Printgrammetry—3-D Model Acquisition Methodology From Google Earth Imagery Data

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***Abstract*—This article proposes a technique named Printgrammetry, a structured workflow that allows the extraction of 3-D models from Google Earth platform through the combination of image captures from the screen monitor with structure from motion algorithms. This technique was developed to help geologists and other geoscientists in acquiring 3-D photo-realistic models of outcrops and natural landscapes of big proportions without the need of field mapping and expensive equipment. The methodology is detailed aiming to permit easy reproducibility and focused on achieving the highest resolution possible by working with the best images that the platform can provide. The results have shown that it is possible to obtain visually high-quality models from natural landscapes from Google Earth by acquiring images at high level of detail regions of the software, using a 4K monitor, multidirectional screenshots, and by marking homogeneously spaced targets for georeferencing and scaling. The geometric quality assessment performed using light detection and ranging ground truth data as comparison shows that the Printgrammetry dense point clouds have reached 98.1% of the total covered area under 5 m of distance for the Half Dome case study and 96.7% for the Raplee Ridge case study. The generated 3-D models were then visualized and interacted through an immersive virtual reality software that allowed geologists to manipulate this virtual field environment in different scales. This technique is considered by the authors to have a promising potential for research, industrial, and educational projects that do not require high-precision models.**

***Index Terms*—Digital outcrop model, geosciences, Google Earth (GE), photogrammetry.**

I. Introduction

THE past two decades have seen an increasing popularization of 3-D modeling techniques, hugely motivated by technological advancements in hardware and software. These techniques have provided, among other features, the transposition of real-world objects to the digital media, allowing a detailed photo-realistic visualization of its geometry and texture [1], [2]. For these reasons, this digitization of real-world objects has assisted several researchers and professionals in their respective projects. As a good example of it, we can mention an important activity related to geological studies, which is the 3-D modeling of outcrops for geometric and structural data extraction [3]. An outcrop can be defined as a rock exposure on the surface of the earth, that can occur naturally by the erosion of the soil or by human action, such as roadblocks, quarries, etc. The study of outcrops is crucial in the decision-making of engineering processes such as mining and oil exploration, as well as in academic studies that have been hugely benefited from 3-D photo-realistic reconstructions [4], [5], once additional quantitative data can be extracted from digital outcrops, optimizing geologist's field activities.

The 3-D modeling of outcrops have a strong bias for industrial and research projects, where it is commonly referred to as digital outcrop models (DOM) or virtual outcrop models (VOM) [3]. However, it also has potential when applied to geoscience education for field trips and teaching purposes. Through DOMs, it is possible to develop a virtual field environment (VFE), which is an immersive geological digital learning environment through virtual reality (VR) technology, where geological sites can be recreated and visualized in immersive VR (iVR), allowing students to experience virtual field trips to a vast number of sites that they could not otherwise, for being too expensive or even dangerous [6]–[8].

To be able to map an outcrop and build a DOM, there are two main techniques reported in the literature that suit different scenarios. One is LiDAR (light detection and ranging), which is extensively used in the field of geosciences via terrestrial laser scanners (TLS) or via aerial vehicles, through airborne laser scanners (ALS) [9]. It utilizes a laser scanner to generate point clouds that can be triangulated and textured with digital photos [3], [10]–[14]. Despite the high precision of those equipment to digitally represent the geometry of an outcrop [15], some disadvantages of TLS and ALS are related to its heavyweight, purchase cost, and operational complexity [16], [17].

Recently, DOM generation using LiDAR methodology is being replaced in several case scenarios by digital photogrammetry, due to the emergence and popularization of unmanned aerial vehicles (UAV), popularly known as drones, even though terrestrial photogrammetry (using manually controlled digital cameras) is also used [18]–[20]. In digital photogrammetry technique, which is based on structure from motion (SfM)

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algorithms, a point cloud can be obtained using digital photos that are captured with a given overlap between them [21]. To increase 3-D point density, multiview stereo (MVS) algorithm [22] is used and the resultant dense point cloud can also be triangulated and textured with the captured digital photos to build the DOM [17].

Although being a feasible alternative for most case scenarios, photogrammetry of inaccessible or extensive regions may increase the costs and complexity of the task, restricting the available areas of study [23]. Also, when it comes to airspace control regulations worldwide, the most accessible in terms of flight permission for UAVs is at low altitude. According to [24], that approaches UAV's regulations through a review, where 19 countries from different continents were studied, the maximum flying altitude legally allowed varies between 90 and 152 m, in order to protect manned aircraft traffic from any possible risk. This limitation in flying height restricts even further extensive and high topography regions to be mapped, where higher above ground level flight altitudes are required to be able to survey the entire area.

In this sense, Google Earth[1] (GE), which is a digital platform that has the entire globe represented mainly by 2-D satellite images, but also with 3-D photo-realistic representations of cities and geological landmarks, could overcome this limitations. However, GE does not provide a 3-D model export tool for this type of data, which would be useful for visualization and analysis in other software. So, the main objective of this work is to propose an easy-to-reproduce and low-cost alternative for 3-D modeling of large-scale geological landscapes, making it accessible to anyone with interest on the topic, using GE imagery as input dataset. In that way, those 3-D models can be used, for example, in iVR field trips systems for research or education in the geosciences, where the virtual immersive technology is gaining space. For that, a methodology named Printgrammetry was designed.

Printgrammetry is inspired by the work of Chen and Clark [25], who have first published the idea of using screenshot images from GE for building 3-D models. However, some major changes in hardware, software, and in the flight plan itself were implemented to improve the quality of the data acquired. Also, a different validation method is used to assess the quality of the generated product.

This technique results in a product that can be combined with an immersive visualization software developed by Vizlab research group [7], [8]. It tends to bring geoscientists to the most diverse and unreachable field environments and it may positively contribute to future researches and teachings approaches in immersive VR geology. It is important to mention that in this article, the presented technique is focused on geological structures (outcrops), but it can be reproduced to reconstruct buildings and urban areas for engineering and architecture studies, for example. See Supplementary Material for another comparison study related to an urban scenario.

