



## **Real world–based immersive Virtual Reality for research, teaching and communication in volcanology**

A. Tibaldi, F. Bonali, F. Vitello, E. Delage, P. Nomikou, V. Antoniou, U. Becciani, Benjamin van Wyk de Vries, M. Krokos, M. Whitworth

### **► To cite this version:**

A. Tibaldi, F. Bonali, F. Vitello, E. Delage, P. Nomikou, et al.. Real world–based immersive Virtual Reality for research, teaching and communication in volcanology. Bulletin of Volcanology, 2020, 82 (5), 10.1007/s00445-020-01376-6 . hal-02958327

**HAL Id: hal-02958327**

**<https://uca.hal.science/hal-02958327>**

Submitted on 10 Nov 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Bulletin of Volcanology

## Real world-based immersive Virtual Reality for research, teaching and communication in volcanology

--Manuscript Draft--

<b>Manuscript Number:</b>	BUVO-D-19-00117R2	
<b>Full Title:</b>	Real world-based immersive Virtual Reality for research, teaching and communication in volcanology	
<b>Article Type:</b>	Short Scientific Communication	
<b>Corresponding Author:</b>	Alessandro Tibaldi, Ph.D., Msc University of Milan Bicocca Milan, ITALY	
<b>Corresponding Author Secondary Information:</b>		
<b>Order of Authors:</b>	Alessandro Tibaldi, Ph.D., Msc F.L. Bonali Fabio Vitello Emanuel Delage Pareskevi Nomikou Varvara Antoniou Ugo Becciani Benjamin Van Wyk de Vries Mel Krokos Malcolm Whitworth	
<b>Funding Information:</b>	Erasmus+	Not applicable
	Ministero dell'Istruzione, dell'Università e della Ricerca	Prof. Alessandro Tibaldi
<b>Abstract:</b>	Direct outcrop observation and field data collection are key techniques in research, teaching and outreach activities in volcanic areas. However, very often outcrops are of difficult or inaccessible access, such as in areas with active volcanoes or steep cliffs. Classical remote-sensing surveys by satellites or airplanes are expensive, rarely reach sufficient resolution to allow high quality 3D visualisation of volcanic features, and do not facilitate mapping of vertical cliffs. We describe a novel approach that uses the immersive Virtual Reality (VR) based on real world 3D Digital Outcrop Models (DOMs) from images surveyed by unmanned aerial vehicles (UAV). 3D DOMs are built up using the Structure from Motion (SfM) photogrammetry technique, and a Virtual Reality scene is created using game engine technologies. Immersive real-time exploration of the environment is possible through a head mounted display, e.g. Oculus Rift. Tools embedded in the VR environment allow the user to map polygons, lines, point features, measure orientation, dip, inclination, azimuth, area, thickness and even take virtual photographs. Using three examples of volcanic areas with different geological features, we demonstrate the potential of our approach to allow users to be able to virtually map and measure remotely, and to collect data for research and teaching. Our approach is of paramount importance also for outreach, as it allows non-specialist audiences (e.g. common citizens) to experience and appreciate highly complex volcanic features through customised, hands-on immersive VR tools.	
<b>Response to Reviewers:</b>	I have corrected the paper and figures as suggested by the Editor Taddeucci.	
<b>Author Comments:</b>	As suggested by the Editor Taddeucci, I added three videos related to the paper as Supplementary material, and a pdf containing the video captions (a very brief description).	

# Real world-based immersive Virtual Reality for research, teaching and communication in volcanology

Tibaldi A.<sup>1</sup>, Bonali F.L.<sup>1</sup>, Vitello F.<sup>2</sup>, Delage E.<sup>3</sup>, Nomikou P.<sup>4</sup>, Antoniou V.<sup>4</sup>, Becciani U.<sup>2</sup>, Van Wyk de Vries B.<sup>3</sup>, Krokos M.<sup>5</sup>, Whitworth M.<sup>6</sup>

<sup>1</sup> Department of Earth and Environmental Sciences, University of Milan Bicocca, Italy

<sup>2</sup> National Institute of Astrophysics, Catania, Italy

<sup>3</sup> Observatoire du Physique du Globe de Clermont, University Clermont Auvergne, Clermont- Ferrand, France

<sup>4</sup> Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece

<sup>5</sup> School of Creative Technologies, University of Portsmouth, UK

<sup>6</sup> School of the Environment, Geography and Geosciences, University of Portsmouth, UK

