It is characterized by near continuous small scale eruptions interspersed with occasional, more destructive, large magnitude events. A number of repeat surveys have been undertaken on the island, in 2016, 2017 and 2019. During these field seasons data were collected to build a thermal 3D model which captured the structure of the active lava flows (Wakeford et al., 2019). Prior to the most recent field season (June 2019) a major paroxysm (volcanic event) significant modified the geometry of the west crater and added significant volumes of material to the west side of the Sciara del Fuoco (the main lava talus slope). Difference models between the repeat surveys (Fig. 1) illustrate that 171,818 cubic m^3 of material were removed from the crater rim during the eruption and 620,209 m^3 was added to the talus slope. Suggesting that in addition to the material that has been resedimented after the eruption, an additional 450000 m^3 has been added as fresh lava. There is a vertical accretion of the talus slope of over 30 m. These numbers are minimum estimates as some of the material has reached the sea and now lies below the water level.

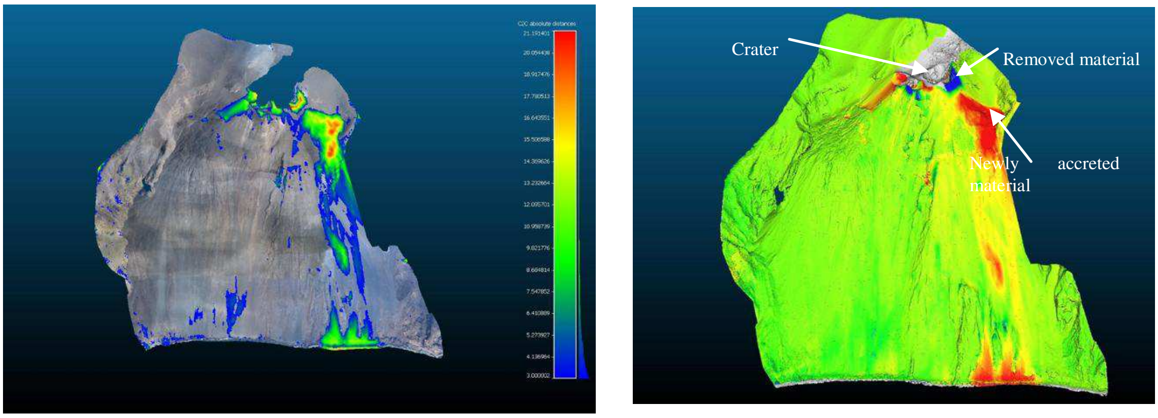

Figure 1. Time series analysis of the models from the Sciara del Fuoco, Stromboli. The talus slope in the view is 900 m high.

Catterline is a historic coastal village on the NE coast of Scotland. The village sits on top of a series of steep coastal cliffs comprised of Quaternary tills and diamictites (Mill of Forest Fm) which are up to 15 m thick, which overlie hard, resistant Devonian Conglomerates. The landslides occur within the tills. UAV mounted photogrammetric surveys have been undertaken annually over the last six years and most recently have been used to the support a pilot study for installing a series of test “Nature Based” slope stabilization solutions in collaboration with Glasgow Caledonia University. The surveys which clearly document the rate and magnitude of the slope have been used as the basis for the series of funding applications as they are a very visual method of communicating the magnitude of the threat with non experts. The virtual outcrops were also used as topographic baselines for a series of GPR surveys which were used to identified depth to solid bedrock before the installation of a series of rock anchors.

Fig 2. Quantifying the magnitude of landslides in successive surveys from Catterline Bay

Both of these case studies highlight the value of repeat surveys in documenting and monitoring change, for communicating with decision makers and as inputs for models predicting future change.

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Monitoring strategy for movements assessment in a challenging remote area: Case study of Cima del Simano (Ticino, Switzerland)

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Key words: *remote sensing, instability monitoring, Insar, Lidar, DGPS, extensometer*

Steep slopes or fractured rocks near vulnerable elements sometimes require monitoring to detect centimetric to millimetric movements aimed at preventing dangerous rockfall events. Sometimes those hazards are challenging to monitor due to a difficult access to the site (high altitude, snow cover or incised valley). To overcome those difficulties, several remote techniques can be applied. Here we present the case study of the mountain Cima del Simano in the Ticino canton in Switzerland. This is a mountain located in the incised valley of Blenio, whose top reaches 2500m height. The upper part is covered by snow half of the year and is difficult to access without a helicopter. The East part of the mountain presents important open fractures that have been periodically monitored since 2006. To evaluate the risks related to this instability, different remote techniques have been coupled to locate the areas in movement, their average speed and acceleration as well as their susceptibility to failure. Among the techniques used, some can detect centimetric movements (Lidar, DGPS, images co-registration and correlation) while the others detect millimetric movements (Ground-based Insar and satellite Insar, extensometers).

The first step to apply this monitoring strategy is to decide where to install the different devices and the frequency of measurement acquisitions for each technique. For instance, the Ground-Based radar should be closer than 4km from the target area to decrease atmospheric biases and its direction should not be too perpendicular to the target slope to avoid foreshortening and layover effects and increase the resolution. Thus, we developed a Matlab routine aimed at guiding the user in the selection of the best radar location among several location possibilities.

After conducting a preliminary review of the different remote sensing techniques, their specifications and limits, we selected the most appropriate deployment of those techniques to monitor Cima del Simano in order to overcome acquisition difficulties.

On the use of low-cost trail cameras for high-resolution monitoring of river bank erosion in cold climates

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Key words: *low-cost camera, photogrammetry, time series analysis, change detection, geomorphology*

Due to global climate change, an increase in extreme weather events, flooding, more timely river break-ups and reduced snow cover is expected in cold climates (COOLEY & PAVELSKY, 2016). Climate change, together with sedimentation on water bodies, might lead to an increased flood risk because of channel changes.

Besides studies on river flow characteristics, spatio-temporally high-resolution observations of bank dynamics during the flow period of open channels are important for hydro-morphological observations and modelling to support flood mitigation at arctic rivers.

We present a novel and cost-effective approach based on stereo photogrammetry using time-lapse images of a river bank captured by low-cost trail cameras to generate spatio-temporal high-resolution 3D models for change detection. The fundamental technique is Structure-from-Motion (SFM), which has already enjoyed great popularity in the geoscientific community for several years (ELTNER & SOFIA, 2020).

Trail cameras are characterised by long operating times with one battery charge and seem to be excellent for long-term monitoring. In a first field campaign, four trail cameras were installed at distances of about 60 metres towards an erosion-prone river bank at Pulmanki River, Finland (see Fig. 1). They were set to time-synchronised serial modes with 2-hour intervals and, with sufficient illumination, reliably captured images between September 2020 and May 2021. Furthermore, we installed six permanent ground control points (GCPs) for georeferencing and scale definition: three on the flanks of the bank and three on the shore towards the cameras.

In the late autumn and winter months, the study area is covered by snow, which is why we split the observation time into two periods. The first period ranges from the day of camera installation to the first heavy snow fall, i.e. 20th September to 16th October 2020. The second period ranges from the day of the areas almost cleared of snow to the day of the data retrieval during a second field campaign, i.e. from 10th April to 16th May 2021.

We propose robust vision methods enabling automated image processing and 3D change detection. This implies the assembly of the individual image data sets, the automatic image measurement of GCPs and the image matching to determine the respective image orientation parameters in a joined reference system via SFM. Dense 3D point clouds are computed for each time stamp via dense matching. However, the low-cost images suffer from low image resolutions and poor image quality, especially in low light conditions, which manifests in image noise, artefacts and aberrations and negatively affects the quality of 3D reconstruction. Therefore, change detection is done by M3C2-PM distance measurement considering precision maps to account for noise in the 3D data (JAMES *et al.*, 2017). The determined changes are further reviewed against local and systematic errors, the latter to be detected by plausibility controls comparing chronological models.

We used this method for the semi-automatic processing of the first observation period and generated 133 high-resolution 3D point clouds with an average inner precision of 2 cm. Only an initial pre-selection of the GCPs based on one image per camera was necessary to provide the basis for subsequent automatic detection. The change mappings reveal quantifiable landslide events even in this first period, which so far would have remained undetected (Fig. 2).

Figure 1: Study area: Pulmanki River, Arola, Finland (69.93°N lat, 28.04°E lon). Red triangles: camera positions.

Figure 2: Landslide detection and quantification within the bank area.

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A DIY Arduino based low-cost and short-range terrestrial laser scanner

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Key words: *lidar, Arduino, low-cost, laser scanning*

A first prototype of a low-cost terrestrial laser scanner has been developed based on Arduino technology. Electronics and mechanical components were partly ordered and partly 3D printed, for a total cost of around USD 350. Conceptually, the operation of the device is simple: two stepper motors drive a laser sensor on two axes (horizontal and vertical), and a distance measurement for each of the motors positions is taken. These components are controlled by an Arduino Mega 2560, a powerful microcontroller known for its simplicity and versatility, which also receives the measurements and stores them on a SD card. A smartphone application was also developed to send scanning parameters to the LiDAR via Bluetooth. This first prototype detects on average 200 points/second at a maximum distance of about 200 m with an average error of 2 cm and a maximum resolution of less than 0.012° (1 point every 2.9 mm at a distance of 15 m). The laser spot diameter is about 30 cm at 50 m range.

Tests have been achieved indoors to compare with high-end commercial LiDAR and SLAM scanners. Measurements errors, noise, effects of surface reflectivity, range and incidence angle are assessed on objects whose geometry are known. Then, the device was tested on a real fast-moving rock slope to detect changes.

This device has two main possible applications: 1) for continuous monitoring in areas where the probability of destruction is too high to put a commercial device thousands of time more expensive. In such situation, it can be programmed to make a scan every hour; 2) for educational purpose, a DIY procedure is proposed to build such a device. That can be used by students in geosciences to understand the principles of laser scanning. Present developments include the coupling of a small solar panel, so that the device can be tested in the field on several consecutive days, and a communication module to send the data.

Direct georeferencing UAV-SfM datasets in high-relief terrain: Practical considerations and assessment along steep inaccessible rock slopes

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Key words: *direct georeferencing, RTK-UAV, SfM photogrammetry, high-relief terrain, steep slopes*

Steep rock slopes present key opportunities and challenges in the geosciences, from excellent outcrop exposures to safety hazards for people and infrastructure. Due to partial or complete inaccessibility, surveying and mapping of near-vertical cliff sections commonly incorporates remote sensing techniques, such as LiDAR and photogrammetry (STURZENEGGER & STEAD, 2009; JABOYEDOFF *et al*., 2015). Ground-based application of these methods are often limited to relatively small areas due to practical limitations (e.g., mobility, costs, line-of-sight occlusions; BUCKLEY *et al*., 2008; HODGETTS, 2013). Recently, SfM-MVS photogrammetry has enabled streamlined integration of UAV images, allowing for broader coverage and fewer data shadows in various geoscience applications (CARRIVICK *et al*., 2016).

However, SfM-MVS photogrammetry relies on measurement of ground control points (GCPs) within a study area (e.g., *Fig. 1*) for reliable absolute accuracy (i.e., location and orientation), relative accuracy (i.e., internal scene reconstruction without deformation), and camera calibration (i.e., interior orientation parameters; CRAMER *et al*., 2017). Several investigations have examined accuracy relative to GCP distribution in UAV-SfM workflows (e.g., HARWIN *et al*., 2015; SANZ-ABLANDO *et al*., 2018), but recommended approaches are not always suitable or practical to implement in high-relief terrain that is inaccessible and/or hazardous.

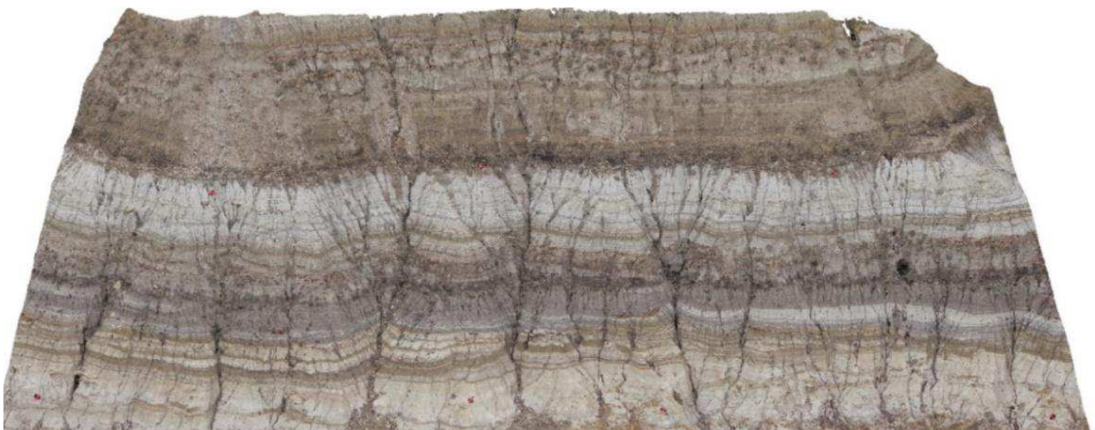

Figure 1: Study area – near-vertical outcrop slope and exposure of Cretaceous fluvial deposits near Drumheller, AB.