Therefore, this article is structured as follows. In the next section, Printgrammetry's workflow is presented, from selecting an available place on GE platform to generating the 3-D model using SfM, and how the generated models were validated using airborne LiDAR point cloud as ground truth data. As study cases, we approach in Section III, the 3-D modeling of two important and widely known outcrops, both located in the USA (see Fig. 1): the Half Dome, located in Yosemite National Park/California; and the Raplee Ridge, located near the town of Mexican Hat/Utah (chosen due its airborne LiDAR data availability). In this same section, the visualization and interaction with the 3-D models generated by Printgrammetry is illustrated, using an iVR software aimed for geologists. Finally, some considerations and future opportunities of this work are elaborated in Section IV.

II. Material and Methods

A set of software were used in this work in order to implement Printgrammetry. The first is Google Earth, used for virtual 3-D imagery acquisition. The service provides two types of platform for the user: one via web browser and the second via desktop application (Google Earth Pro). In this work, the latter option (version 7.3.2.5776) that provides a set of drawing and measuring tools necessary to design the Printgrammetry's flight plan that assists in the screenshot acquisitions was used. Besides GE, Greenshot Software[2] v. 1.2.10 was used for capturing screenshots from the computer monitor to be used in the data processing workflow. This screenshot capture software improves GE imagery data acquisition by allowing personalized configurations to be set in the acquisition process, which is an extensive manual task. To remove outliers of the SfM generated point cloud and to compare LiDAR point cloud data with Printgrammetry data, the software CloudCompare[3] was used. The photogrammetric 3-D model reconstruction was performed in Agisoft Metashape[4] v. 1.4.4. and except for Metashape, all other softwares mentioned above are free to use. Finally, an in-house developed software named MOSIS V2 [26] was used for visualization and interaction with the 3-D model generated by Printgrammetry since it provides total immersion of the user through an iVR system. This software was previously validated by the system usability scale metric [8].

In terms of hardware, the computer configuration used was an Intel i7 sixth-generation CPU, GTX1080 8Gb GPU, and 64GB of RAM. Along with this system configuration, a 4K resolution monitor was employed as a suggestion from Chen and Clark's work [25], in order to enhance screenshot image quality, consequently resulting in a more geometrically accurate 3-D model [27].

A. Printgrammetry Workflow

The Printgrammetry methodology can be divided into a three-step workflow (see Fig. 2) that comprises: 1) selecting the location, which consists of checking the existence of 3-D data from the desired study location on GE; 2) data acquisition, being the Printgrammetry method itself, which is the process of acquiring images to 3-D model generation; and 3) data processing,

[1]Online. [Available]: https://www.google.com/earth/

[2]Online. [Available]: http://getgreenshot.org/

[3]Online. [Available]: https://www.danielgm.net/cc/

[4]Online. [Available]: http://www.agisoft.com/

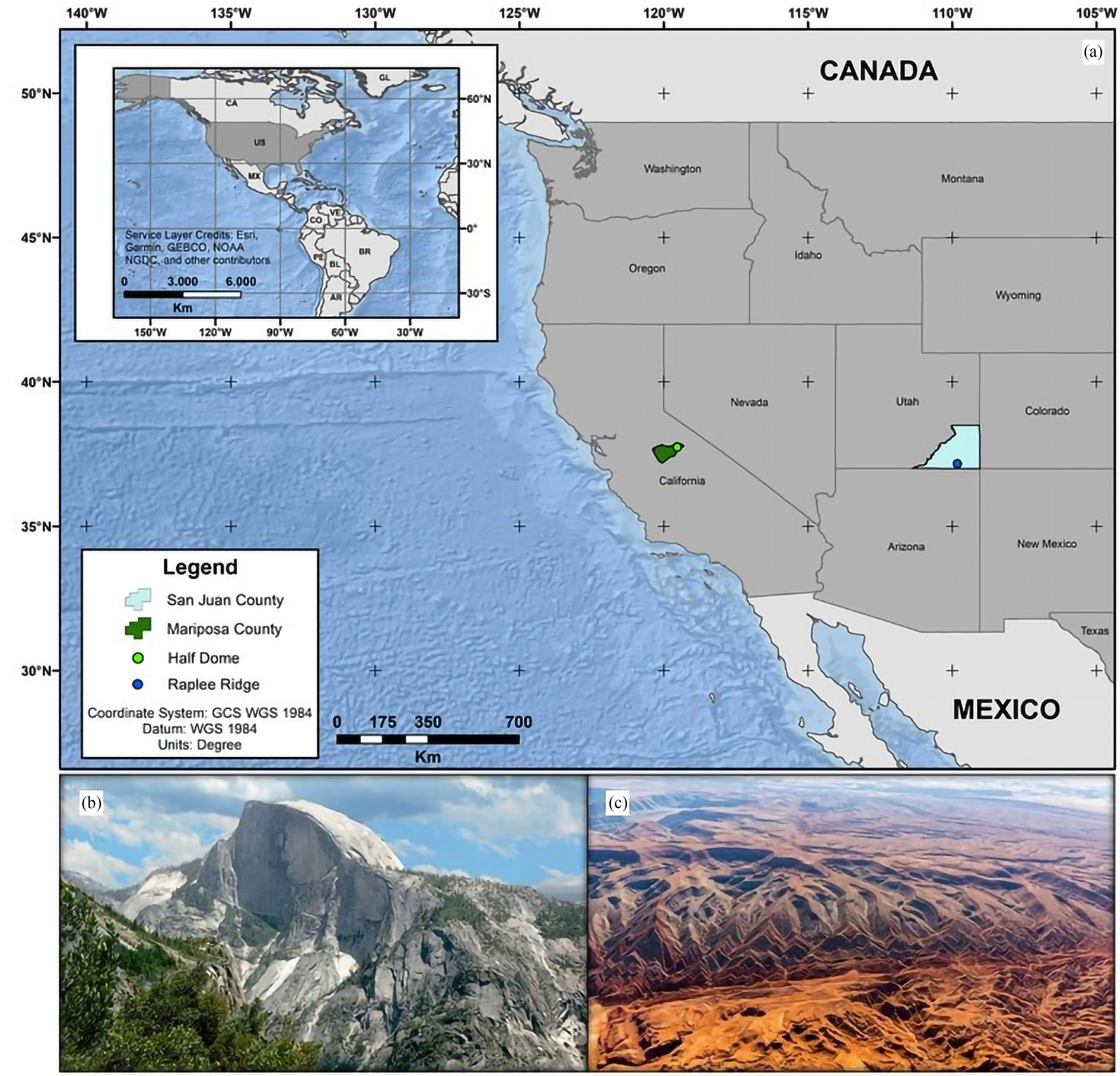


Fig. 1. (A) Map showing the location of Half Dome and Raplee Ridge, study cases of this work, with an illustration of both outcrops, displaying the Half Dome's northwest face (B) and Raplee Ridge's west face of (C).

consisting of an SfM algorithm software that takes the acquired images as input to build the 3-D model on an SfM processing software.