## *Abstract*

Direct outcrop observation and field data collection are key techniques in research, teaching and outreach activities in volcanic areas. However, very often outcrops are of difficult or impossible access, such as in areas with active volcanoes or steep cliffs. Classical remote-sensing surveys by satellites or airplanes are expensive, rarely reach sufficient resolution to allow high quality 3D visualisation of volcanic features, and do not facilitate mapping of vertical cliffs. We describe a novel approach that uses immersive Virtual Reality (VR) based on real world 3D Digital Outcrop Models (DOMs) from images surveyed by “unoccupied aerial system” (UAS). 3D DOMs are built up using the Structure-from-Motion (SfM) photogrammetry technique, and a VR scene is created using game engine technologies. Immersive real-time exploration of the environment is possible through a head-mounted display, e.g. Oculus Rift. Tools embedded in the VR environment allow the user to map polygons, lines and point features. Tools also allow to measure orientation, dip, inclination, azimuth, area, thickness and even take virtual photographs. Using three examples of volcanic areas with different geological features, we demonstrate the potential of our approach to allow users to be able to virtually map and measure remotely, and to collect data for research and teaching. Our approach is of paramount importance also for outreach, as it allows non-specialist audiences (e.g. common citizens) to experience and appreciate highly complex volcanic features through customised, hands-on immersive VR tools.

**Key words:** Volcanology, Teaching & Scientific Communication, Immersive Virtual Reality, Head-Mounted Displays

## **Introduction**

Research activity, teaching and learning in volcanological sciences need the collection and observation of data in the field, which typically constitute the backbone of any applied study in petrography, geochemistry, geohazard, and many other areas. Outcrops can often be difficult to access for logistical reasons, or even impossible to inspect, e.g. in the case of steep or vertical cliffs. Data collection can also be dangerous, as in active volcanic areas with explosions, gas, hot fumes, etc., or other areas prone to geological hazards. Also, teaching and learning is classically based on 2D images, although geological objects are 3D; to overcome this

problem, university geoscience courses typically include extensive fieldwork programmes, but these involve expensive and time-consuming trips.

In the case of extra-university communication addressing audiences within the society at large, including administrators, politicians, media and individual citizens, immersive Virtual Reality (VR) can allow different target groups to experience volcanic features in inclusive and novel (or otherwise impossible) ways. The term immersive VR refers to the perception of being physically present in a non-physical world. The perception is obtained by surrounding the user with images, sound or other stimuli, providing the feeling of being immersed in the environment. In Earth Sciences, this is essentially achieved by surrounding images (Granshaw and Duggan-Haas, 2012; Trexler et al., 2018; Zhao et al., 2019). As immersive VR can be fun, and different, it also engages people and allows them to express their thoughts and feeling about natural sites. This results in outreach and embracing communication, a two-way process that can help scientists understand the needs and opinions of society. Moreover, game engines have reached a high level of technological maturity offering rich toolsets of mechanisms for implementing 2D/3D visualisation and exploration workflows in immersive VR environments realised on dedicated game consoles, personal computers or mobile platforms (Andrade, 2015; Lawson, 2016; Christopoulou and Xinogalos, 2017).

Remote or dangerous volcanic areas have been classically studied by aerial or satellite remotely-sensed images, which have several limitations: 1) high-resolution data are very expensive to cover large-scale geological objects and the resolution can be poor for some targets, 2) it can be challenging to plan a specific survey by an airplane, due to high costs or remoteness of the site, 3) it is impossible to map steep to vertical slopes by images acquired in vertical nadir, and 4) images are mostly 2D. Recently, unoccupied aerial systems (UASs), due to their high imaging capabilities, have been used to study volcanic eruption sites (Müller et al., 2017), dykes (Dering et al., 2019), volcano-tectonic relations (Walter et al., 2018; Bonali et al., 2019) and active faults in volcanic areas (Rust and Whitworth, 2019), as well as faults and landslides in non-volcanic environment (Rathje and Franke, 2016; Gao et al., 2017). UASs are also known as drones, aerial photography systems and unmanned aerial vehicles. Recently, some studies have used the Structure from Motion (SfM) technique to create 3D Digital Outcrop Models (DOMs) of UAS-mapped areas (Benassi et al., 2017; Burns and Delparte, 2017; Cook, 2017; Pavlis and Mason, 2017), but none of these approaches has fully exploited the 3D nature of the modelled structures to allow the user to interact with the full 3D geometry of the model for measurement and mapping purposes. An attempt in this sense has been done by Gonzaga et al. (2017), although their approach is just focused on single, limited outcrops.

Here we present an approach that allows a more complete understanding of volcanic features for teaching, learning and research, using immersive VR based on real world 3D DOMs scenario. Our approach, in fact, establishes a framework that provides a unique blend of tools allowing: i) the study of geological or volcanological sites at a wide range of scales, from small outcrops to large areas, ii) wide range of measurements, and iii) wide range of exploration scenarios. Using three examples of volcanic areas with different features, we demonstrate the potential of this type of approach to optimize the users' geological experience by allowing them to move around outcrops and take quantitative measurements. Furthermore, this

allows far more embracing contact and exchange with a wider audience; we started to present our immersive VR at schools, national and international exhibitions (e.g. Fig. 1a) open days, and with the public in all sorts of situations, provoking very positive feedbacks and popularizing volcanological sciences and geological features of volcanic areas. We also used the feedback from students and colleagues to improve our software and tools.