Direct georeferencing (DG) of UAV-SfM datasets (without use of GCPs) is becoming increasingly possible with the integration of advanced GNSS positioning capabilities onboard commercially available UAVs. Although DG datasets can produce horizontal precisions comparable to ground sample distance (~cm), errors in the vertical (z) vector are often notably higher (HUGENHOLTZ *et al*., 2016; FORLANI *et al*., 2018; KALACSKA *et al*., 2020). DG datasets may be suitable in relatively flat and featureless terrain, but little work has been done detailing applicability to high-relief terrain comprised of near-vertical slopes.

To evaluate the accuracy and precision of DG datasets derived from RTK-enabled UAV images along laterally extensive sub-vertical rock slopes, we compare more than 80 scenarios with variations to imaging and georeferencing strategies. Variables include orthogonal and nadir imaging angles combined with direct, indirect, and integrated georeferencing (with various GCP distribution) strategies. RTK-UAV datasets are compared with a reference model collected contemporaneously with a ground-based LiDAR. Results exhibit similar horizontal accuracy and systematic vertical offsets to previous DG studies (*Fig. 2*), suggesting caution to applications requiring centimetric accuracy for absolute positioning and/or repeat surveying/monitoring (e.g., slope stability, morphometric change). However, further analysis of scene morphology and geometry reveals promising results for relative precision, indicating reliability for within model measurements (relative accuracy) without the need for ground control points.

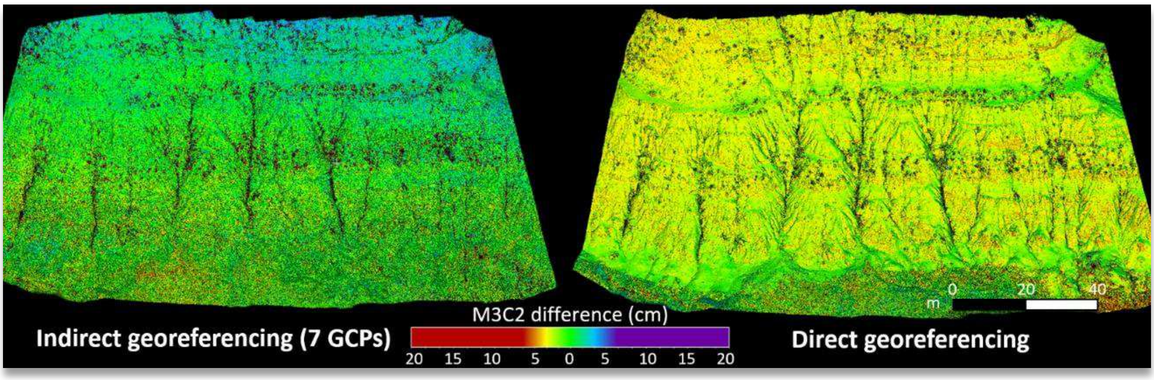

Figure 2. M3C2 difference between UAV datasets and ground-based LiDAR reference dataset. Left: indirect georeferencing with 7 GCPs (mean = 3 cm); Right: direct georeferencing (no GCPs) using RTK-UAV (mean = 4 cm).

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Submarine fieldwork with L3 students using the Minerve virtual reality software

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Key words: *Fieldwork, Submarine environment, Active tectonics, virtual reality, teaching, Minerve*

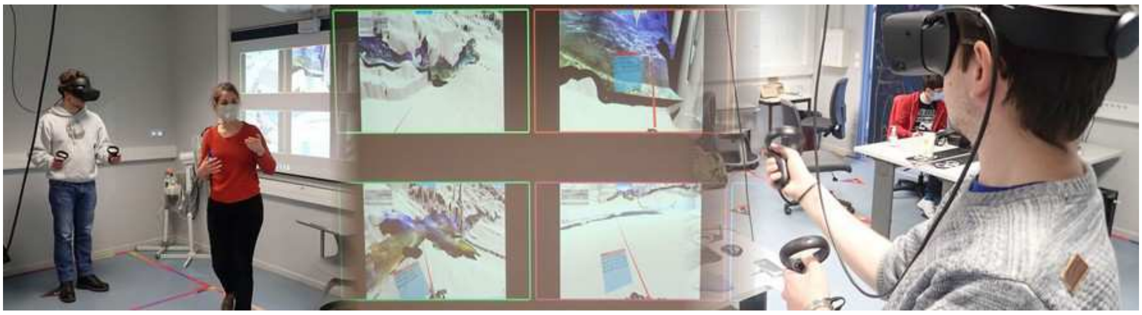
Fieldwork is essential in Earth Sciences learning. The observation of geological objects *in situ*, their 3D and 2D representation, are key to decipher their nature and geological history. While often considered as attractive for students that appreciate facing the subjects of study, fieldwork may be unfeasible (e.g., dangerous or remote places). We may require instead virtual imaging to make a proper fieldwork-like analyses. This is the case for studies of extraterrestrial objects, or from submarine areas, that are fascinating and preserved.

Here, we present a virtual fieldwork and associated lab sessions targeting L3 students on an introduction to active tectonics. We benefit from very high resolution (~1m) DEM and DOM (Digital Elevation Model and Digital Orthophoto Map) of the submarine Roseau fault scarp (French Antilles), constructed from ROV VICTOR videos acquired during the ODEMAR and SUBSAINTES oceanographic cruises of the Flotte Océanographique Française (2013 and 2017, respectively). These DEM/DOM have been used to better understand the 2004 Les Saintes earthquake (Mw 6.3) and the seismic cycle over this major active normal fault (Escartin et al. 2016; Istenic et al., 2019; Hughes et al., 2021). To better analyze the fine scarp topography and texture and interact in 3D, the DEM/DOM are imported in the MINERVE Virtual Reality software, developed by J. Billant (Billant et al. 2019) where users can easily measure strike, dip, rake, distances, map geological features, etc, skills that students should master at the end of the License.

The teaching sequence, adapted for groups of up to 12 students, starts by mapping exercises and understanding of the tectonic context using vector (earthquake catalogs, plate boundaries) and raster (10m DEM, openstreet maps, etc) images gathered on a QGIS project. After identifying potential candidate faults for the 2004 rupture in a 10m larger scale DEM, the students switch to VR immersion. With the virtual fieldwork, the students' goals are: describing and identifying the morphology associated with the active fault, measuring the last coseismic displacement on fault scarps, mapping the fault, and understand the erosive and sedimentary processes interacting with tectonics (dejection cones, roughness of the scarp, etc). Students ultimately propose scenarios of fault behavior during the seismic cycle.

Because of the Covid-19 sanitary restrictions, we conduct the first sessions with 4 reduced groups of 4 to 6 students each, during reduced sessions of 2-hours, with 1h dedicated to VR fieldwork. We have tested two different pedagogic strategies : a first one where students, in two different groups and sessions, were alone on the field and guided by a teacher outside the VR environment in the Univ Lyon 1 virtual lab; and a second one where the students from two groups were all together on a single VR environment, together with the instructor (J. Billant), teaching remotely from Nice. Student feedback was collected immediately after the lab session via online inquiry, and its analysis will help us in the future improve both the virtual fieldwork for the students, and the MINERVE software.

Overall, this first try of immersive field work is both a pedagogic and technical success, and opens new perspectives for teaching geology.



Figures 1 : Use of the MINERVE software for immersive submarine field work in the Univ. Lyon 1 virtual lab with L3 Géosciences students.

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Video of the sequence : https://mediacenter.univ-lyon1.fr/videos/?video=MEDIA210429115155948&autostart=true

Virtual Field Trips during a Pandemic: lessons learnt and implications for future field trips

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Key words: *Virtual Field Trip, Virtual Outcrop, LIME*

A virtual outcrop (VO) is a photorealistic model of a geological outcrop. Over the past two decades these have increasingly supplemented traditional field work, enabling high-resolution documentation and interpretation of large-scale exposures, especially where access is challenging. Initially developed for research purposes their application in teaching through virtual fieldtrips (VFTs) has also been growing. This was significantly accelerated by the 2020 global pandemic when fieldwork was impossible and teaching moved largely online. Despite their widespread uptake, there has been little systematic research on the use of VFTs, both the respect to the optimal delivery methods and how they compare to traditional trips. Over the past year, two separate VFTs (one ten day and one 5 day) were constructed and delivered to MSc. students studying Integrated Petroleum Geoscience at the University of Aberdeen. The VFTs were a direct replacement for traditional trips to Utah (USA) and the Pyrenees (Spain) and incorporated broadly similar localities and learning goals as physical trips in previous years. Virtual outcrops were presented in LIME and integrated various data including VOs, sedimentary logs, field photos, geological maps, figures, 360^{o} photos, DEMs and gigapans. At the end of each course a questionnaire designed to appraise the effectiveness of the course was delivered to the students with a goal of addressing the effectiveness of the delivery, the user experience, and the learning outcome.

The VFT's were delivered in real time, were tutor led and location based. The learning was "problem based" so that students where provided a brief overview of each location prior to been allocated time to explore the VO and associated data in small groups VO (fig. 1). On reconvening a discussion was started about the locality from fine scaled features (e.g. sedimentological structures) to the significance of the exposure in a larger basin scale. The format followed aimed to emulate that of traditional fieldwork.

Analysis of the results suggested that students (97%) would prefer the go to the field. This is largely for the same reasons people enjoy going on holiday and include visiting new places, getting exercise in the fresh air, seeing different cultures. More significantly, the desired earning outcomes were achieved, in most cases better than on traditional trips. 65% of students stated they learnt concepts they would not have during a traditional fieldtrip. Key advantages of the approach were, the ability to visit outcrops in a logical (rather than logistical order), significant time saving on travel, the ability to change the scale of observation rapidly and the ability to bring in analogue data at scale. Students were also more engages, less distracted and less tired than on traditional trips.

The results are still being analysed to optimize the delivery method, but they suggest that VFTs, based on VOs have a significant contribution to make to learning in the geosciences, either as stand along events or as an addition to traditional trips.

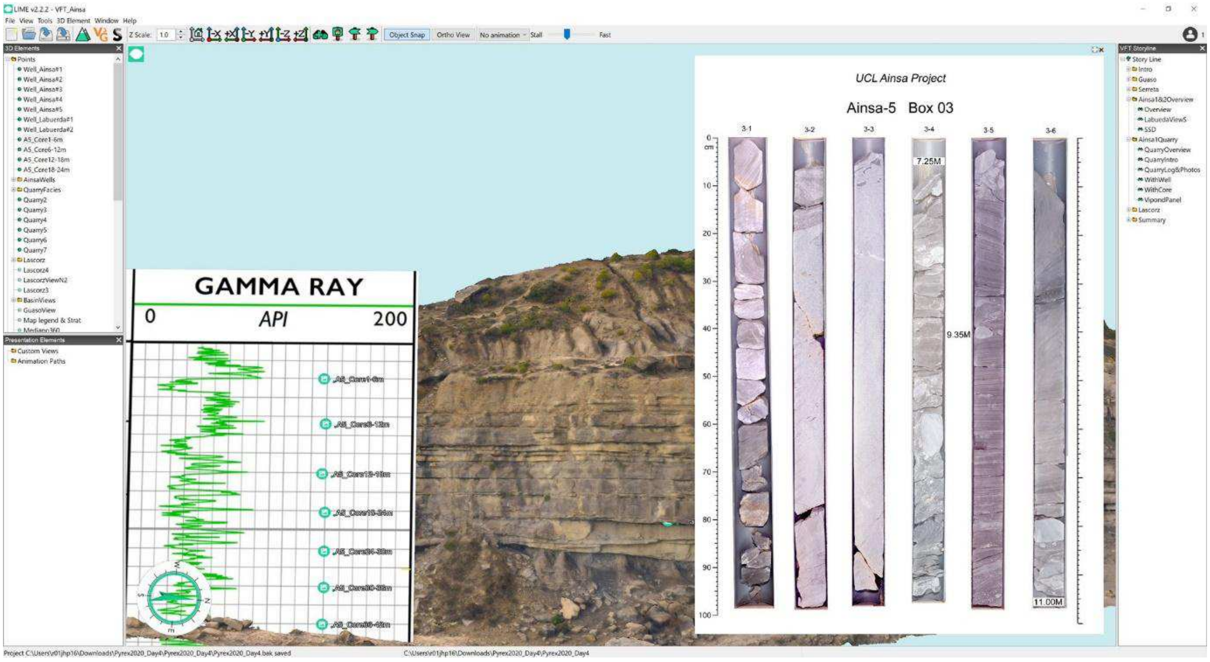

Figure 1: Screenshot of LIME window during the Pyrenees Virtual Field Trip, illustrating integration of multiple datasets, including well based gamma ray and core photos, with the Virtual Outcrop.

Virtuafield: a pedagogical VR application for training and evaluating students on field practice

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Key words: *Virtual Reality, Education, Field trips, Evaluation.*

Students have few occasions to train in the field during their academic curricula. Field trips are expensive and require complex logistics. Despite their pedagogical interest, many outcrops are inaccessible for students as they are far away from their campus or too dangerous (e.g., cliffs, road sides, unsecured countries). Depending on the university location, it may be difficult for professors to allow student to propose various geological and geomorphological contexts for field trips (e.g., carbonate, silicoclastic, metamorphic and volcanic rocks, extensive and compressive tectonics).