1) Select Location: The first step to build a 3-D model of a given area using GE is to ensure that the area of interest has 3-D imagery available on the platform. As GE is essentially built upon 2-D satellite imagery, for the software to provide a realistic 3-D geometry of places, it is necessary that they have performed a flight over an area with remote sensing equipment on board (like metric cameras or LiDAR). This activity is more complex and time consuming than today's satellite imagery systems, being the reason why the regions that provide realistic 3-D visualization are limited, being essentially big cities or famous architecture and widely known geological formations (landscapes). Even so, the Google Earth platform offers a large quantity of 3-D mapped places all over the world and all of the available places can be found at their website,[5] which is a recommended source to check before starting any Printgrammetry project.

[5]Online. [Available]: https://earth.app.goo.gl/SxxU9k

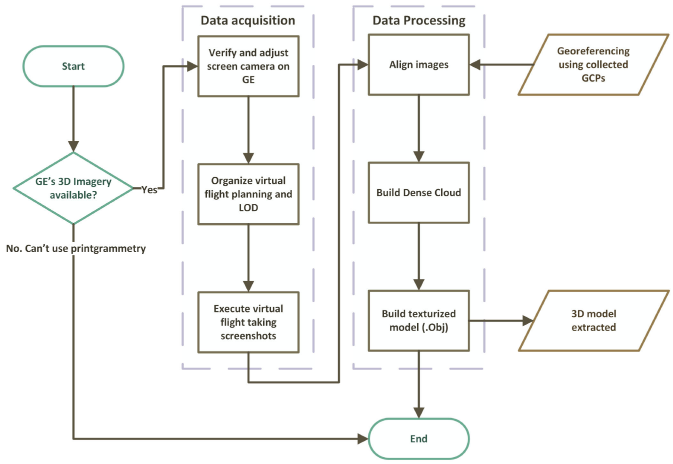


Fig. 2. Printgrammetry workflow.

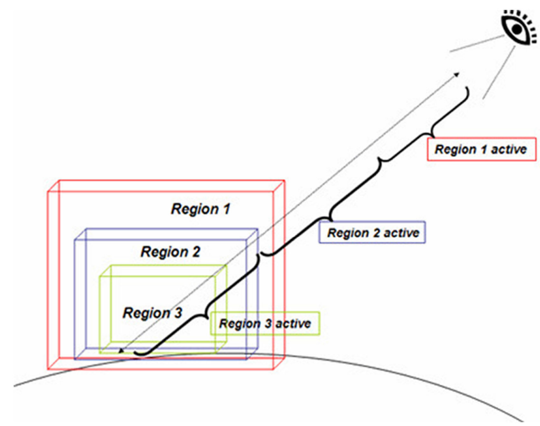


Fig. 3. LOD and active regions [29].

In order to demonstrate the technique that is the focus of this work, and describe it along this article, two geological formations of different dimensions and aspects that could impact on the SfM's workflow for having extremely different colors pallet, textures, and slope, which is the case of Half Dome and Raplee Ridge, were chosen (see Fig. 1). Also, those regions were chosen for being very popular and for having LiDAR data freely available for download[6] that could be used as ground truth.

2) Data Acquisition: This phase describes the steps necessary for the proper screenshot acquisition of GE imagery being displayed at the monitor, and all the configurations involved in this process. It ensures image acquisition at the best possible quality by making use of a workflow that facilitates this manual tiresome task. The developed workflow consists of the following steps.

A) Camera setup: The quality of the camera and its images is a major factor on the SfM technique, directly influencing the resultant 3-D model. In this sense, camera resolution plays an important role in 3-D models geometry and metric accuracy. In Printgrammetry, the digital camera can be seen as the monitor's screen used to take screenshots from GE.

For the study cases described in this article, a 4K resolution (3840 $\times$ 2160 pixels) monitor that provides an 8.3 megapixels (MP) screenshot of the whole monitor was used. However, considering GE impossibility of displaying imagery in full screen, it was necessary to use the Greenshot Software.[7] This free license software, allows the user to easily select which screenshot monitor area will be acquired. Therefore, in order to remove borders and nonimage elements (Google Earth watermark and the navigational system) of the displayed GE imagery, it was necessary to set Greenshot preferences on the *Capture Window* hotkey. This hotkey was used to select a 3634 $\times$ 1735 pixels monitor area that has provided 6.3 MP images surpassing the minimum resolution recommended by Agisoft's user manual [28] and following Chen and Clark's suggestions of image quality improvement when using a higher resolution monitor.

[6]Online. [Available]: https://opentopography.org/
[7]Online. [Available]: https://getgreenshot.org/

Also, considering that it would be taken as an expressive amount of images, the authors suggest, in this step, to define a hotkey to the *Capture last region tool*. This tool helps to optimize Greenshot's screenshot output automatically to a given file storage location that can be defined at the *Output tab* in the software's preferences and also the *Image format*.

This phase consists of covering a given study area that the user intend to extract imagery from GE 3-D topographic relief, with parallel flight lines right under the highest level of detail (LOD) region as a flight plan, populating the study area with graphic elements to guide the dataset acquisition.

LOD is an important concept to this workflow since it is related to different working regions of GE software. Because computer screens have a limited amount of space, large amounts of data are loaded and shown when users reach an active region. Each active region has a set of LOD boundaries that specifies the projected screen size of the pixel region required for the associated one to become active (see Fig. 3). As the user's point of view approaches, regions with more precise detail levels become active as it takes up more space on the screen. The regions with more accurate LODs replace the previously loaded regions with closer ones, thus, with higher resolution, as illustrated in Fig. 4 [29].