### **3D modelling and data input (Part I)**

Our approach consists of creating immersive VR that provides scientists and students with virtual ways to study rock outcrops and collect measurements (e.g. Fig. 1b), replicating classical field activity. The first step consists of creating a high-resolution 3D DOM, which is based off a real world scene, with UAS surveys planned at a scale suitable for the research purposes and using the SfM workflow (e.g. James and Robson, 2014; James et al., 2017; Bonali et al., 2019). We would like to remark that 3D DOM can be also referred as “Virtual Outcrops (VO)” (Xu et al., 1999; Tavani et al., 2014) that, with our approach, can be studied in first person. A Wavefront Object File (OBJ) - in the form of a Tiled model - was selected to store the 3D geometry and texture, based on the UAS-collected high-resolution images, as it can be easily imported and managed in the Unity game engine (Unity is a cross-platform game engine developed by Unity Technologies, and a game engine is a software-development environment designed for people to build video games) (Krokos et al., 2019). The resolution and accuracy of the resulting model depends on the UAS camera resolution, UAS distance to target during photo acquisition, number of established ground control points and level of quality during SfM processing (details in Westboy et al., 2012; Bonali et al., 2019). For example, when flying about 25 m above the target, we achieve a resolution of 8 mm/pixel, as shown in our example of the Greek Metaxa mine that will be described below. All surveys in the present work have been done using a quadcopter equipped with a 20 MPX camera, including EXIF (Exchangeable Image file Format) information and GPS coordinates, provided by the integrated Satellite Positioning Systems GPS/GLONASS (referred to the WGS84 datum). Thanks to a built-in high precision 3-axis gimbal, flights are smooth, and the image collection is steady. The model we used provides constantly stable flights thanks to the integrated GPS system, including position holding, altitude lock and stable hovering. Hereunder we summarise the overall steps to produce a high-resolution 3D DOM (Part I of the overall workflow shown in Figure 1c).

The first step is to define the area to be surveyed, the UAS flight missions, including paths orientations and flight height, that can be planned and managed using dedicated software, particularly for pictures acquired in nadir orientation. The UAS has been manually driven to collect pictures with oblique orientation of the camera and to detail vertical cliffs. Photo overlap has also to be defined, as suggested by Gerloni et al. (2018), Bonali et al. (2019), Krokos et al. (2019) and Antoniou et al. (2019). In fact, it is recommended that UAS-captured photos should have an overlap of 90% along the path and 80% in lateral direction, in order to obtain a greater alignment of images and to reduce the distortions on the resulting texture. The photos have been captured every 2 seconds (equal time interval mode), with a constant velocity of 3 m/s (low speed) and in optimal light conditions suitable for the camera ISO range (100-1600) (Bonali et al., 2019).

117 In order to allow for the co-registration of datasets and the calibration of models resulting from SfM processing  
118 (e.g. Orthomosaics and DSMs), World Geodetic System (WGS84) coordinates of, at least, four artificial  
119 Ground Control Points (GCPs) must be established near each corner within each surveyed area and one in the  
120 central part (e.g. James and Robson, 2012; Turner et al., 2012; Westoby et al., 2012; James et al., 2017) for  
121 reducing the ‘doming’ effect resulting from SfM processing. Wherever possible, GCPs were surveyed with the  
122 Emlid Reach RS©, low-cost single frequency receivers (Rover and Base) in RTK configuration (with  
123 centimetre-level accuracy), finally correcting the z (altitude above the sea level ) values of the GCPs using the  
124 regional geoid model to obtain the orthometric height for the models.