Nowadays, the photogrammetry or LIDAR techniques provide High-Resolution (HR) 3D representations of outcrop geometries and textures, often termed as Digital Outcrop Models (DOM, BELLIAN, et al. 2005). Digital Elevation Models (DEM) and DOMs are already used as pedagogical supports for practical exercises on computers such as fault throw calculation, seismic occurrence, or 3D geological modelling from outcrop interpretations. However, DOMs and DEMs also represent an ideal support for providing a realistic 3D scenes of a field case. The computer engines are not a convenient support for visualizing a 3D geometry because it still depends on a 2D screen and does not preserve the 1:1 scale, which is of paramount importance for geological and geomorphological interpretations.

The Virtual Reality (VR) technique is the ultimate way to provide a full 3D view, which can preserve the 1:1 scale, while benefiting from the numerical nature of the support (DOMs). Thus, several software or toolkits have been proposed for research purposes (GERLONI, et al. 2018; LE MOUELIC, et al. 2018) and some for education (JANISZEWSKI, M., et al. 2020).

Aix-Marseille University launched the *VirtuaField* project whose objective is to integrate DOMs and DEMs into a VR application to provide students with a pedagogical tool enabling learning field practice. The software also provides a QCM plug-in, directly integrated in the 3D scene, for evaluating the student skills.

Prototypes were provided by the VR2Planets company from the case study of La Fare les Oliviers (SE France). This case study shows diffuse fractures and fracture corridors as well as sedimentological and geomorphological structures. The prototypes have been tested in training experiences with volunteer students. The tests have been operated in different ways: 1) a single student discovering the geological case study; 2) a training course on this case study performed by a professor with three students. Surveys have been performed in order to obtain feedbacks from students on the software ergonomics and comfort as well as on the ability of the *VirtuaField* application to gain field skills, but also on the more pertinent way to design the pedagogical tools.

The synthesis of the student feedbacks are presented as well as a first outline of the pedagogical guidelines on using VR tools for educational purposes. Examples of *Virtuafield* applications will be also shown to illustrate its potential use for education.

Figure 1:.Example of testing session:two students follow the professor courses. The professor may decide to

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Assisting the Interpretation of Digital Outcrops with Geometric Surface Constraints

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Key words: *Guided Interpretation, Digital Outcrops, Discrete Geometry, Facies-Based Geomodelling*

Digital interpretations of outcrop analogues are an important source for the soft-conditioning of deterministic geomodels (Enge et al., 2007) and as a sampling source for stochastic geomodels (Mitten et al., 2020). The interpretations are either represented as (i) indicator attributes of large digital outcrop point clouds (Rarity et al., 2014), or as (ii) separated interpolation surfaces (Enge et al., 2007), interpolated from the outcrop surface, or as (iii) image-draped auxiliary information to the outcrop surface (Buckley et al., 2019). Those representations are not ideal for inclusion in subsequent geomodelling stages, as they either require specific technologies from the modelling package that are not coherently supported (i.e. case (i) and (iii)), or introduce new sources of uncertainty or bias from sampling- and interpolation artefacts (i.e. case (ii)).

In order to better align the interpretation- and geomodelling process with the surveyed digital outcrop surface geometry, an assisted interpretation approach is presented (fig. 1), which numerically expands manually-outlined geological interpretations on the surface. Those geological interpretations are represented as indicator function $I = \{i_1, i_2 \dots i_N\}$ for each outcrop surface element.

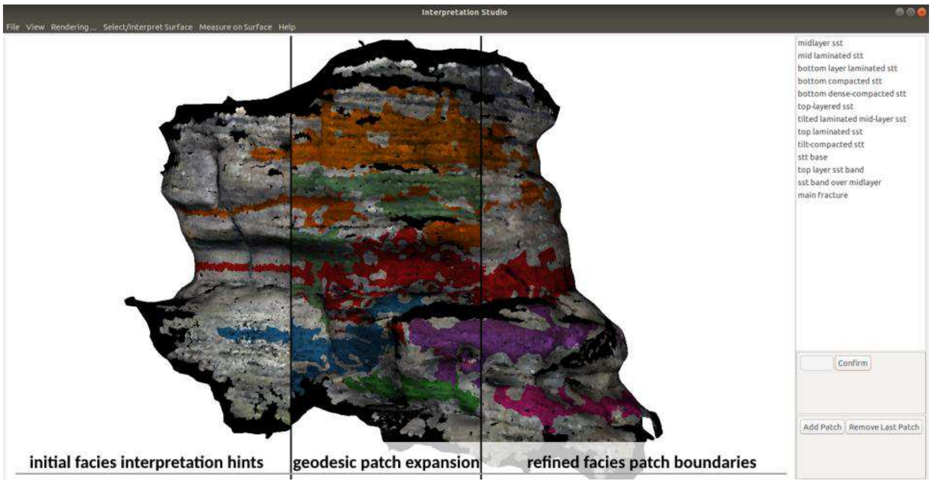

Figure 1. Illustration of the guided interpretation process: initial interpretation areas (i.e. facies, in this case) are geodesically expanded over the outcrop surface. The over-extending, noisy areas are pruned via morphological filtering and then refined in a constrained optimization step.

The chosen representation for embedded interpretations facilitates trivial point-sample extraction over the whole surface, but also the sampling of pseudo-well logs for hard conditioning of reservoir models in target geomodelling software, e.g. Schlumberger Petrel. The indicator function is transferred during the corner-point sampling of the pseudo-well. Constructing a gridded facies model directly from the wells is demonstrated in fig. 2 (right).

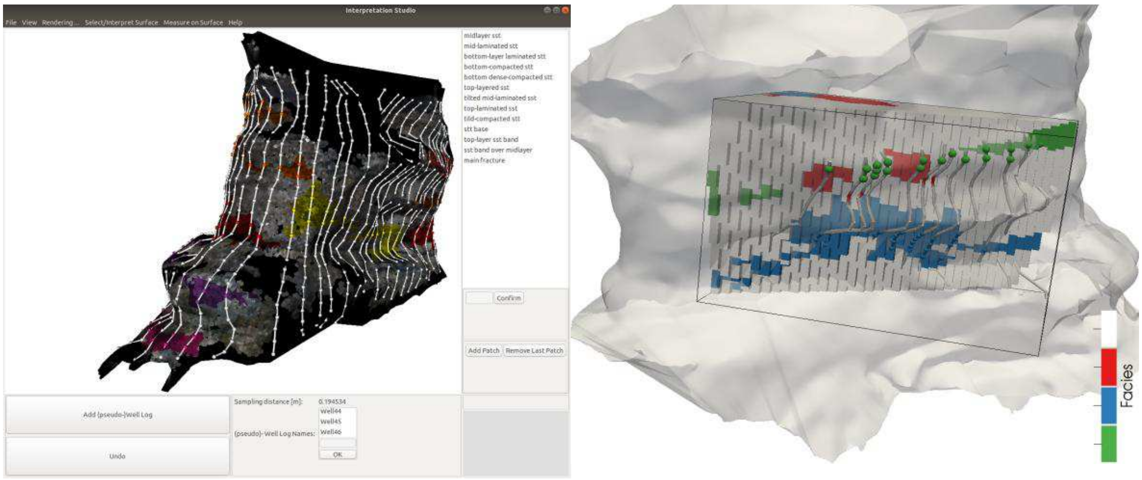

Figure 2. Extraction of pseudo-well logs from photo-textured, attributed surfaces (left). Such pseudo-welllogs can simply be used as hard-conditioning parameters for gridded facies-based geomodels (right)

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From the Cloud to the Digital Outcrop Model: Sedimentary Interpretation in the Mosis Suite

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Key words: *Digital Outcrop Model, Virtual Reality, Cloud Computing, Sedimentary Profile*

The Digital Geoscience Revolution consolidated digital techniques in the arsenal of the geoscientists (BUCKLEY *et al*, 2019). As a byproduct however, there are new challenges in storing, sharing, and interpreting multiscale geological data. In this context, the Mosis Suite (GONZAGA *et al*, 2018) was created. Mosis is a software suite that assists the geoscientists in various phases of field studies, ranging all the way from pre-field preparation to post field data storage and interpretation. In this abstract, we present a novel way to create interpretations in Digital Outcrop Models (DOM) using two applications from the suite, Mosis HUB and Mosis XP.

Mosis HUB is a multiscale data storage hosted in the Google Cloud Platform. It manages access to raw and processed data that are acquired in field studies such as DOM, Unmanned Aerial Vehicle imagery, LiDAR, 3D models of rock samples, and laboratorial analysis. Mosis XP is a visualization and interpretation system, it offers several tools for DOM analysis, such as measurements, lines, planes, and lithologic profiles. Both applications are integrated so that models uploaded in Mosis HUB are accessible through Mosis XP. We present here a sedimentary interpretation created in Mosis XP using the Lithologic Profile tool. In this case, the DOM was obtained from the imaging of an extractive mine of the mining company Extrativa Santa Fé Ltda, located at Tremembé in the State of São Paulo, Brazil. The outcrop is on the central portion of Taubaté Basin and is referent to Tremembé Formation, with ages of Oligocene of the Basin. This formation is composed of sediments associated with a lacustrine system of the Playa-Lake types, represented by massive green argillites, shales rhythmites and marls, dolomites, and sandstone (RICCOMINI, 1989), and has potential for hydroncarbon generation (BERGAMASHI *et al*, 2010).

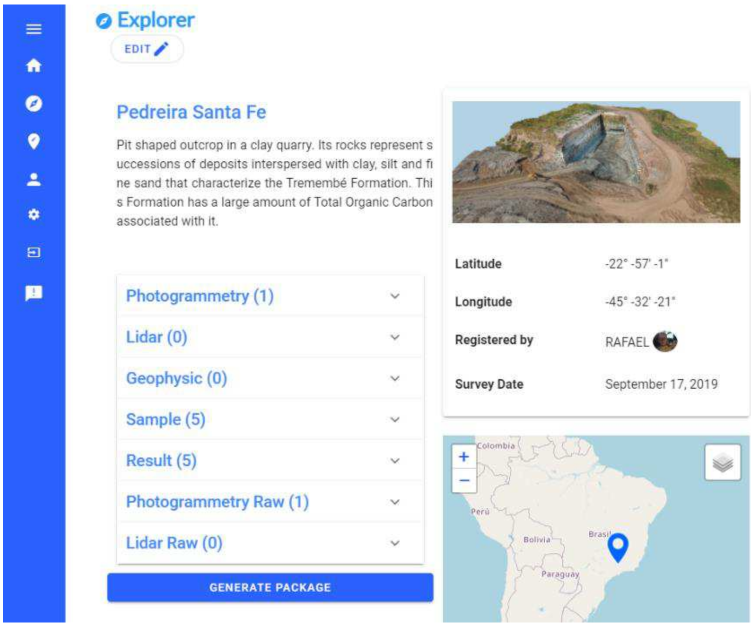

Figure 1: Mosis HUB web interface where it is possible to access data collected from the survey on Santa Fé Outctrop. The survey shown has photogrammetry data (raw imagery and DOM), five samples with description and 3D models, and reflectance spectra of the samples.

To create interpretations, the user accesses the Mosis HUB and downloads the DOM from the Santa Fé outcrop as shown in Figure 1. This DOM is georeferenced using RTK GPS technology and consists of optimized mesh files and multi-resolution textures. Based on information from the Mosis HUB and the 3D visualization on Mosis XP, a sedimentary profile is created according to granulometry, in addition to the possibility of select colors and textures which distinguish the layers on the outcrop. As depicted in Figure 2, we identified five distinct layers in the DOM from top to bottom: A) Papyraceous shale with lamellar structure and yellowish coloration; B) Gray silty shale with the presence of ostracods; C) Gray silty shale; D) Dark gray clay shale; and E) Massive green argillite with the presence of smectite clay.

The Mosis Suite is a viable option to assist the geoscientists in dealing with multiscale data collected in field surveys. It offers a set of interpretation tools, like the Lithologic Profile, to organize the geological knowledge, allowing for individualization of rock packages. By providing a common tool for interpretation and data storage, the Mosis Suite can help to establish geological understanding of outcropping formations.

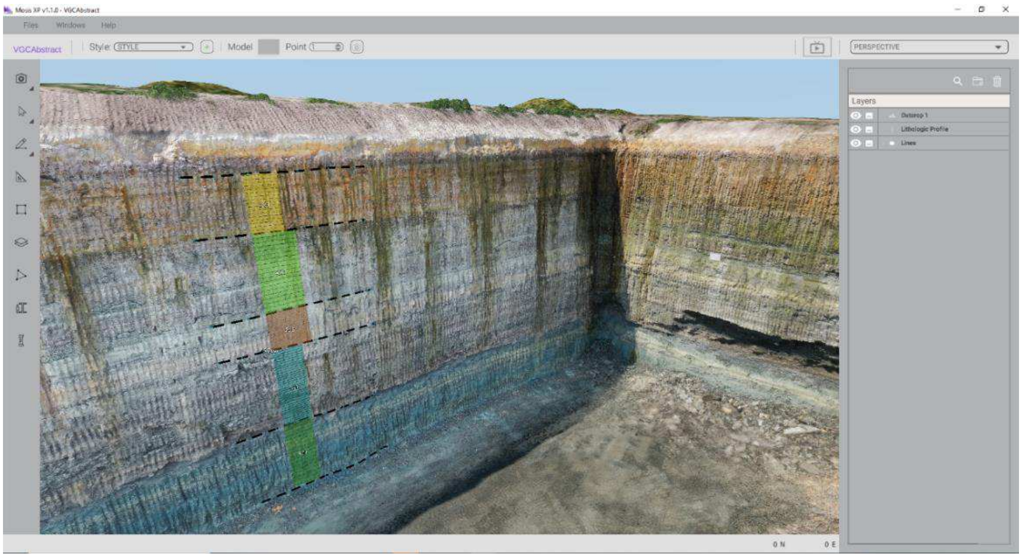

Figure 2: Screen capture of the sedimentary profile, consisting of five distinct layers, created using the Lithologic Profile tool in Mosis XP.