Using GE's *Polygon tool*, limits need to be drawn over the study area perimeter, setting the desired 3-D model boundaries that facilitate the parallel multidirectional flight lines to be drawn. The close spacing of these flight lines ensures the image overlap of both front and side images. The GE camera needs to be set at approximately 45 downward looking angle to maximize coverage of both vertical and horizontal surfaces in a single passage while the back-and-forth flight directions maximized multidirectional (see Fig. 5) coverage of 3-D structures [25].

However, before lines were set and drawn, it is necessary to ensure maximum LOD in GE imagery, an important visual information that is used to define the flight altitudes. In the case of rough terrains, these flight altitudes will be dynamic, meaning that the camera's altitude will need to vary in order to assure this maximum LOD. To verify if this step is done, the user needs to

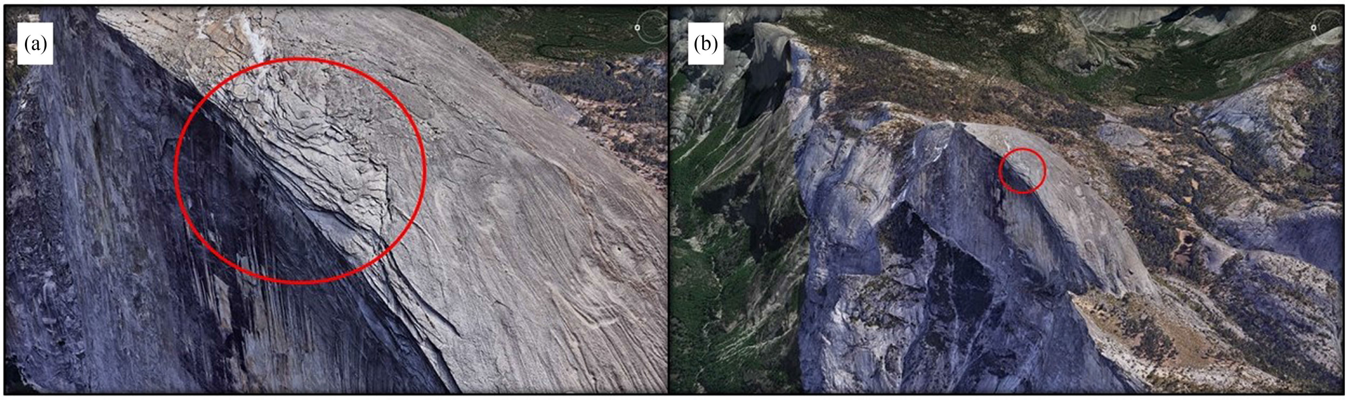


Fig. 4. Example of different LODs of Half Dome in GE Pro, showing geological features in a higher LOD image (A) that cannot be visualized in a lower LOD (B).

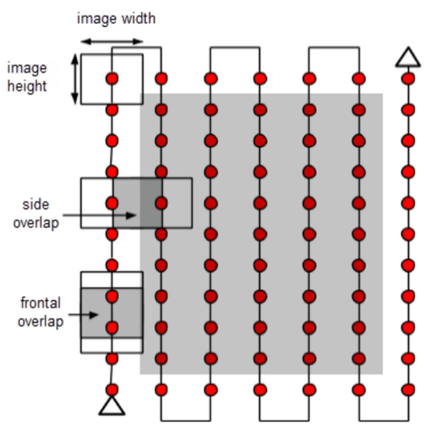


Fig. 5. Flight path illustration with multidirectional coverage of 3-D structures [30].

check the completion of the progress bar located at the bottom right window of the software before each screenshot.

The user is then ready to start drawing the parallel flight lines (GE *Path Tool*) taking into consideration image overlaps and the desired LOD. Overlap is the common area imaged between two consecutive images in the same flight range (see Fig. 5). In conventional photogrammetric surveys, this value is 60%, however, in surveys using drones, it is recommended not to cover less than 70%. This value is justified in the event that some image presents some fault, as out of focus or not recorded. Either way, a minimum 70% overlap was adopted between images being done in a visual manner since these problems are not expected to occur.

Finally, it is necessary to acquire a set of distinguishable homogeneously spaced target's geographic coordinates which will work as ground control points (GCP) for georeferencing and scaling of the SfM reconstructed model. The GE working horizontal reference system is WGS84, which can be configured to be displayed as geographic coordinate system (latitude and longitude) or projected coordinate system (UTM). The vertical reference system is assumed to be EGM96, as GE documentation did not clearly specify this information. It is recommended to use the *Marker Tool* to extract the geographic positioning values from the chosen targets as a visual resource in the software.

B) Screenshot: This is the last step of the data acquisition phase, where Greenshot is already configured and the flight lines were drawn right over the last active region boundary. It is important to remember to remove all interface panels and visible layers before starting to acquire the screenshots. If this is not done, the 3-D model will be displayed with markers, text fields, and lines that can compromise the quality of the Printgrammetry product.

The user then can manually move the camera following the drawn flight path and acquire images using Greenshot hotkeys throughout the whole area like on a drone flight plan. The user must pay attention to turn-OFF the layer that displays the lines of the flight path while taking the screenshots and turn-ON only when a visual guidance is needed. While performing the image acquisition process, the user must assure that the same object is covered in at least four front overlapping images and four side overlapping images in order to guarantee the planned overlap of around 70% (see Fig. 5).

C) Data Processing: Data processing phase uses Agisoft Metashape software to process the imagery data to generate a dense point cloud and a high-resolution 3-D textured model in five steps processing workflow. If desired, other photogrammetry software can be used, but the authors only guarantee the reported results in Section III using Metashape.

The first step consists of a photoalignment that place image's respective virtual cameras in space. In this alignment process, as Greenshot software does not provide camera information and position, Metashape makes an attempt to estimate camera lens characteristics which is an important feature for correcting image distortions. In the case of a positive outcome, the initial image alignment place photos in their relative locations and calculates the sparse point cloud/tie points.

The following step involves establishing GCPs (previously acquired) in the images from the data acquisition phase to refine, scale, and specialize the model in a given coordinate system. Upon reaching a satisfactory status, a camera optimization tool can be used to calibrate camera parameters and refine images geographic absolute positions.

After all images are correctly located and all GCPs were established, Metashape uses the SfM algorithm to generate a dense point cloud. It results in a more populated point cloud containing usually millions of points that resembles a photo-realistic 3-D rendering of the environment.