125 Focusing on data processing aimed at 3D DOM production, photos have been processed with the use of Agisoft  
126 Metashape (<http://www.agisoft.com/>). This is a SfM software becoming increasingly widely used in the  
127 geological community for both UAS and field based SfM studies for its user-friendly interface, intuitive  
128 workflow and high quality of points clouds (Benassi et al., 2017; Burns et al., 2017; Cook, 2017). The SfM  
129 technique allowed to identify matching features in different photos, collected along a defined flight path (Fig.  
130 5b), and combined them to create a sparse and dense cloud, and the Wavefront OBJ Tiled model (further  
131 details in Stal et al., 2012; Westoby et al., 2012). The first step was to obtain an initial low-quality photo  
132 alignment, only considering measured camera locations (Reference preselection mode). After that, photos with  
133 quality value <0.5, or out of focus, were excluded from further photogrammetric processing, following the  
134 software user manual (Agisoft LLC, 2018). The focal length and photo dimensions were automatically detected  
135 by the software, after the import of digital images and then used for the subsequent calibration of the intrinsic  
136 parameters of the camera (principal point coordinates, distortion coefficients). After this first quality check,  
137 we added Ground Control Points (GCPs) in all photos, where available, in order to: i) scale and georeference  
138 the point cloud (and thus the resulting model); ii) optimize extrinsic parameters, such as estimated camera  
139 locations and orientations; iii) improve the accuracy of the final model. We then realigned the photos using  
140 high accuracy settings: as a result of this step, camera location and orientation were better established, and the  
141 sparse point cloud was computed by the software. The next step consisted in reconstructing the dense point  
142 cloud, calculated from the sparse point cloud, using a Mild depth filtering and medium/high quality settings.  
143 The 3D tiled model was then reconstructed using the dense cloud as source data for a Medium number of Face  
144 count and exported in the format OBJ tiled model. The information provided with the OBJ Tiled Model must  
145 be imported in the Unity game engine in order to replicate a real-world reference system.

146  
147  
148

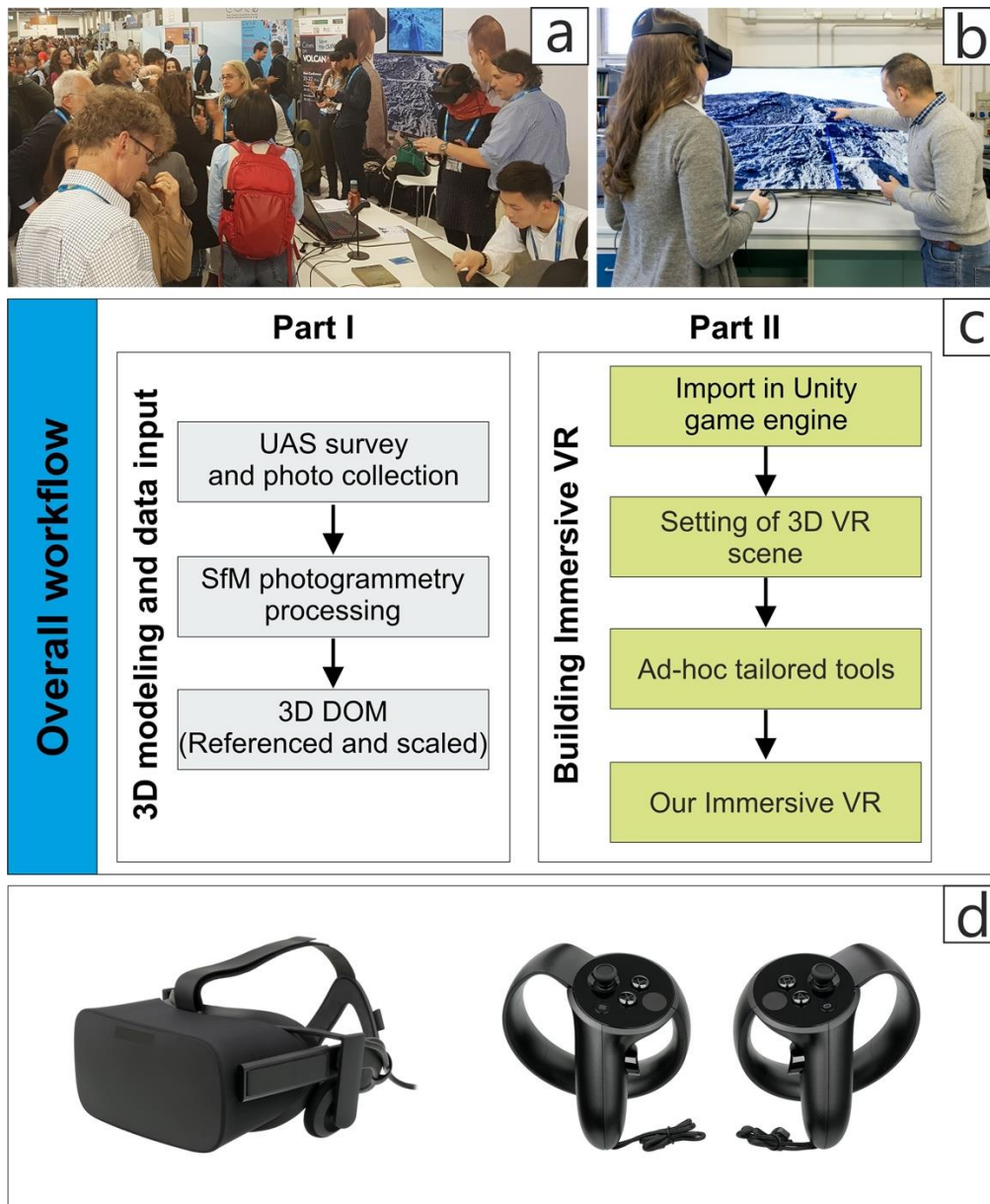


Figure 1. a) International outreach event using immersive VR in the framework of the the EGU General Assembly 2019; b) Example of teacher and student activity using immersive VR.; c) Processing workflow overview; d) VR headset on the left and sticks used to interact with the scene, on the right.