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Towards the Automated Interpretation of Virtual Outcrops

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Key words: *Virtual outcrop, machine learning, automated interpretation, vegetation removal*

In the last 15 years the application of virtual outcrops both as a mechanism for extracting quantitative geological information and as a teaching and learning tool has become well established. The recent COVID-19 pandemic has reduced and removed the ability for geologists to undertake fieldwork and has further driven the development and uptake of the virtual alternative. Advances in data collection methods, especially the advent of UAVs and SfM have driven a proliferation in the availability of virtual outcrops, although the speed at which they can be interpreted remains a major bottle neck. Software tools such as Lime (Buckley et al. 2019) allow for manual interpretation and the preparation of overlies that map out the various elements in the cliff sections, but these techniques to classify 3D models are both time consuming and labour intensive.

The overall goal of this project is an automated machine learning system that is trained on previously interpreted virtual outcrops and is able to provide an automated classification of factors such as lithology and depositional facies. Whilst such outcomes have been achieved using specialist sensors such as hyper-spectral imaging (Kurz et al. 200) the aim is to be able to achieve classification on standard virtual outcrops.

A variety of methods are currently being tested and appraised. Part of the most positive workflow to date involves a new, purpose built tool to add in the automatic masking of vegetation, scree and other features collectively termed "non-geology". This tool has application as a pre-processing stage to the fully automated interpretation but also as useful tool for the geologist undertaking traditional interpretation as well.

The tool works by exporting a series of different outcrop attributes in generated in LIME including parameters to describe dip, slope orientation, colour and feature continuity. The user is then able to interact with the parameters and their tolerance to generate a mask that can be manually edited if required and then exported to create an overlay in LIME.

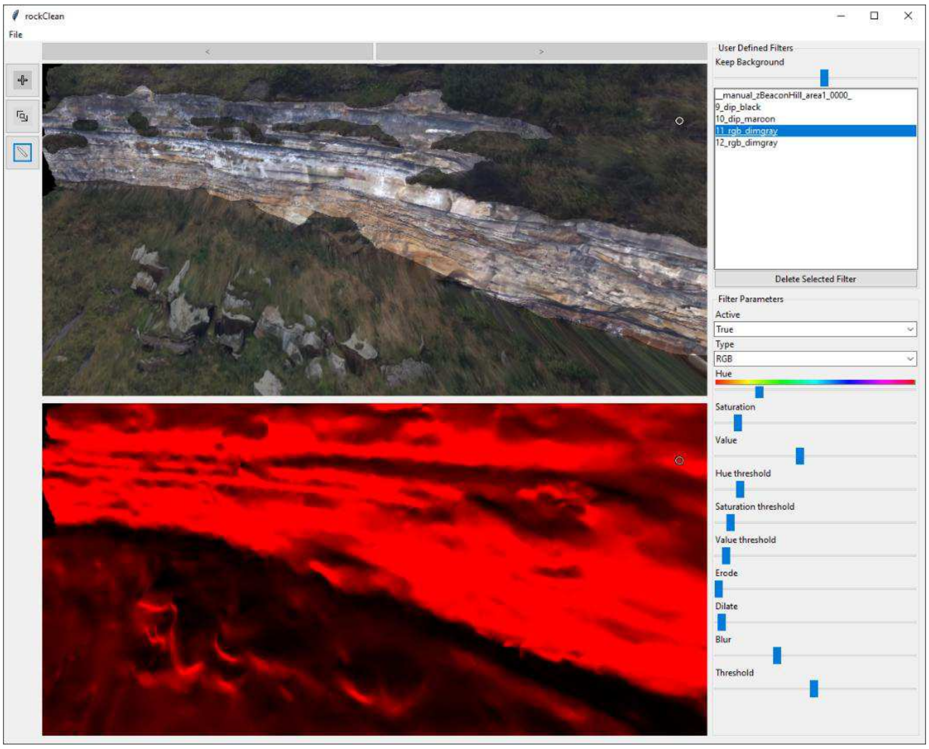

Figure 1: Screenshot of tool removing regions of predominately low geological information.

Initial results are promising, and the tool is set to become part of the standard interpretation workflow within the VOG Group. It is a significant step towards the automated interpretation of virtual outcrop data.

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Svalbox: an interactive geoscientific portal for Svalbard

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Key words: *Svalbard, geology, seismic, digital outcrop models, open access*

Svalbard is a Norwegian high Arctic archipelago, located halfway between the North Pole and mainland northern Norway at 74-81°N. Svalbard's geological record is exceptional, both in terms of outcrop quality and stratigraphic coverage within a relatively small area. The Devonian to Paleogene stratigraphic record is particularly well-exposed with only a few significant hiatuses. The extreme latitude of Svalbard exerts strong seasonal control on field activities, with a long dark season, significant snow/ice cover, and harsh weather conditions, all of which require careful planning. The summer field season runs from July to September.

The Svalbox project was initiated by The University Centre in Svalbard (UNIS) in 2016 to extend the field season. Svalbox is primarily an open-access repository of digital models from Svalbard, accessible at www.svalbox.no. The outcrop models are largely processed using Structure-from-Motion (SfM) photogrammetry, with photographs acquired from boats, the ground or drones. In addition to outcrops, SfM has also been used to digitize drill cores and rock samples (Betlem et al., 2020) and cultural heritage sites. In the early days of Svalbox, outcrop models were acquired opportunistically based on ongoing teaching and research projects at UNIS. Since the Covid-19 pandemic, we have experienced increased use of the Svalbox portal beyond UNIS and have started to run dedicated Svalbox data acquisition campaigns to more inaccessible areas of Svalbard. At present, more than 100 outcrop models are available through Svalbox, including the world-renowned Festningen section.

Svalbox is, however, more than a repository of digital models from Svalbard. The project aims to place the outcrops into geological context by integration with other geoscientific data, including seismic, borehole, 360° imagery and published data (Senger et al., 2021; Senger et al., 2020). At present, Svalbox is organised as a database with a UNIS-internal Petrel-based portal containing the full range of geoscientific data, and an open-access web-based portal continuously expanded with both data and data types (Fig. 1; www.svalbox.no).

In this contribution, we illustrate the capabilities of the Svalbox portal, and present our ambitions towards the next development phase of Svalbox.

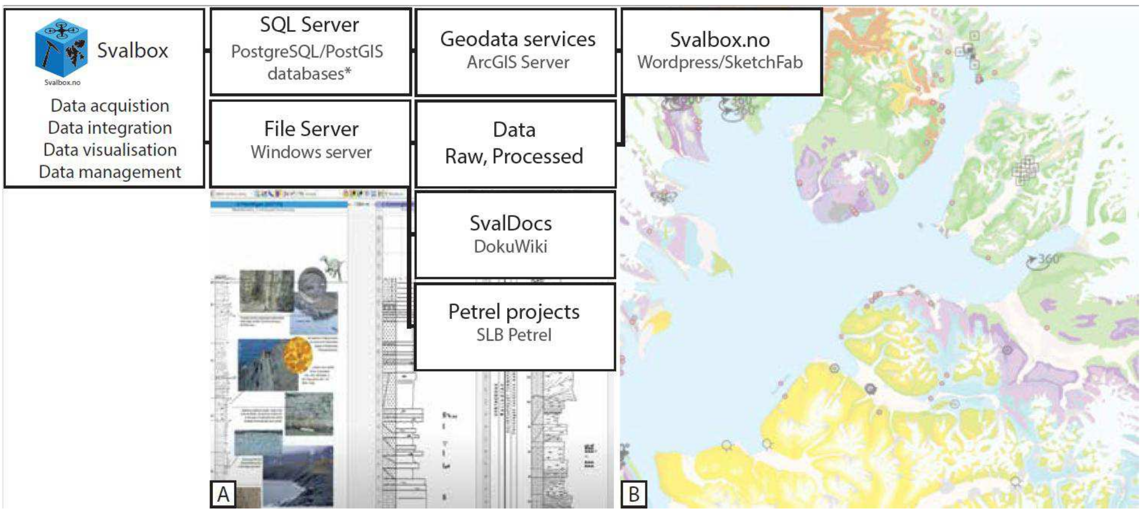

Figure 1: Overview of the Svalbox concept and its main elements, from Senger et al. (2021). A) Screenshot from the UNIS-internal part of Svalbox, illustrating the correlation of multi-scale sedimentological logs from the Festningen

outcrop integrated within the Petrel platform. B) Screenshot of the open-access part of Svalbox, with geological maps overlain with digital outcrop models, 360° imagery and geophysical data sets.

Acknowledgements: Svalbox is co-funded by the University of the Arctic (UArctic), the Research Centre for Arctic Petroleum Exploration (ARCEx) and UNIS. We sincerely appreciate data access from UNIS students and colleagues.

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The use of 3D virtual objects in geoscience education – The example of the collaborative project of the Société Géologique de France

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Key words: *photogrammetry, virtual 3D objects, blended learning*

"The best geologist is the one who has seen the most rocks, outcrops and fossils." Unfortunately, not every student has the opportunity to undertake a large number of labs and field trips because of lack of time, logistical and financial factors or safety. In many cases, the main issue is simply that objects (rocks, minerals, fossils) with a high pedagogic value, are either not available in a lab or not accessible for students outside the time slot devoted for the lab. The recent and rapid development of digital photogrammetric techniques (structure from motion) and X-ray tomography allows to create virtual 3D models of outcrops, hand-sample of rocks, minerals and fossils. Therefore, these virtual 3D models are becoming widely used in geoscience education to support traditional lectures and lab-based learning. It is expected that the use of virtual 3D objects improves learning outcomes and experiences.

Although digitalization is now a straightforward task, it requires some skills and remains very time-consuming. To address these issues, more than 15 French universities are organized into a consortium "Géologie virtuelle" supported and hosted by the Société Géologique de France (SGF). The goal is to share technical skills, learning models (e.g., blended learning, flipped learning) and virtual 3D models. In addition, the SGF owns a Sketchfab repository (https://sketchfab.com/sgfrance), where all the contributors can share their virtual 3D models with the geoscientific community.

During this presentation, we will present the consortium and several examples of blended learning environments that integrate virtual 3D models, like virtual field trips with 3D hand-samples and outcrops or online self-learning modules.

V3Geo: an online repository supporting virtual geoscience, virtual field trips and geoscience education

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Key words: *virtual outcrop, visualisation, open data, database, sharing*

Over the last decade, the adoption of virtual 3D models in geoscience has increased dramatically thanks to innovations in automated photogrammetric processing and low cost unmanned aerial vehicles (UAVs; drones). For geologists and geoscientists, the ease and speed of acquiring a 3D model dataset is resulting in a new paradigm for field geology, where virtual models complement and offer new possibilities for quantitative and qualitative applications. This has intensified during the ongoing COVID-19 pandemic. Although the number and quality of 3D models is proliferating, a challenge remains in how to optimally utilize these models to achieve end results in research and education. In particular, working with large 3D datasets and sharing results with students, collaborators and others is an ongoing challenge. The current status of web technologies and 3D visualization allows new approaches to increasing the accessibility of 3D models in geoscience and beyond. In this contribution, we present V3Geo as an online database of virtual 3D models to support educational, scientific and professional activities within virtual geoscience.

V3Geo is a cloud-based repository for virtual 3D models, allowing storage, search and visualization of 3D models within the web browser. These models are typically acquired through photogrammetry (also known as structure-from-motion), laser scanning or other laboratory-based 3D modelling methods. As such it is independent of scale and can handle outcrops of tens of kilometers in size down to laboratory 3D imaging of a hand sample or microscopic features. In addition, models are tiled – organized as a multiresolution level of detail hierarchy (BUCKLEY et al., 2008) that are optimized for streaming over the internet and efficient rendering. This allows multiple sections to be combined in the same viewing session, allowing large amounts of 3D data or areas to be visualized without performance or memory limitations.

A classification schema and metadata allow the 3D model database to be searched using standard filters, as well as a free-text search. A 3D web viewer efficiently streams the model data over the internet, allowing 3D models to be explored interactively without any software installation. A simple measurement tool allows users to make measurements of widths, thicknesses, fault throws etc.