The fourth step builds a solid mesh by interconnecting the points of the point cloud in order to build multiple triangles, which finally provides a 3-D model of the mapped environment. This model is then textured with the taken images which maps the mesh for photorealism.

B. *Quality Assessment*

This section will describe the proposed method for assessing the quality of Printgrammetry's products, which consists of comparing distances between the dense point cloud generated in Metashape and airborne LiDAR data of the same area available at Open Topography database. Point clouds from LiDAR are commonly used in the geosciences as ground truth data for validation and statistical analyses of other techniques because it provides dense datasets with trustworthy and high accurate geometry [31].

Before the comparison between both point clouds could be done, it was necessary to align them. Theoretically, as the point clouds are georeferenced, they should be superimposed when opened in a geographic information system (GIS) software. However, the Printgrammetry point cloud was georeferenced using GE targets, while LiDAR point cloud had an ideal georeferencing with GPS stations and data postprocessing, which is far more precise than using GE coordinates. This would add errors on the statistical results that would compromise the validation. Because of that, the *Registration Tool* was used in CloudCompare to manually align both point clouds, allowing the Cloud-to-Cloud (C2C) distance to be computed properly.

The C2C is a measurement method in CloudCompare Software used for computing the absolute distances between clouds. The cloud comparison was performed from local models to avoid problems related to C2C distance based only on the nearest neighbor, mainly under the possibility of low-density regions when the nearest neighbor is not the actual nearest point on the surface represented by the cloud. In that way, the local model used was the C2C based on the least-square best fitting plane that goes through the nearest point and its neighbors, used directly to compute distances between clouds.

These local model captures features that help to go through the difference between the clouds, understanding and evaluating the potential of the methodology in question. As C2C method is based on least squares, the measured distance is sensitive to the cloud roughness, outliers and point spacing [32], although this sensitivity is reduced using more points (6 were chosen) rather than accurate distance measurement.

Considering that the user may want to use only Printgrammetry for some application, it would be important to consider the outlier removal as a first step. As outliers may influence the C2C method, we have applied a statistical outlier removal (SOR) clean tool in CloudCompare before cloud comparison, which first computes the average distance of each point to its neighbors (6 were chosen), then it rejects the points that are further than the average distance plus 1 standard deviation.

With the distances between clouds computed, the descriptive statistics can be calculated to estimate the model quality such as the mean, the median, the standard deviation, and the root-mean-squared-error (RMSE). As the standard deviation do not represent the precision considering the median, the normalized median absolute deviation (NMAD)[33] was also used.

III. Results

A. *Case Study 1: Half Dome—Yosemite Valley, California*

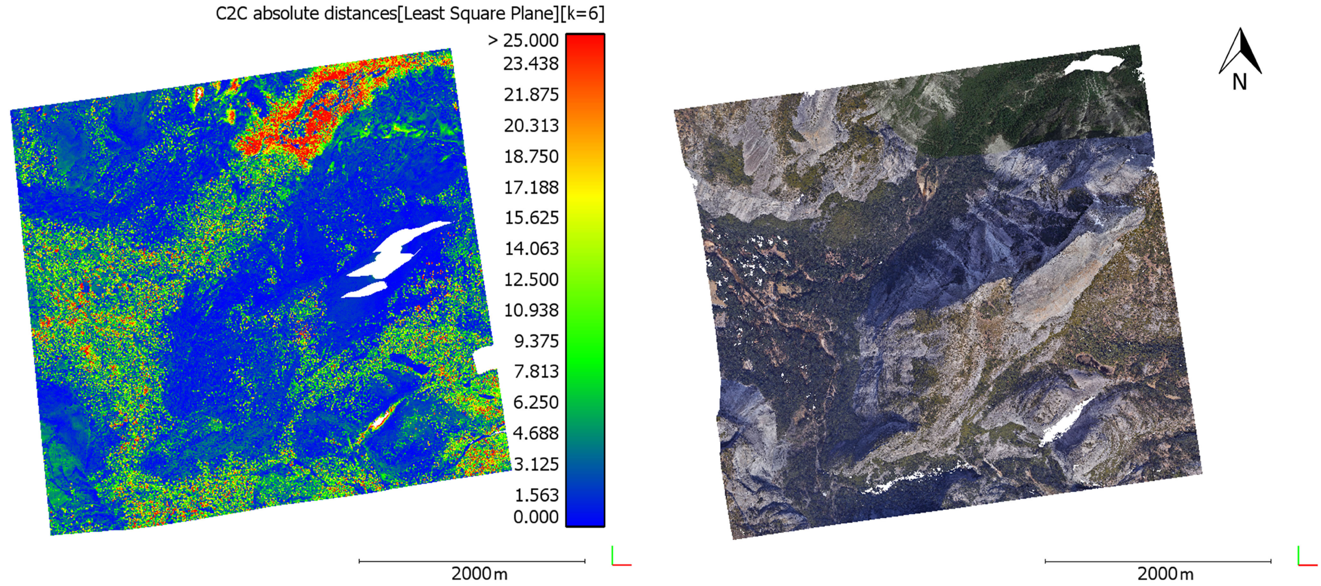
Yosemite Valley is a deeply carved valley in the gently sloping western flank of the Sierra Nevada. At the head of the valley stands Half Dome, the most colossal and recognizable rock monument in the Sierra Nevada, a medium to coarse-grained granodiorite containing well-formed plates of biotite and crystals of hornblende. It is smoothly rounded on three of its sides and a sheer vertical face on the fourth. The area of study is located at the eastern end of Yosemite Valley between UTM zone 11N projection (WGS84 reference system): [272910m E; 4181945m N] and [278458m E; 4178435m N], which circumvent Half Dome [34].

1) LiDAR Data: The LiDAR point cloud from Half Dome was downloaded from the National Center of Airborne Laser Mapping (NCALM) as result of a mapping project conducted in August 2010 [35]. In the survey, an Optech GEMINI Airborne Laser Terrain Mapper was employed to digitize 35.1 km^2 of land that comprises Half Dome and part of Yosemite Valley that surrounds it. The airplane flew at an altitude of 700 m in a flight plan in grid format, respecting 50% of swath overlap between each flight path in a survey that lasted almost four hours. For georreferencing the generated data, four GPS stations was used as ground reference to the on-board GPS and the airplane path position was corrected using kinematic postprocessing, referenced to NAD83 horizontal reference system and NAVD88 for orthometric heights, converted from GRS80 ellipsoidal heights.