### Building Immersive VR (Part II)

The target of our approach is to comprehensively simulate field experiences and observational behaviours of geoscientists using high-resolution datasets and models. Our approach provides interaction experiences realising navigation/exploration workflows that may not even be possible in the actual field, thus giving unique spatial awareness insights in comprehending complex volcanological processes. An example can be the monitoring of a steep slope on an active volcano, where uprising magma, intrusions, or earthquake shaking can destabilise the slope with the possibility of slope failure. These multiple hazards create a complex scenario that requires field inspection and collection of reliable field measures, but this can be impossible for the impending threats.

165 We developed a software that provides end users with a holistic view of an area of interest, by allowing  
166 exploration of specific features from several points of view and at a range of different scales (see supplemental  
167 videos 1, 2 and 3), starting from technologies commonly used in entertainment applications (such as video  
168 games). Those include modern game engines (Unity, <https://unity.com>) combined with Virtual Reality devices  
169 (Oculus Rift, <https://www.oculus.com/>). Unity supports modularity and extensibility to build modular assets  
170 that are easily expanded and sustained long term. Furthermore, Unity supports several file formats as used in  
171 industry-leading 3D applications (e.g. 3DS Max, Blender). Unity is also well documented as it is supported by  
172 large numbers of communities of software developers. Although the development of our software framework  
173 is based on the Unity game engine and Oculus, we have deployed generic functionalities of game engines and  
174 head mounted displays abstracting as much as possible from specific realisations.

175 Our system supports a high-performance visualisation layer underpinning a comprehensive set of navigation,  
176 interaction and accurate measurement tools to allow geoscientists full appreciation of on-shore settings. Unlike  
177 other software for handling digital outcrops (VRGS, [www.vrgeoscience.com](http://www.vrgeoscience.com), or MOSIS of Gonzaga et al.,  
178 2017), our focus has been on developing a fully integrated software suite for seamless VR navigation of wide  
179 areas. Moreover, our software enables, via appropriate controls, rich user interactions and on-the-fly  
180 visualisation adjustments. The uniqueness of our framework lies on the modularity of its underlying  
181 architecture enabling support for multiple mechanisms to select and deploy navigation approaches. It enables  
182 incorporation of several import and export mechanisms to ensure the creation of data products with long-term  
183 sustainability. The 3D DOM/Tiled model approach is built upon UAS-based SfM techniques and is thus able  
184 to provide centimetric pixel size resolution for textures. The use of Wavefront OBJ Tiled model was  
185 successfully designed and tested by Krokos et al. (2019) who applied it to areas of different extents and  
186 resolutions, respectively ranging 50-1000 m (along the longest) and 0.8-4 cm, also considering the present  
187 work. The use of 3D DOM allows improved representations of geometrical features especially around regions  
188 that are vertical to the terrain.

189 Starting from the processed datasets (see Part I), the user must perform few preliminary operations in order to  
190 make the scene navigable: an invisible object called “collider” must be assigned to each mesh for the purposes  
191 of physical collisions, and the scene has to be properly referenced and scaled by employing information derived  
192 from SfM processing. Thus, the scene dimension (in meters) and the corresponding geographic coordinates  
193 must be defined, as well as the altitude referred to the 3D reconstructed model. All informations are included  
194 in the Tiled Model folder, in Wavefront OBJ format, provided by SfM software we used. Finally, to optimize  
195 the rendering performance of the scene, we also suggest the use of Unity Levels of Detail (LODs) methodology  
196 to reduce the number of details shown when the model is far away from the camera. For this case, in the Tiled  
197 Model folder different level of details for the model that can be set up in Unity engine are already provided.

198 First of all, the user will see the scenario in first person and walk on a “solid ground surface” to allow them to  
199 move around within the virtual scene, or the user can fly over the area, allowing him to have a different view  
200 of the outcrop that may open perspectives that are not possible to experience during real fieldwork (see  
201 supplemental video 1).