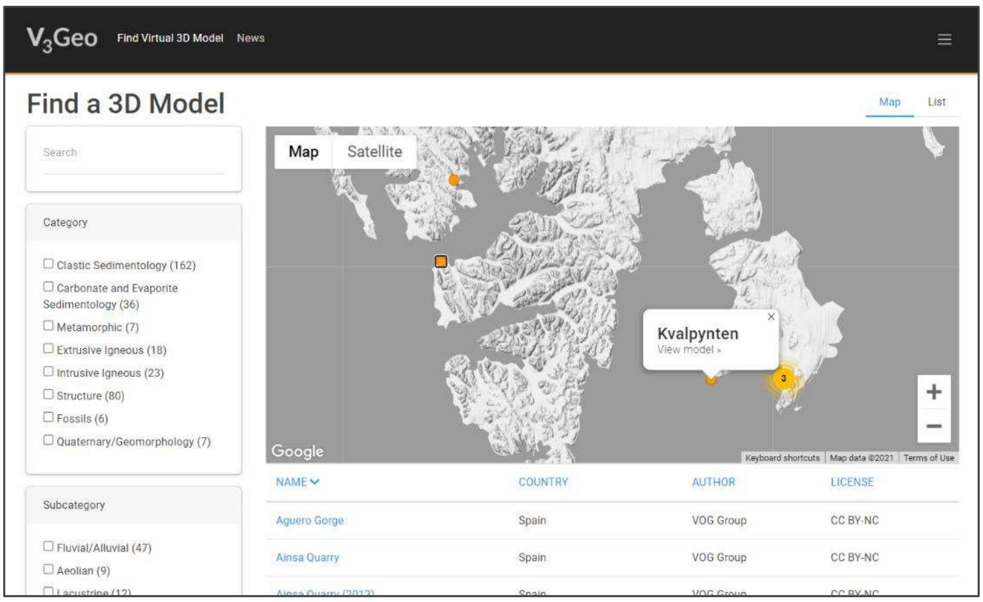

Figure 1: Search page for browsing virtual 3D models stored in V3Geo.

V3Geo is now accepting contributions from the geoscience community. Contributed models are subject to a technical review (quality control) to ensure underlying reliability for scientific and professional usage. This encompasses factors such as georeferencing, model scaling and orientation, 3D model size, formats, texture size, and general quality and suitability. Contributors are then asked to complete a metadata form for populating the model description page, which gives details about the author, geology or geoscience features represented by the model, and references. Creative Commons licenses are used to govern model usage and copyright. The 3D viewer is embeddable, and there is an additional link to the LIME interpretation, visualization and presentation software (Buckley et al., 2019) for working further with the datasets. Both public and private model storage is available. Future updates are planned to include interpretations, reviewing tools as well as Digital Object Identifiers. As such, V3Geo is envisaged as a sustainable resource for supporting virtual geoscience, with applications in teaching, virtual field trip creation, and a source of quantitative outcrop data and more.

Acknowledgements: The SAFARI project consortium is thanked for helping to support the V3Geo initiative. Contributors from organisations worldwide are acknowledged for their ongoing support and submissions to the repository. OMT is thanked for creating the V3Geo infrastructure and interface.

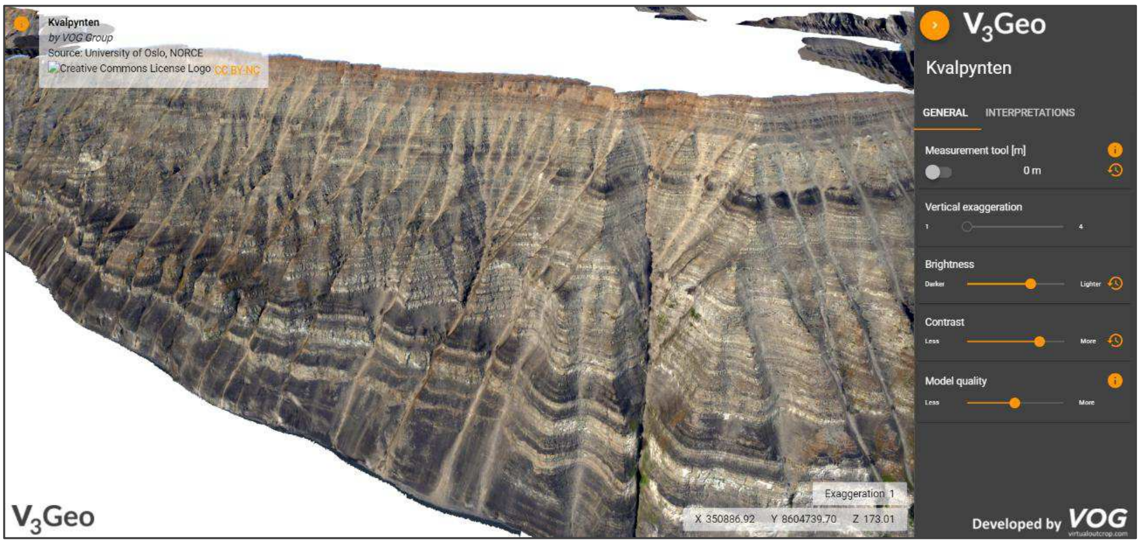

Figure 2. V3Geo web viewer for interactive browsing virtual 3D models in the browser.

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3D Modelling of fault network in the nucleus of comet 67P: implications for its internal structure and evolution

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Key words: *Comet nucleus, Internal structure, Erosion, Structural modelling; Shear-faults,*

Cometary nuclei are small bodies of kilometre scale, which are known to be among the most primitive objects of the solar system, formed on its infancy, around 4.5 Gyrs. They are predominantly composed of different ices (H_20, CO, CO_2, N_2), silica dust and organic molecules (GROUSSIN et al., 2019). The first space mission to image a comet nucleus dates from only 1986, with the flyby of the comet Halley by the Giotto probe. Since then, several missions allowed imaging of 6 cometary nuclei, until the (ESA) Rosetta mission, which orbited for 2 years the nucleus of comet 67P/Churyumov–Gerasimenko. The Rosetta orbiter acquired thousands of images of the nucleus of 67P, with an unprecedented spatial resolution, down to 20 cm/pixel (Keller et al., 2007), revealing its bilobate nature and allowing to perform detailed geological interpretations of its surface features (SUNSHINE et al., 2016; MATONTI et al., 2019).

Using high resolution (down meter scale precision) DTM and high resolution images, we constructed a 3D model of fractures and faults existing at depth in the neck of 67P nucleus. This model is constrained at the surface by 3D hard data, consisting of digitalized polylines of fractures and faults lineaments traced directly upon the DTM surface (JORDA et al., 2016; Fig. 1), hence integrating 3D/depth information. Before tracing, the visualization of faults lineaments has been greatly enhanced by computing and displaying the surface principal curvatures on the whole DTM surface (grayscale in Fig. 1). At depth, the fracture and fault planes are inferred from statistical data (in terms of length, direction, aspect ratio, Fig. 2), which are derived from surface observations and image interpretations performed in previous work (MATONTI et al., 2019).
An interpolation of the Gocad-Skua geomodeller is used to build the 3D model in the region of the comet neck, where the fracture and fault widely crop out. A stochastic approach will be investigated to extrapolate fracture/fault networks below the surface in order to account for uncertainties. The simulations are conditioned to the deterministic 3D model of fracture/fault networks, and input parameters will be obtained from the statistical analysis.

Our model shows that faults are organized in 2 sets displaying 2 distinct directions and dip angles and that the fault network propagates below the surface, down to 100's of meters. This study allows for the first time the representation of quantitative geometrical data on the internal structure of a comet nucleus. The deformations focused especially on the neck of the nucleus, by breaking down and weakening the comet material, strongly impacting its erosion rate, thus its evolution on long time scales.

In future works, we aim to determine which areas of the fault network or individual fault are, or have been, the most prone to undergo slip events. We will then investigate for possible links between these events and the comet nucleus outgassing activity.

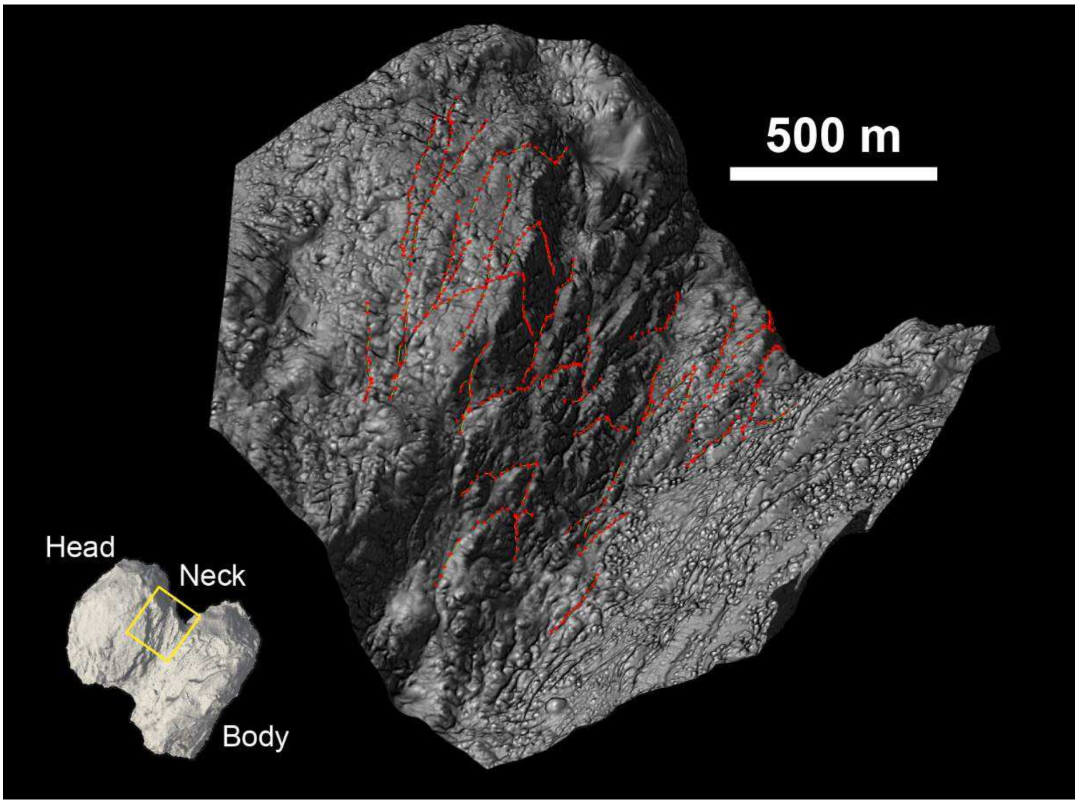

Figure 1: DTM surface from the 3D shape model spc_shap8-V2.1, displaying the surface principal curvature in grayscale. In red, examples of digitalized fault lineaments traced directly on the polygonal surface. The yellow box shows the location of the displayed DTM surface.

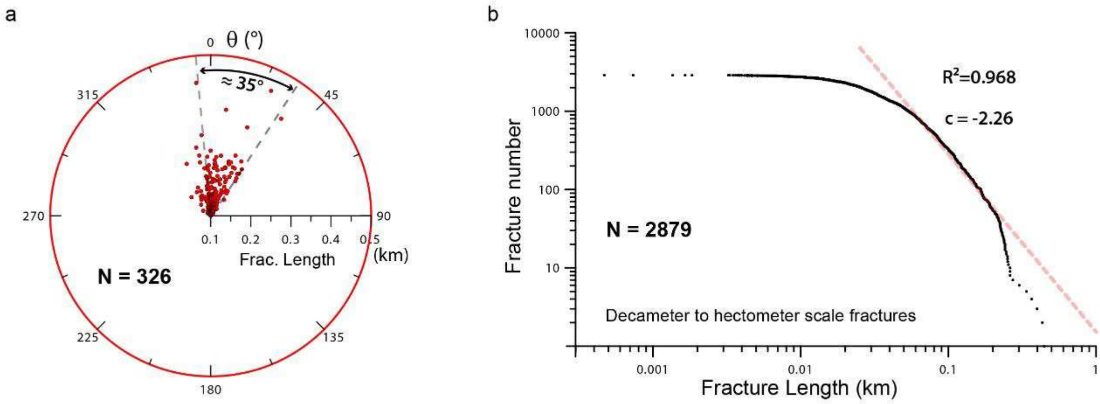

Figure 2: a: Faults directions at the Neck of 67P, relative to the Neck middle plane. b: Cumulative length distribution of the faults indicating a power law distribution for fractures length >30m.