The downloaded point cloud has originally 237 million points, but it covers a larger area than the one generated by Printgrammetry, so it had to be cropped. After this procedure, the resultant pointcloud, which was effectively used for comparison, has about 43 753 000 points.

2) Printgrammetry Results: Using the Printgrammetry methodology, 514 images were acquired from Half Dome and its surroundings. The processed images within the Agisoft Metashape using the SfM and MVS algorithms in high-quality settings generated a dense point cloud of 28 million points. A total of six GCPs were collected from natural and distinguishable targets present in the study area. The processing report from Metashape estimated a total RMSE of 4.4 m for all GCPs, which is equivalent to 0.4 pixel on the 3-D model (see Table II).

Through CloudCompare software, the outliers present in the point cloud that generates noise to the dataset were removed using the SOR Clean Tool. It removed a total of 380 000 points



(a) (b)

Fig. 6. Half Dome study area showing both LiDAR and Printgrammetry resultant point clouds. (a) LiDAR point cloud colored with scalar field of C2C absolute distance (least squares measurement method). (b) Printgrammetry point cloud colored with RGB images captured in acquisition phase.

TABLE I
C2C Statistics Based on the Absolute Distance Between Points for the Half Dome Model (in Meters)

mean	median	standard deviation	NMAD	RMSE
3.945	2.358	4.772	2.232	6.191

TABLE II
Parameters Involving Half Dome Reconstruction by Printgrammetry

Parameters	Half Dome project
3D model extension	5.21 km
3D model area	22.5 km^2
N. of images	514
Dense point cloud	28,463,809 pts
N. of GCPs	6
GCP total RMSE	4.407 m

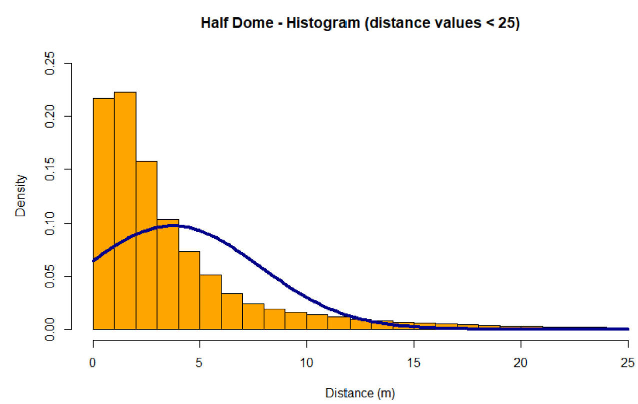


Fig. 7. Histogram of C2C distances of Half Dome based on Gaussian distribution.

considered as outliers by the cleaning tool. After that, both point clouds were aligned using the *Registration Tool* in order to superimpose them, allowing the C2C to be computed. As a result, the point cloud that represents the difference between both LiDAR and Printgrammetry point clouds returned a mean distance of 3.945 m with a standard deviation of 4.772 m and an RMSE of 6.191 m (see Table I).

The difference between both point clouds is represented by the scalar field (SF) indicated in Fig. 6. According to the figure, its possible to see that most of green dots, which represents errors between 5 and 15 m approximately, are distributed along with the region of the valley, characterized by the presence of a dense forest. It also shows areas with larger errors (colored in red) where there is a lack of data from the SfM reconstruction, which has influenced on the C2C results since the point neighbors are far from each other. Besides that, one can notice that the northern region of the Printgrammetry point cloud is colored with a darker tone of green. That transition in color represents the change on GE database from the 3-D model generated from airplane survey to the ordinary estimated 3-D data from 2-D satellite imagery. This also justifies the larger error in that region. For the geologic important area, which is the rock exposure itself, it is mostly represented by blue points.

The histogram of the errors distribution (Fig. 7) shows that 91% of the point cloud is associated with an error below 5 m and 98.1% are below 10 m. Because of the very low density of errors above 25 m (0.01% of the point cloud), for better visualization purposes, the SF distribution was limited to a maximum value of 25 m. Even though it is not a representative value, the maximum error reached for this point cloud was of 336 m, located at the northern region.

After the geometry of the point cloud was statistically assessed, it was triangulated and textured in order to produce the realistic DOM. The 3-D model consists of 6 975 566 triangles that were mapped for photorealism with 12 textures of 8K resolution each. It was then uploaded for visualization and tests on MOSIS V2 [see Fig. 10(a)], being also available for visualization and download on Sketchfab platform [36].

The interaction with the 3-D model on the iVR software provided an immersive visualization of the VFE in multiscale. It's set of tools helped geologist testers to approach classroom minor concepts of Half Dome geological contexts on this shifting scale environment. The scale and teleport tool gave them speed to perform geological analysis by allowing free movement around the valley, even reaching dangerous region without the need of climbing gear or being exposed as they could not otherwise. By using the free drawing and measurement tool they extracted trustworthy information of the valley's width between North Dome and Half Dome with measurements of about 2.5 km, and also on its length close to 4.2 km in between Glacier Point and Half Dome.

B. Case Study 2: Raplee Ridge—Colorado Plateau, Utah

Raplee Ridge monocline is a steplike fold in rock strata consisting of a zone of steeper dip within an otherwise gently-dipping sequence, located in southeast Utah. A N-S oriented fold structure of about 14-km long and 2-km wide, close to the town of Mexican Hat, exposing thick sedimentary rock package lying just across the San Juan River. It also lies west to the laterally continuous Comb Ridge monocline, one of the numerous minor anticlines and intervening synclines or downwarps on the crest of the large Monument Upwarp dating back to the Laramide orogeny when North America was compressed from the west. The area of study is located in between UTM zone 12S projection (WGS84 references system): [603813m E; 4116222m N] and [606487m E; 4107454m N].