Our software also includes a series of tools embedded in the VR environment, represented by symbols that appear on the screen by pressing a button of the joystick (Fig. 1d) (see supplemental video 2). Such tools have been developed by our research team that comprises also software developers and required some months of work in strict collaboration with geologists. The tools were in fact customized on the classical needs of geologists and volcanologists in the field, which are of paramount importance to quantitatively describe the features of a given area. Directly on the screen you can choose the tool you need. The tools have been developed with the idea of allowing the user to take measurements like being in the field, but with the advantage that the user can change the angle of view in order to better select the proper perspective to take measures. Once you have selected the tool, you point with the joystick the object to be analysed. A tool allows to assess geographic location by coordinates. Another tool allows to select a point feature. By other tools it is possible to map polygons and lines, and measure areas. In these cases, it is necessary to click with the joystick in different points on the virtual ground. Other tools allow the measurement of dip, inclination, and azimuth of an object. By clicking on two points with another tool, it is possible to measure thickness of volcanological objects such as bedding, dykes, etc, and with another tool it is possible to reconstruct the topographic profile. Finally, the system allows to take virtual photographs and notes.

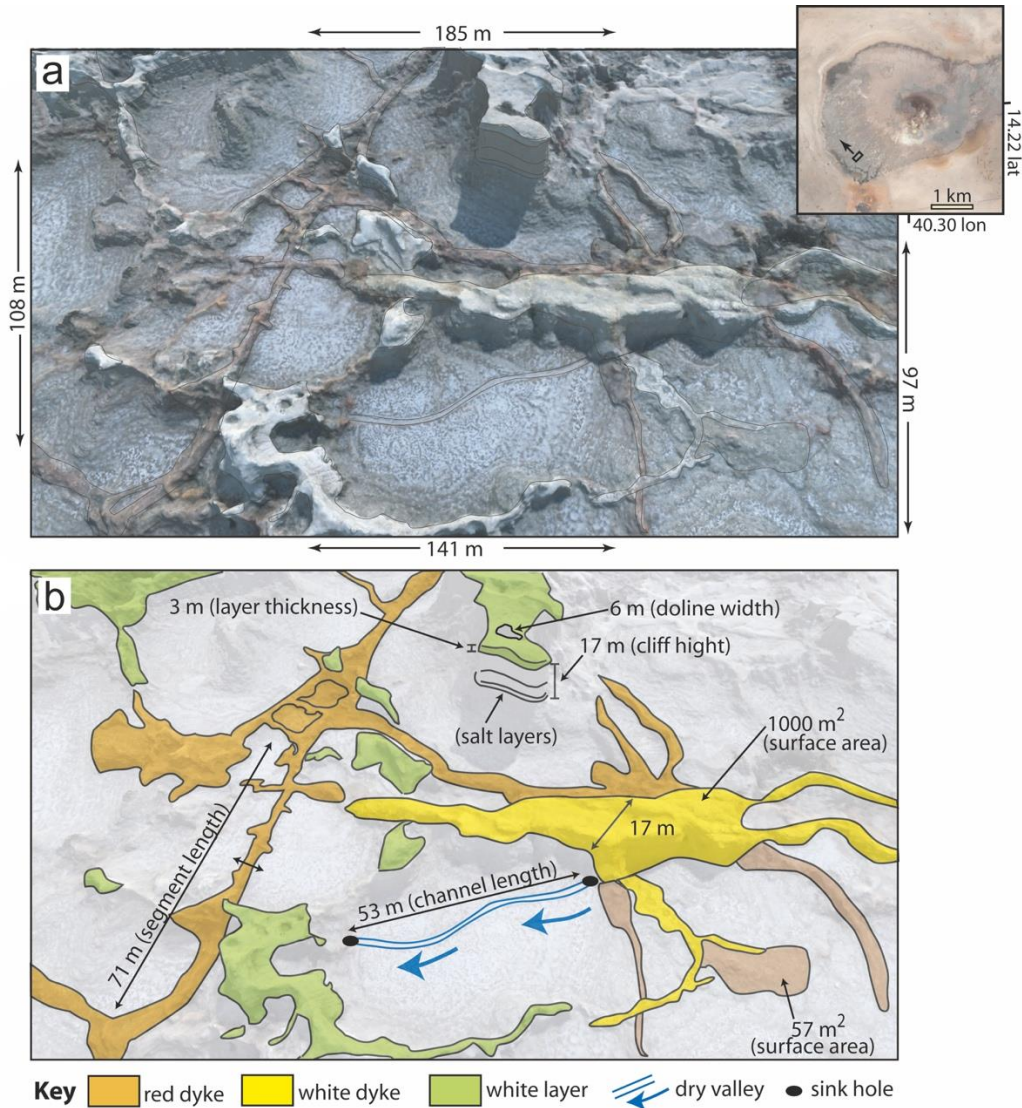
## **Case studies**

### **The Dallol Volcano, Ethiopia**

The active Dallol Volcano was one of the most inaccessible places on Earth, but recently has opened up due to a new road, and there is rapid increase of tourists visiting the incredible geothermal manifestations. This has led to increased risk from multiple geohazards and from the extreme climate. Assessing hazards requires detailed topographic and geologic information, but the area is dangerous and hard to access. Thus, the area was surveyed by UAS and data was processed following our approach (Fig. 2a). Particularly, the 3D DOM is based on 229 pictures acquired with nadir camera orientation, at a flight height of 113 m, obtaining a texture resolution of 2.87 cm/pixel over an area of 0.176 km<sup>2</sup>. Photo alignment has been processed with high quality setting and using Generic and Reference preselection. The dense cloud has also been built up using high quality, whereas GCPs have been not collected in the field due to hard logistic condition. In the VR