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Contribution of drone photogrammetry to 3D outcrop modeling of facies, porosity, and permeability heterogeneities in carbonate reservoirs (Paris Basin, Middle Jurassic)

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Keywords: *Carbonates; Digital outcrop modeling; Drone; Photogrammetry; Facies; Reservoir*

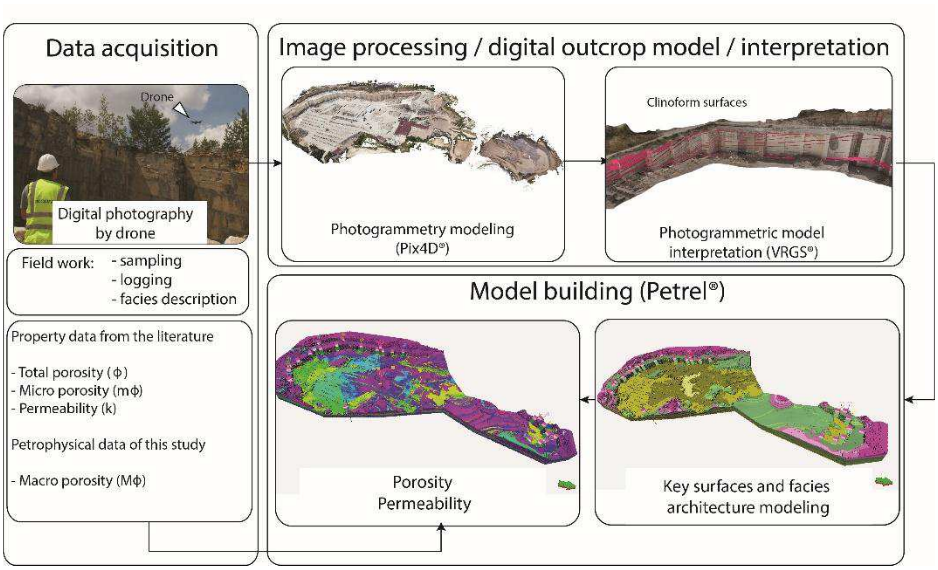

Figure 1: Overview of the workflow for generating the 3D facies, porosity, and permeability model. First the pictures were captured by a drone equipped with 20 Mega Pixel camera and GPS during two days of field work at Massangis quarry. Sample observations were made on thin sections and macroporosity acquired by image analysis. Previous petrophysical data were collected from the literature (Casteleyn et al., 2010, 2011; Makhloufi et al., 2013). *Images were processed using Pix4D® and the resulting Digital Outcrop Model interpreted using Virtual Reality Geological Studio (VRGS®). Facies, porosity, and permeability were modeled using Petrel® software. (Issued from Thomas et al., 2021).*

This work illustrates the value of drone photogrammetry in creating a hectometer-scale geological model of complex carbonate geobodies (Fig. 1). Although drone photogrammetry is now commonly used for modeling the sedimentary facies and architecture of sandstone outcrops (*Cabello et al., 2018*), its use is still marginal in creating geomodels of carbonate geobodies (*Tomassetti et al., 2018*). Drone photogrammetry can generate accurate line drawing correlation and detailed architecture analysis along inaccessible vertical faces of outcrops and it provides better observations from new angles (*Schmitz et al., 2014*). This work models the Bathonian limestones of Massangis quarry (Burgundy) covering an area of 0.4 km² and being usually considered as an analogue of the *Oolite Blanche* geothermal reservoir in the center of the Paris Basin. The Massangis quarry model is a good analogue for reservoir microporosity and secondary porosity associated with dedolomitization. Ten facies are described and grouped into three facies associations (FA1) clinoforms, (FA2) tidal to subtidal facies, and (FA3) lagoonal facies (Fig. 2). The clinoforms are sets of giant marine sand waves 15–20 m high that prograded N70° across the platform as part of a regressive systems tract. Moldic rhombohedral pore spaces associated with dedolomitization are well-expressed within clinoforms and in the bioturbated levels of lagoonal facies. Drone photogrammetry combined with the "Truncated Gaussian with Trends" algorithm implemented in Petrel® software is used to create a geological model that faithfully reproduces the facies architecture observed in the quarry cliffs (Fig. 2). Drone photogrammetry can be combined with field work to describe and locate facies and so constrain the spatial distribution of petrophysical properties. The combination of these tools also allows to constrain the shapes of geobodies and to extend them over the whole of the quarry for a spatial 3D visualization of the facies and petrophysical properties.

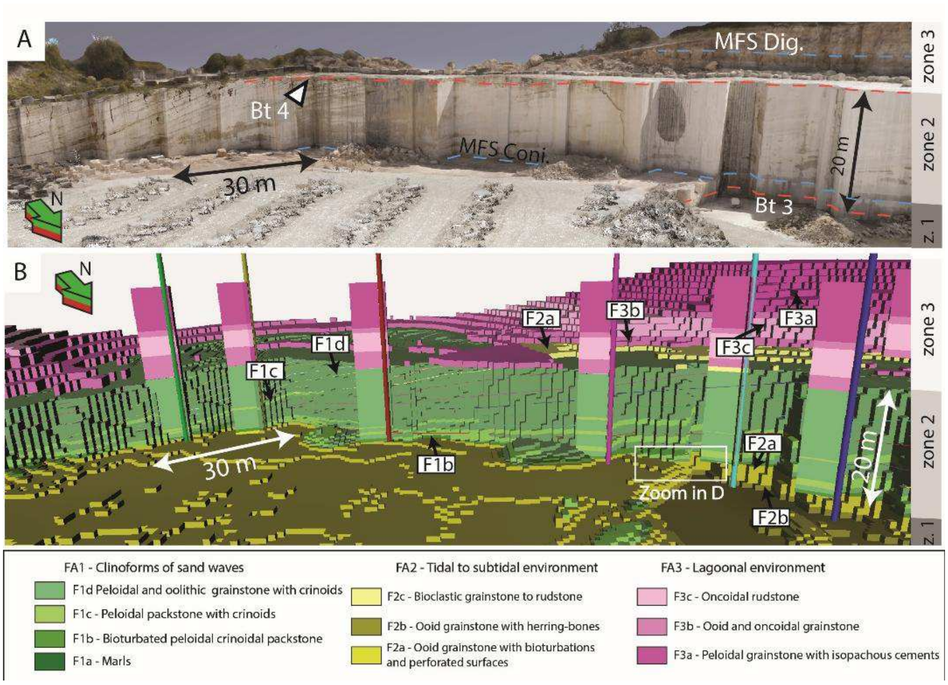

Figure 2. A- Panoramic view of the 3D model in VRGS® B- Relief-extruded part of the same part of the quarry showing the correlation between the field and photographic observations and the final facies model. (Issued from Thomas et al., 2021).

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InSAR and LiDAR analysis on Large Scale Rock Stability in La Grave, France : Preliminary Result

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Keywords: *Rock stability, LicSBAS, LiDAR, InSAR*

Rock stability has always become one of main concern in mountainous area, especially when it is close to roads or houses. As is in La Grave, France it requires regular monitoring to prevent any dangerous hazard along ± 8 km the roads. Based on this condition, satellite InSAR time series analysis of Sentinel-1 for 4 years (2017 – 2020) was carried out on both ascending and descending orbits using the Small Base Line Subset algorithm (SBAS) through the LicSBAS library (Python-based Open Source Software) to derive the time series and velocity of the displacement and to identifying unstable areas. For further measurement, analysis of potential sources of rock instability was also conducted using slope angle distribution method coupled with structural analysis from a 3D point cloud acquires with long range LiDAR. And then applied kinematic test from 3D point cloud data to identify potential failure in the rock cliff. So based on this approach, the coupling method using InSAR and LiDAR could define the best way to identify rock stability in large scale area.

Mineralogical and structural characterization of massive sulphide deposits in the Iberian Pyrite Belt using hyperspectral digital outcrops

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Key words: *hyperspectral imaging, open-pit mine, mineral exploration, point clouds*

Open-pit mines create near-perfect exposures of geologically complicated structures and mineralisations, providing excellent targets for digital outcrop analyses. The objectivity, detail and 3-D nature of digital outcrop models allow the characterisation of geological features such as fractures, faults and lithologies that can inform decisions on mine operation and design, and regional exploration targeting. In the following contribution, we integrate photogrammetric digital outcrop models with terrestrial hyperspectral scans to generate 3-D hyperspectral point clouds (hyperclouds) of the Tharsis volcanic-hosted massive sulphide deposit (Huelva, Spain).

Hyperspectral data in the visible–near (VNIR) and short-wave infrared (SWIR) range were acquired from multiple locations within two pits, Filon Norte and Sierra Bullones (Fig. 1A), aligned along the main mineralised trend at Tharsis. These exposures provide multiple sections across the mineralised zone, allowing us to investigate the 3-D architecture of the Tharsis deposit and characterise associated alteration.

The digital outcrop models were generated by co-registering Structure-from-Motion photogrammetric point clouds of the mine faces with radiometrically and topographically corrected hyperspectral images. We use traditional image processing approaches such as band ratios and minimum wavelength mapping to identify lithologies that differ in their iron, mica, chlorite and carbonate content and composition. Based on sample analytical training data, machine learning techniques are used to derive classification maps. These imaging products are mapped into multiple sets of composite hyperclouds (Fig. 1B), which enable a semi-automatic delineation of discontinuities on the point clouds guided by changes in the hyperspectral attributes, and an estimation of structural orientations from their intersection with the surface to derive simple 3D geological models.

At Tharsis, we use this approach to identify and characterise stacked thrust packages containing repeated shale and volcanic units. As the massive sulphide mineralisation predates and is truncated by these thrusts, it is possible that undiscovered mineralisation might be located by understanding the geometry of the thrust system. Additionally, preliminary analyses suggest different alteration mineral assemblages within the volcanic units. These may reflect juxtapositions of different alteration zones within the broader volcanogenic massive sulphide system, and hence also provide a useful targeting tool.

Multiple hyperspectral scenes of open-pit mine faces merged into a single composite hypercloud provide a unique 3-D dataset to characterize both mineralogy and structures of mineral deposits. They are easily combined with other spatial geological data such as drill core logs, geophysical maps and sections, and sample analytical data in a single 3-D environment, enabling integrative data analysis that will improve our understanding of mineral system architecture.

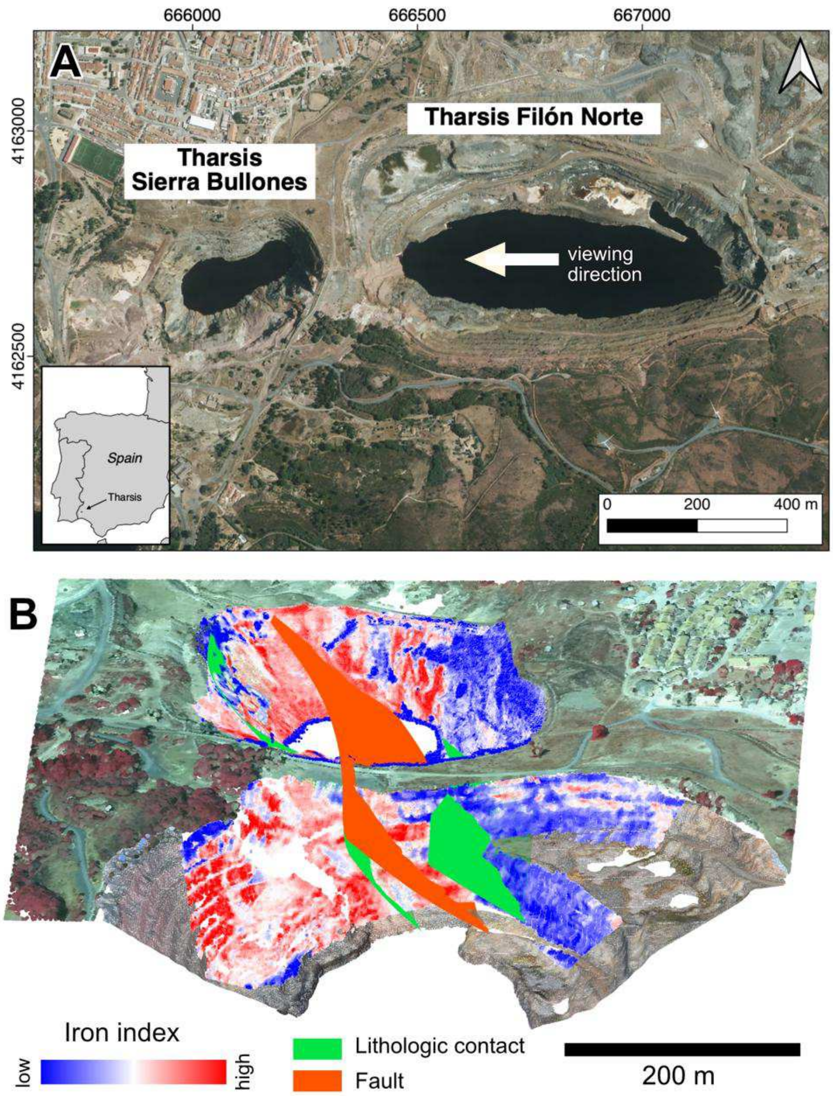

Figure 1: (A) Location map of the study area. (B) Oblique view to the west showing one of multiple sets of hyperspectral point clouds based on which lithological contacts, alteration zoning and tectonic structures were delineated.

Acknowledgements: We gratefully acknowledge Tharsis Mining for mine access and logistical support during fieldwork.

Numerical Architecture of the Observatory of the Vadose Zone (OZNS)

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Key words: *Photogrammetry, Laboratory-scale measurement, Laser scanning (lidar), Structural geology*

The Observatory of the Vadose Zone (OZNS) is addressing the role of the unsaturated zone in the transfers of water, heat, and pollutant, between the soil and the aquifer. This project implements a unique observatory within the Beauce Limestone Formation at Villamblain (France). This observatory consists of a large central well (20 m deep and with a diameter of 6.1 m) surrounded by satellite drill holes and surface installations within an area with a radius of a few tens of meters. The overall observatory spans from the surface down to 25 m depth, reaching the aquifer and the barrier layer of the Molasses du Gâtinais. The instrumented surface, central well, and satellite drill holes will produce decade-long records of the vadose zone to evaluate its impact on water and pollutant transfers, while monitoring its long-term evolution in a context of climate change.