1) LiDAR Data: Just like Half Dome LiDAR data, the Raplee Ridge point cloud was obtained from Open Topography and the field survey was conducted as part of a project of NCALM in February 2005, covering a total area of 52 km^2 [37]. Flight altitude varied between 500 and 850 m given the mountainous landscape of the region and the overlap swath was of 50%. The aerial survey time took approximately four hours as well and two GPS ground reference station were used during the survey. This project was also referenced to the same reference grid used in the Half Dome LiDAR project, both horizontal and vertical. The report does not mention the equipment used during the LiDAR survey.

The generated point cloud has a total of 114 759 898 points. As well as Half Dome, the point cloud had to be cropped in order to meet the same area as the one generated by Printgrammetry. It resulted in 42 556 294 points.

2) Printgrammetry Results: To reconstruct the 3-D model of Raplee Ridge, 1 111 screenshots from GE were taken, however, from all captured images, 110 photos were rejected on the camera alignment stage in Metashape. The images resulted in a point cloud with almost 140 000 000 points originally, but after applying the SOR cleaning tool, the final point cloud ended up with 128 000 000 points, eliminating over 11 100 000 points in the process, considered as outliers by the algorithm. For the GCP survey, seven natural targets widely spread over the outcrop were chosen. The estimated total RMSE for all GCPs was of 1.4 m, which represents 0.2 pixel on the model (see Table IV).

TABLE III
C2C Statistics Based on the Absolute Distance Between Points for the Raplee Ridge Model (in Meters)

mean	median	standard deviation	NMAD	RMSE
2.044	0.896	5.651	0.840	6.000

TABLE IV
Parameters Involving Raplee Ridge Reconstruction by Printgrammetry

Parameters	**Raplee Ridge project**
3D model extension	9.11 km
3D model area	18.5 km^2
N. of images	1,001
Dense point cloud	127,989,307
N. of GCPs	7
GCP total RMSE	1.38m

The statistical results from comparing Printgrammetry point cloud with LiDAR on CloudCompare shows that the mean error was about 2 m, with a standard deviation of 5.6 m (see Table III). The distances between LiDAR and Printgrammetry products computed by C2C are visible through Fig. 8 and displays the distribution of distances mostly of the blue class, represented by distances below 4 m. The points with greater values (green to red) are concentrated at the northeastern region of the point cloud, which is consequence of lack of information in the Printgrammetry point cloud in this region. From the resultant histogram (Fig. 9), numbers show that 93.3% of points are below 5 m of distance and 96.7% are below 10 m. Just like Half Dome, Raplee Ridge histogram was limited to distances below 25 m because those values represents only 0.01% of the point cloud. The maximum distance computed was 166 m.

The 3-D model from Raplee Ridge has 27 812 230 triangles (or faces) and 4 textures with an 8K resolution to cover the whole outcrop. Just like Half Dome, the 3-D model of Raplee Ridge can be checked on Sketchfab [38]. It is important to mention that both DOMs uploaded to Sketchfab were automatically downgraded by the platform because the uploader account has a free registration. This justifies the lower number of triangles displayed at the website compared to the number reported in this article. For this reason, the models available at Sketchfab have lower resolution than the original product.

On MOSIS V2, the Raplee Ridge 3-D model was visualized in iVR and some measurements were taken using its set of tools on the slopes in order to quantify the length of geological structures and to highlight important geological features as represented in Fig. 10(b).

IV. Discussion and Conclusion

The Printgrammetry methodology, described in this article, is a digital photogrammetric modeling methodology of GE imagery based on the work of Chen and Clark [25]. It was designed considering some important aspects addressed by the

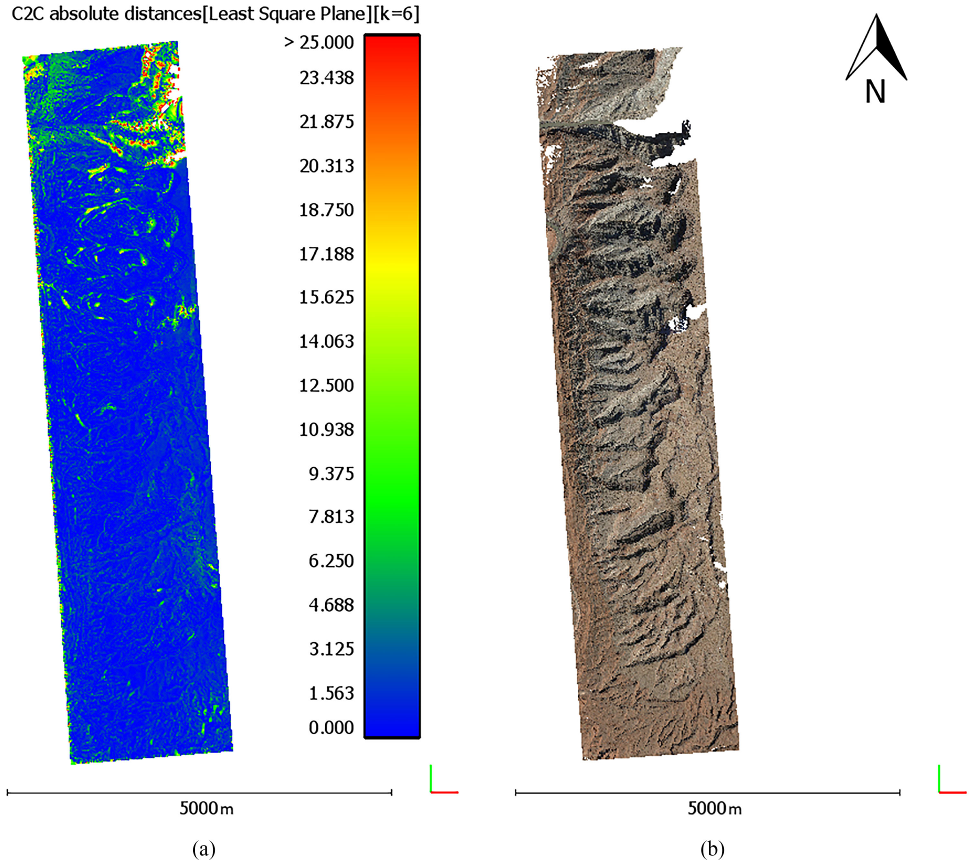


Fig. 8. Raplee Ridge study area showing both LiDAR and Printgrammetry resultant point clouds. (a) LiDAR point cloud colored with SF of C2C absolute distance (least squares measurement method). (b) Printgrammetry point cloud colored with RGB images captured in acquisition phase.