environment, we have been able to access areas impossible in the field, making measurements and observing features. We have detected different types of dykes and found erupted products (Fig. 2b). We have also characterized and quantified salt karst structures, to start integrating measurements into a hydrogeological–volcanological model. Tower morphologies are topped by a 3-m thick white eruption deposit. A tower of salt layers has a vertical sided doline (sink hole) which is 6 m across, and at least 5 m deep, set on a flat area above a 17-m high cliff. Dykes of red clay, possibly filled karst pathways, from Dallol’s central hydrothermal area, are mapped and selected measurements shown. A white dyke, made of salt and magma is up to 17 m wide outcropping over 1000 m<sup>2</sup>. A small dry river channel between source and sink holes is 53 m long. This Dallol reconstruction has already been shown in Ethiopia and internationally, and has been used to get opinions of stakeholders on the nature of the geological object, its use in geotourism and possibilities of

239 protection. Users who know the area, mostly geologists so far, have expressed amazement at the ability to see  
 240 the geological features that they have missed in the field. Prospective visitors (non geologists) have also  
 241 expressed amazement and wonder at being able to fly around such a landscape.

242



243

244

245 **Figure 2.** a) 3D representation of an area of the Dallol volcano (Ethiopia) captured using camera tool in  
 246 Immersive VR. (distances show the measured length of the edges of the perspective). Inset shows full view of  
 247 Dallol volcano and locates the area described, with arrow for view direction. b) Interpretation with some  
 248 examples of quantitative measurements taken in Immersive VR environment. Selected features mapped in this  
 249 area include red dykes related to infilling of the karst system, a white dyke magmatic–hydrothermal intrusion,  
 250 white eruptive layers, and sink holes.

251

252

### The Metaxa mine, Greece

253

254

255

256

257

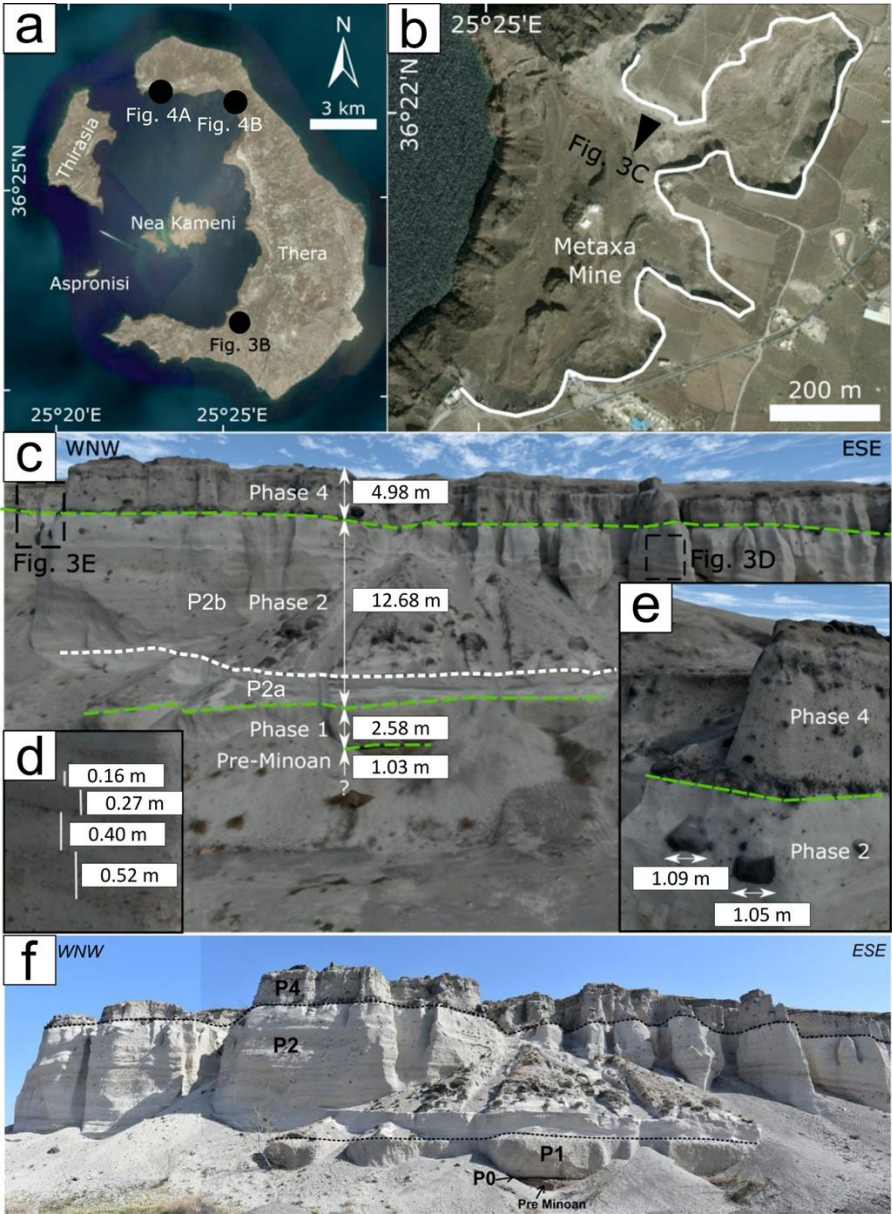
The Metaxa Mine is a unique geotope of Santorini volcano (Greece) where the pumice layers of the famous Late Bronze Age (LBA) (well-known also as Minoan) eruption are exposed (see supplemental video 3). It is nowadays abandoned and it is located in the central part of Santorini island, overlooking the famous Santorini caldera (Figs. 3a, b). The latter was created after the catastrophic Minoan eruption (Friedrich et al., 2006; Druitt, 2014), which has influenced the decline of the Minoan civilization on Crete, making it an iconic event