From its initial conception, the central well has been designed to provide the best access to the whole vadose zone while minimizing the induced chemical and mechanical perturbations. The structure of the well is metal-free and the main structure is made of materials that are similar to the host rock. This access is primarily designed for easily installing, maintaining, and testing geophysical and hydrological sensors over the lifetime of the observatory, but it also provides a unique chance to observe the complex structuration of the vadose zone and its host. In particular, the scale and configurations of the site provide a unique view of this rock. They are made accessible at a micro-to-decametric scale, which extends drill core observations, and provide a nearly 3D view thanks to the large well, which is interesting by comparison with typical outcrops at that scale (e.g., quarries), which are mostly 2D. Preliminary observations, from surrounding drill cores, revealed a particularly complex limestone formation, which consists of a series of terrestrial limestones, with palustrine and lacustrine facies and breccias, affected by a long history of fractures and alterations, silicification, and karstification. A very detailed characterisation of these facies will thus be required for providing a high-resolution context for the various measurements and simulations of the transfers in the vadose zone. This contribution presents the construction of the numerical architecture and the acquisition process implemented for accommodating the very restricted access to direct observations during the construction of the well, which encompasses laser scanning (lidar) and high-resolution photogrammetry.

Figure 1: three-dimensional reconstruction of well core sample showing karstified limestone from OZNS

Comparison of single and multi-camera time-lapse landslide monitoring: A case study from the Siguas Valley in Southern Peru

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Key words: *Time-lapse imagery, change detection, landslide monitoring.*

There has been recent interest in using both terrestrial laser scanning and time-lapse imagery to monitor geological processes at higher temporal rates. A primary motivation behind this is the ability to detect, characterize, and understand processes occurring over a short duration, which in some instances could be precursory to larger hazardous events. The use of time-lapse imagery (TLI) monitoring is, in general, a lower accuracy close range remote sensing technique. However, it may be useful in instances requiring a lower deployment cost, lower power consumption or the requirement to install the equipment inconspicuously.

Both single and multi-camera TLI monitoring can be used detect and monitor landslide activity (Kahn et al. 2021, Blanch et al. 2021). Multi-camera systems allow photogrammetric 3D model construction for volumetric and change analysis. Single image monitoring can be combined with computer vision to detect key geological features and to monitor change. For example, Kahn et al. (2021) demonstrated the potential of using a single-camera TLI system to monitor a landslide to produce slope-velocity vectors in near real-time. As both single-image and photogrammetric methods can be used to monitor geological processes, the purpose of this study is to compare and evaluate the advantages and disadvantages of TLI single-camera and multi-camera monitoring at a landslide case study site.

The case study site is located within the Siguas Valley, Majes district, southern Peru (Fig. 1). The region surrounding the Siguas valley has been subject to extensive irrigation following a large irrigation project in the 1980s. As a consequence, increased landslide activity was observed within the Siguas valley in subsequent years (Grabet et al. 2020). These landslides threaten to dam off the Siguas river, cause erosion of agriculture land, and threaten to encroach on valuable infrastructure, such as the Pan-American Highway and local industrial buildings. Additionally, the region is seismically active, which is also a contributing factor to landslide activity in the region.

A five-camera time lapse system was installed opposing a landslide in the valley (Fig. 1). Multiple photos are collected during the day. Monitoring commenced in 23 Nov 2020 and is ongoing. Several earthquakes have occurred in the region during the monitoring period including a Mw 5.6 earthquake on 16 Dec 2020. Processes including landslide creep, earthquake induced activity, and progressive development of rock detachments at the back scarp have been observed thus far. The effectiveness of both TLI single camera monitoring vs. multi-camera photogrammetry is evaluated in the context of detecting and monitoring the geological processes at this case study site.

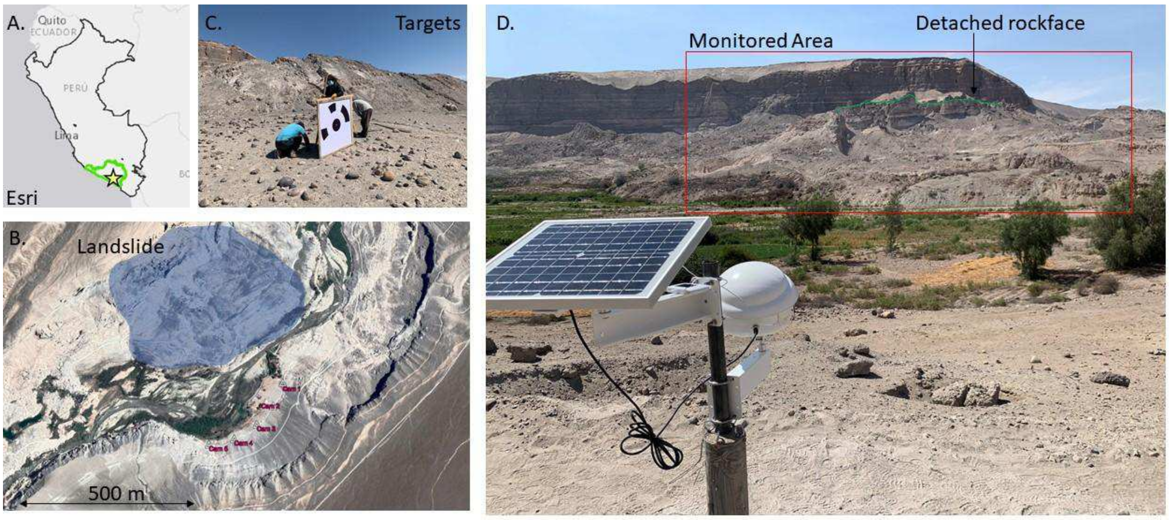

Figure 1: Site setup and location of monitored landslide. A. Location of landslide in Siguas Valley southern Peru (modified Graber et al. 2020; data Esri) B. Satellite image showing location of cameras and landslide being monitored (imagery CNET/Airbus). C. Installation of one of six coded targets on the landslide. D. Time-lapse photography setup and area of landslide being monitored.

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Rapid digitization of hard rock tunnels using 360-degree cameras and SfM photogrammetry

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Keywords: *photogrammetry, scanning, tunneling, 360-degree camera, digitization*

Photogrammetric scanning can be employed for the digitization of underground spaces, for example for visualization and training purposes (Uotinen et al., 2019). However, such a technique requires capturing a large number of photos, which can be time-consuming, especially if all surfaces of the tunnel have to be scanned. The acquisition time can be reduced by using a 360-degree camera, which has two or more lenses so that multiple photos are captured at each camera location. Barazzetti et al. (2018) has demonstrated that 360-degree cameras can be successfully used to produce photogrammetric models of interiors. However, no previous attempt to scan an underground rock tunnel with a 360-degree camera was realized. Therefore, this paper demonstrates a method for rapid scanning of hard rock tunnels using a 360-degree camera and Structure-from-Motion (SfM) photogrammetry.

A high-resolution 360-degree camera – Insta360 Pro was used to scan a 10 m long section of the Underground Research Laboratory of Aalto University (URLA) (see Figure 1a). The tunnel is located in granitic rocks at a depth of 20 m below the Otaniemi campus in Espoo, Finland. The camera has 6 sensors with spherical lenses and 6 photos are captured each time, which usually are combined into a single equirectangular panorama. However, in this study, the raw spherical images from each lens were used instead. In total, 162 photos were captured from 27 locations spaced evenly in two rows (see Figure 1b). A 3D model was reconstructed using SfM photogrammetry in Reality Capture software.

As a result, a high-resolution colored point cloud of the tunnel section was produced (see Figure 1b). The model consisted of 38 million points, with an average point density of 23.5 pts/cm^2. The accuracy of the scan was tested by measuring distances between control points attached to the walls of the tunnel, and the average error was 0.0086 m. Next, the time to capture the photos was compared against a more conventional method that utilizes DSLR cameras described in Janiszewski et al. (2020a). Capturing the images of the same tunnel section with the 360-camera took only 10 min in comparison to 64 min for the DSLR model. Even though the quality of the model was visually inferior compared to the DSLR model, it is considered sufficient for visualization and VR-based training in systems, such as the system presented in Janiszewski et al. (2020b). One possibility to improve the resolution and visual quality of the 360-degree camera-based model is to capture additional images with a DSLR camera and create a model from both types of images. An improved model created with 12 extra high-res images of the unsupported wall of the tunnel section is presented in Figure 2. It has a lower average error of 0.0070 m and only adds 6 min of acquisition time.

The results of this study demonstrate that 360-degree cameras can be used for the rapid digitization of underground tunnels to produce their digital twins of sufficient quality for visualization and virtual training. Future studies will investigate whether the 3D model produced from 360 images has sufficient quality for remote mapping of discontinuities and their properties.

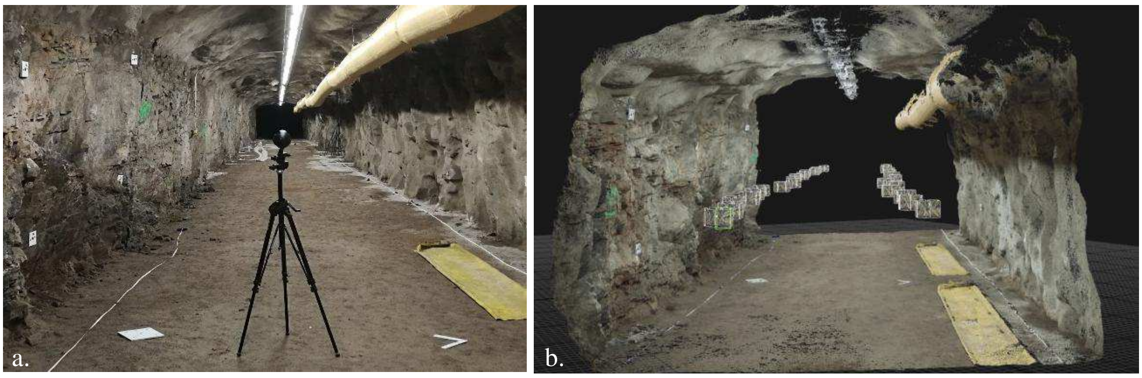

Figure 1: Image acquisition with the 360-degree camera at the test site of the Underground Research Laboratory of Aalto University (a), and the 3D model of the site reconstructed with SfM photogrammetry (b).

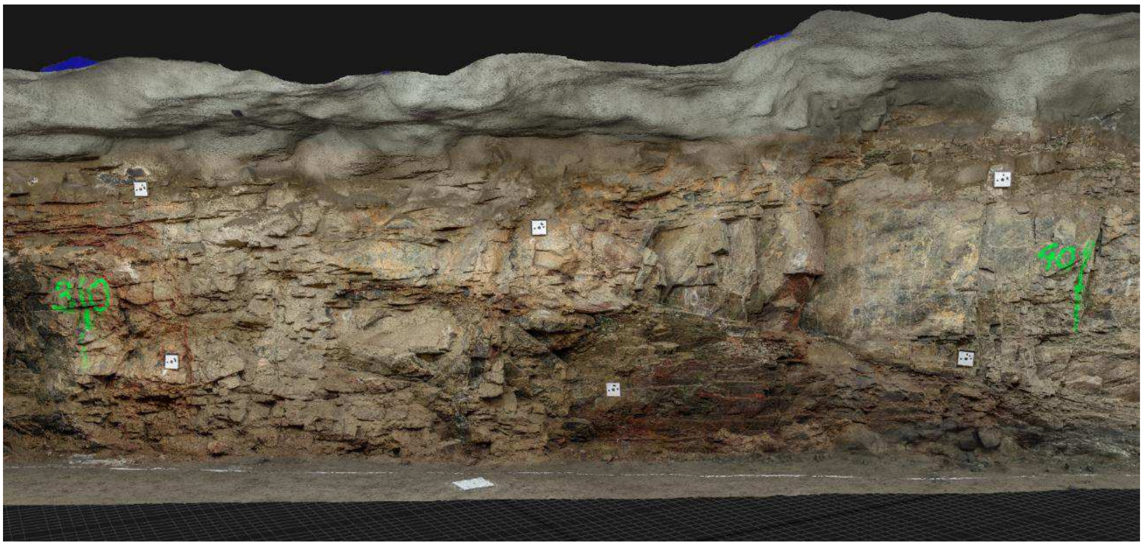

Figure 2. Textured mesh of a 360-degree camera-based photogrammetric model improved by adding extra DSLR images of the tunnel wall.

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Using Virtual Reality to replicate “*in situ*” field work on Mars

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Key words: *Digital Outcrop Model, Virtual Reality, Photogrammetry, Virtual field-trip, Sedimentology, Planetary Geology, Mars*

Planetary Geology, the study of planetary surfaces and morphologies of the planets and moons of the solar system, relies on data gathered by robotic probes (orbiters, landers, rovers) sent throughout the system. These data are returned to Earth for analysis and interpretation of the geological properties of the different planetary bodies. However, only one of these planetary bodies has been visited by humankind until now, Earth’s Moon (Luna), by 6 manned missions of the Apollo program. This means that exploration and understanding of the other bodies rely on remote data, whose characterization might sometime be tricky, particularly due to the lack of “in-person” approach.

To try and overcome these problematics, the growing use of 3D reconstructions and their integration within Virtual Reality (VR) environments is enabling us to visualize and experience with unprecedented accuracy the geological data returned by probes. This is notably the case with the sedimentary record of the planet Mars, as 3D shape and spatial distribution of the sedimentary structures observed there by the rovers of different missions have critical importance to understand the past environments associated with stable liquid water at the surface.

In this work, we focus on the geological characterization of the Kimberley outcrop in Gale crater, Mars. This outcrop was traversed by the *Curiosity* rover of the Mars Science Laboratory mission in 2014. While a detrital record deposited in a fluvial environment is understood for this outcrop, its stratigraphic relationships within this series and with its immediate to local surroundings are still poorly constrained, highlighting the need for a finer characterization of the sedimentary record.