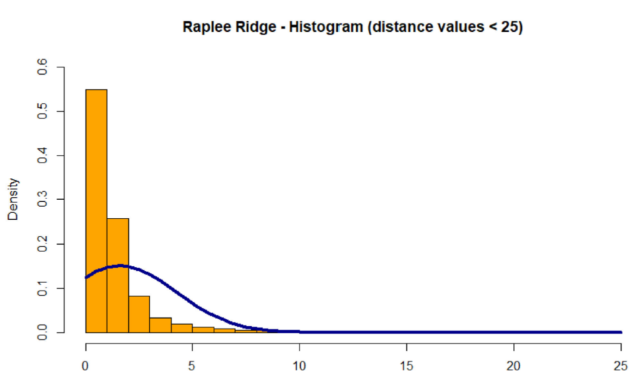


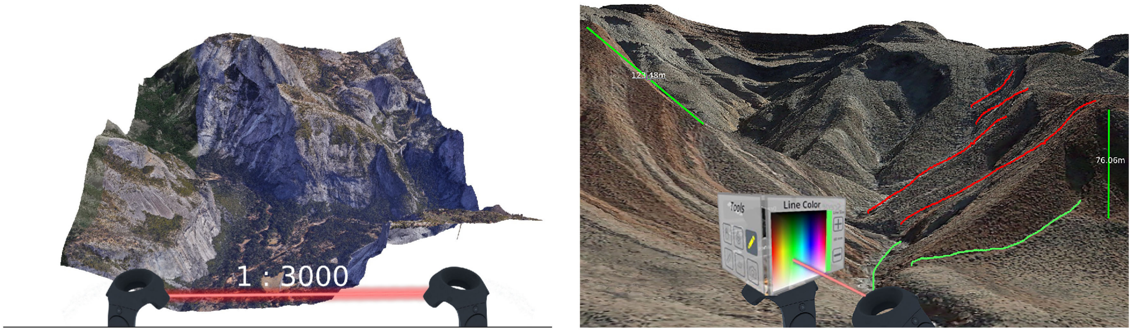
Fig. 9. Histogram of C2C distances of Raplee Ridge based on Gaussian distribution.

aforementioned authors in their discussion about the significant variability of their results when comparing GE imagery-based models with real-world LiDAR data. This methodology also took into consideration the SfM algorithm, focusing on the following three factors on the information content in digital images to reconstruct 3-D environments [28]:

1) the quality of the camera and its images;
2) the different perspectives of the environment captured by those images;
3) the quality of the environment itself.

The quality of the camera was enhanced by using a higher resolution screen monitor to achieve better image results in the data acquisition phase. Combined with that, the fixed flight altitude established on traditional photogrammetry methodology was substituted by the altitude where the LOD of GE system reached its higher resolution, since this is the criteria that ensures maximum detail possible from GE dataset. The LOD mechanism is not approached on the work of Chen and Clark and was found in this work to be essential for the quality of the developed 3-D model.

Comparing the Printgrammetry generated point clouds with ground truth LiDAR data, it is possible to say that GE database offers trustworthy 3-D data and the presented technique can extract them without considerable loss in the model's geometry, given that the regions of higher errors are attached mainly to problems with GE database itself or areas that were not properly covered during data acquisition phase, such as holes on the 3-D models. In this sense, results from Printgrammetry show that Raplee Ridge is statistically more accurate and homogeneous than Half Dome. This can be a consequence of the difference between outcrops in terms of slope and vegetation, where Half Dome has its prominent valley and a dense forest while Raplee Ridge has no vegetation with a smoother slope. It is important to highlight that although we performed an outlier removal using SOR, which is important before carrying out the C2C



(a) (b)

Fig. 10. Visualization of DOMs generated by Printgrammetry technique. (a) Half Dome iVR view in a 1:3000 scale. (b) User of the system immersed in the Raplee Ridge DOM using some interpretation tools.

comparison, we suggest further investigation using other methods such as in [39], based on interquartile range and medcouple, where the same Printgrammetry point cloud of Raplee Ridge outcrop is used as case study. This method takes into consideration the skewness of the data distribution, performing an outlier cleaning that can adapt with the different data characteristics.

In terms of DOMs, the software MOSIS V2, developed by Vizlab Laboratory, offered a series of interpretative tools and it proposes new forms of interaction with large territorial models. Both large and small scale visualization was possible in iVR, offering strong virtual field trip application to be held in this software for teaching and training geologists. Its suite of tools with the potential to perform interpretations directly on the model worked intuitively and its ease element manipulation makes the use of the virtual immersion a differential factor for the environmental analysis. However, further studies that focus on the immersion and gain that this software can provide using Printgrammetry 3-D models need to be conducted, as these were not the main objective of this work.

Recently, Google has released another GE application named Google Earth Studio.[8] It is a combination of the Google Earth satellite imagery and 3-D models database with video editing tools, allowing to make animations for several case scenarios. The authors see this application as a powerful tool that can improve considerably the Printgrammetry methodology, as it can automate the image acquisition step, which is mostly manual at the present version. Also, the images generated by this new service come with GPS information of the camera's position attached to the image file. This information helps the photo's alignment stage in SfM algorithm and it is believed that it can reduce or even eliminate the need of using GCPs for scaling and georeferencing the 3-D model. For those reasons, the software will be studied and tested in the near future to see if it can improve the methodology presented in this work.

Overall, we can state that the Printgrammetry methodology can be seen as a tool that enables to "export" a 3-D model available on GE's database to the user's computer, a feature that is not made available through the software's options. This raises the possibility of anyone to use the model in a specific software with specific tools. In this case, we applied the resultant model from Printgrammetry in a VR software for geological measurements and interpretations, proving the importance and possibilities that this technique can offer to several study areas and not only geology for being able to capture large areas without the need of field efforts, saving time, and expenses with equipment and personnel. It is important to emphasize that the quality of the generated model is directly attached to the quality provided by GE service, which makes it impossible to generate products that are geometrically or visually superior than the original one. However, high resolution 3-D models can be found in several places around the world provided by GE (like the ones demonstrated in this article) and if the high LOD is respected, those models can meet the needs for several research, industrial, and educational projects.

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