As part of the European Horizon 2020 project PlanMap, we developed an integrated VR application dedicated to the geological characterization of the Kimberley outcrop on Mars (CARAVACA *et al.*, 2020a). The VR environment (Fig. 1) is based on regional high resolution orbital data and a local photogrammetric Digital Outcrop Model made from *Curiosity* data (CARAVACA *et al.*, 2020b).

The VR application allows to freely roam around the reconstructed outcrop and its vicinity within a ~3x3 km area, observable at various scales (real scale, Fig. 2a; regional scale, Fig. 2b). It features a complete set of measurement tools (with accuracy at the mm-scale) including distance (Fig. 2a), angles and strike/dip (Fig. 2b) measurements. The application also allows to switch basemaps between greyscale and colour orthoimages, geomorphological map, or a 360 panorama (Fig. 2c) in a GIS-like manner to access various information. Finally, the user has also the ability to reproject actual images taken by the various cameras onboard the rover on the 3D mesh from their exact point of view (Fig. 2d).

These VR tools represent first steps toward a complete “field-trip” to a remote and otherwise inaccessible Martian geological outcrop, in order to explore and characterize its sedimentary record in an accurate and efficient way.

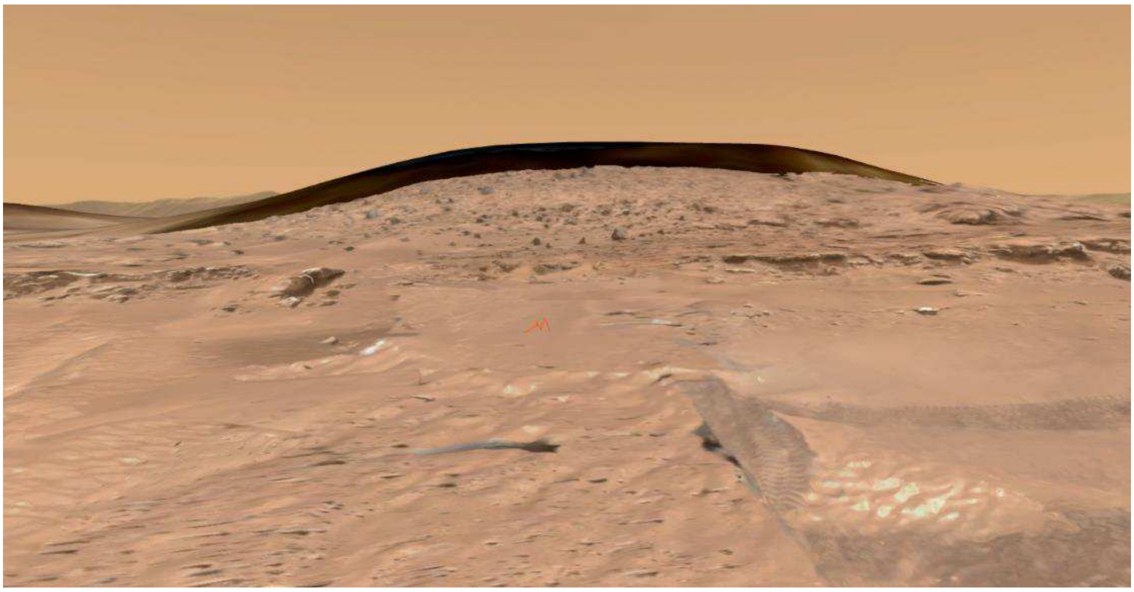

Figure 1: View of the VR environment toward the Kimberley outcrop (Gale crater, Mars), reconstructed from regional orbital data and a photogrammetric Digital Outcrop Model based on Curiosity *rover images (visible on Sketchfab at: https://skfb.ly/6RXJD.*

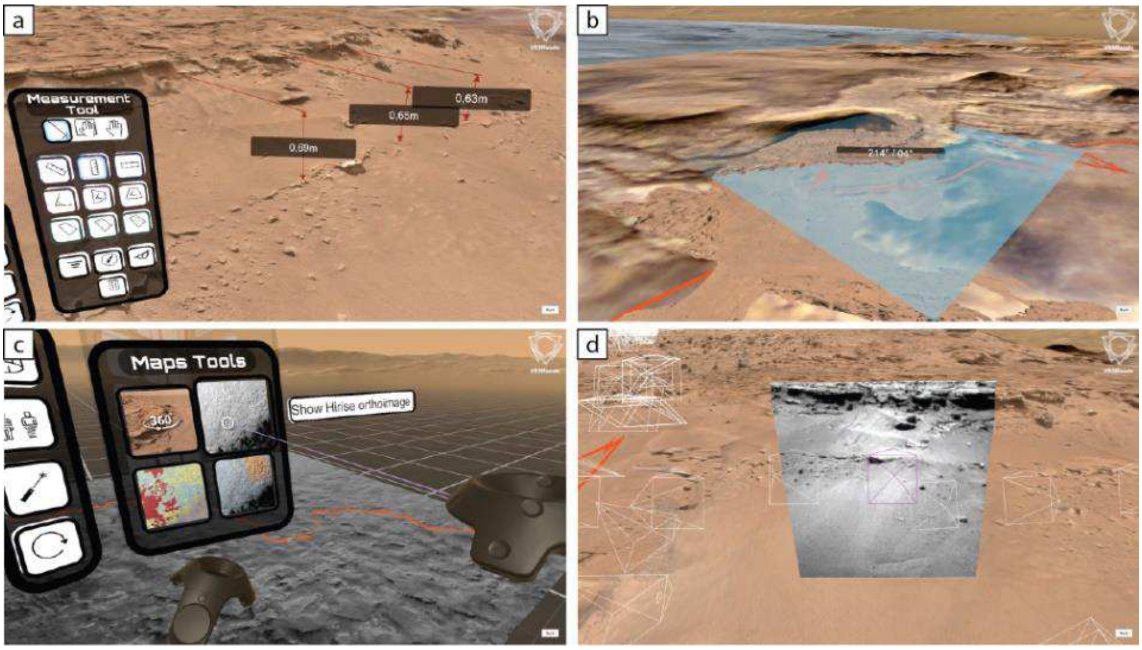

Figure 2. In-application views of the various measurement tools. a) Example of vertical distance measurements. b) Strike and dip measurement using the best-fit plane computation tool. c) Map selection tool, with greyscale and colour orthoimages, geomorphological map and 360 panorama. d) Example of actual Navcam image taken by the rover Curiosity *reprojected on the 3D DOM from its original point of view.*

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Virtual fieldwork for undergraduate students in Geosciences: report from educational attempts in University Lyon 1.

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Keywords: *Fieldwork, virtual tours, photosphere, innovative teaching*

An essential step in Earth Sciences studies is to learn how to observe geological objects *in situ*, during field works. This specificity of Geosciences is often appealing to students and crucial for their understanding of geological concepts.

At Université Lyon 1 though, an undergraduate student meets Geosciences for the first time in very specific conditions in large class of ~800 students gathering both future geologists and biologists. Planning fieldwork for such a large group is challenging and costly. Later in their first year, some students who want to specialize in Geosciences can benefit from fieldwork excursions in Lyon's surrounding areas. However, these excursions are daily, optional, and are highly dependent on the potential bad weather. These crucial field experiences were cancelled during the Covid-19 crisis and can be a major impediment for physically disabled people. These difficulties argue for developing virtual tools to introduce fieldwork to a broad audience, and support existing field trips. Several tools have been developed in Lyon in recent years. Here, we present two test-cases and discuss their pedagogical use.

The *Terrain Géologique Virtuel* projects (TGVs) are virtual visits designed as introductory fieldtrips that propose 360° panoramas, high-resolution zooms on lithologies, and additional documents. Students can navigate between scales (landscape geology, outcrop, lithology) and between 2D (maps) and 3D environments (immersed virtual views, Figure 1). TGVs can be visualized on web browsers remotely and played on all OS platforms or through VR apparatus available in a dedicated room. Tests have been conducted on the Pilat core complex during confinement with first and second year undergraduate students but TGVs could complement fieldwork at all levels, from preparing students to the fieldwork's best practices to bringing an interactive support for field report's correction. Scriptwriting of the sequence is essential to guide students when TGVs are used in full autonomy. A strong limitation of virtual tours is that no measurement of geological structures can be done and therefore, skills associated with the use of geological compass cannot be mastered.

Figure 1: Snapshot of a TGV virtual tour on the Coiron basaltic plateau (French Massif Central).

We also built a fully virtual excursion on the Tournon-sur-Rhône area (France) where the metamorphic rocks' fieldwork usually takes place for third year undergraduate students. Exercises were based on geolocated photographs, the Google Earth 3D viewer and a high-resolution 3D model of a key outcrop uploaded on the OSU Lyon Sketchfab platform (Figure 2; https://sketchfab.com/OSU_Lyon1). Geological mapping that is usually done by map drawing was conducted using QGIS. The students have acquired some understanding of metamorphic petrology, but lacked the understanding of the 3D arrangement of the structures.

Due to the Covid-19 crisis, we experimented 100% virtual field investigations for students from L1 to L3. The software and data were operational. Nevertheless, best experiences need a complete screenwriting and teachers had to highly interact online with students with unequal internet access. We conclude that the virtual field trips cannot replace traditional field experiences but can bring new and complementary skills to students, can improve investigations before and/or after the field, or can help students who are not able to go in the field.

Figure 2. 3D digital outcrop model of a key outcrop in the Tournon-sur-Rhône area (https://skfb.ly/onQUO; French Massif Central).

Time-lapse photogrammetry to feed a soil erosion model

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Key words: *SfM, 4D, change detection, data assimilation*

Soil erosion is a severe issue leading to long-term loss of fertile land. Due to the complexity, variability and discontinuity of erosional processes, model approaches to predict erosion risks are solely partially transferable to different spatial and temporal scales. Time-lapse photogrammetric approaches allow for the monitoring of the earth surface with very high spatio-temporal resolution. Amongst others, multi-temporal change detection enables to identify movements of the soil in both vertical and lateral directions.

In this study we introduce a photogrammetric workflow, using time-lapse imagery and videos at different scales to measure soil erosion across-scales. The image-based data is captured and processed to provide a large dataset of observations that will eventually be implemented in a physically based soil erosion model to validate predicted surface changes. At the largest scale UAV imagery is captured before and after rainfall events to measure soil surface changes at the scale of a small-catchment. More detailed, at the hillslope scale, a permanent camera-setup is installed to monitor the soil surface. The data acquisition is based on low-cost weather station data, which are used for event-based camera triggering. The system aims to capture multi-angle time-lapse images of the soil surface during rainfall events. For this purpose, five synchronised cameras on a rig at a height of about four meter are located at three slope positions. In addition, a low-cost thermal camera is utilised at each camera rig to be used as an indicator of soil moisture and RGB videos are acquired to allow for flow velocity measurements. At the smallest scale, the micro plot, rainfall simulations are performed and the surface is measured with eight to eleven synchronised time-lapse cameras at ten seconds intervals to observe aggregate breakdown and pool formations. Runoff and sediment measurements at the outlet will allow for data validation on all scales.

The flexible cross-scale applicable photogrammetric methods combined with physical-based methods of soil erosion modelling shall enable an improved understanding of soil erosion processes on various spatial and temporal observation scales. Eventually, the photogrammetric approaches are aimed for implementation to adjust an erosion model to enable across-scale description and validation of scale-dependent processes to offer new perspectives on both interconnectivity of sediment transport and the relationship between event frequency and magnitude.

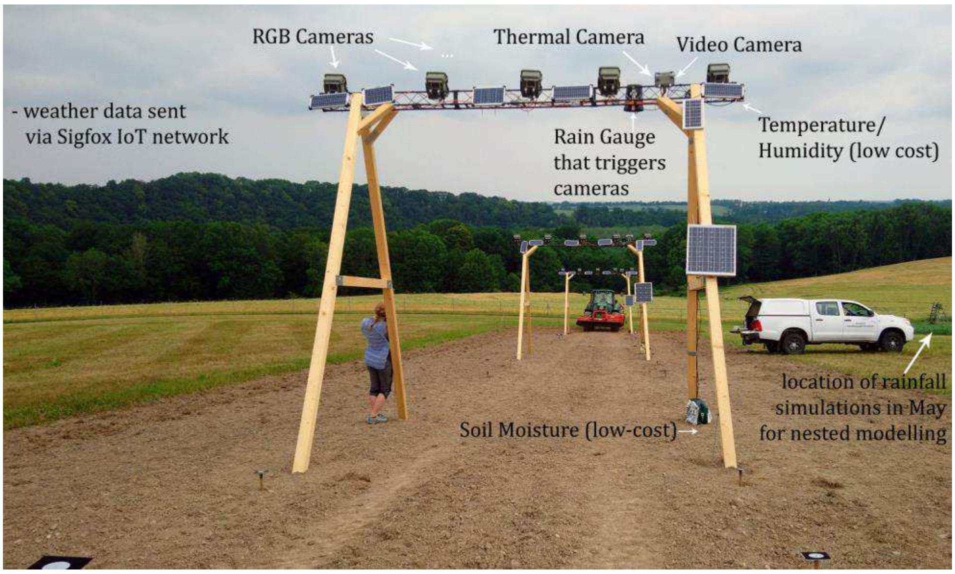

Figure 1: Hillslope setup to measure soil erosion during the rainfall event based on time-lapse SfM photogrammetry