258 in both volcanology and archaeology disciplines. The mine contains the so-called “Famous section” which  
 259 shows the pumice layers of the eruption along a length of 150 m (see the pictures collected from our immersive  
 260 VR in Fig. 3c) and classical field activity (Fig. 3d). From the area which is located on the east side of the  
 261 Famous section, about 1.3 million m<sup>3</sup> were excavated in the early years of mining. A total of 4.5 million m<sup>3</sup> is  
 262 estimated to have been extracted from the Metaxa mine, according to 3D digital model of the terrain (Antoniou  
 263 et al., 2019). Our approach provides an excellent way to access the vertical and overhanging cliffs in immersive  
 264 VR and to analyse it in detail in a way that was not possible before. The resulting 3D DOM has a pixel  
 265 resolution of 8 mm and allows the recognition and measurement of the thickness not only of the main different  
 266 pyroclastic layers, but also of the single eruptive pulse events (Fig. 3d), and even the diameter (down to 1-2  
 267 cm) of the lithic clasts embedded in the vertical exposure (Fig. 3e). Pictures have been taken in two main  
 268 different missions: the first was devoted to capture a set of photos in nadir camera view (n=1121) to cover the  
 269 whole selected area; in the second we collected photos (n=992) of the vertical outcrops with the camera  
 270 oriented orthogonal to the vertical cliff, in order to add as much details as possible to the resulting model.  
 271 Photo alignment has been processed with high quality setting and both using Generic and Reference  
 272 preselection, the dense cloud has also been built up using medium quality, considering the extent and resolution  
 273 of the final model, and a set of 20 uniformly distributed Ground Control Points have been included in order to  
 274 co-register the 3D model to the World Geodetic System (WGS84) (Smith et al., 2016; Esposito et al., 2017).  
 275 The resulting 3D DOM is as large as 349 x 383 m.

276 In Figure 3c, we can distinguish: a) The 103-cm-thick Pre-Minoan base, b) a reverse-graded pumice fall deposit  
 277 of 258 cm thickness from the first main Plinian eruption (Phase 1, P1), c) the 731-cm-thick pyroclastic surge  
 278 deposits with multiple bedsets, dune-like bedforms with wavelengths of several meters or more and bomb sag  
 279 horizons (Phase 2, P2) (Bond and Sparks 1976; Heiken and McCoy, 1984; McClelland and Thomas, 1990),  
 280 and d) within eruptive Phase 2, it is easy to distinguish the lowest fine-grained bedset (P2a) from the overlying  
 281 coarse grained sequence of multiple bedsets (P2b) and the 498-cm-thick fine-grained, nonwelded ignimbrite  
 282 (P4). The precursory explosion phase (P0) is characterized by a thin lapilli fallout layer of 10 cm in thickness,  
 283 shown in the field-panoramic view of the Famous section (Fig. 3f). These measures have been obtained by our  
 284 VR approach and similar detailed values did not exist for the site. At general, Phase 1 corresponds to a Plinian  
 285 eruption, whereas Phase 2 was characterized by syn-plinian pyroclastic surges. In Phase 3, eruption of ‘cold’  
 286 phreatomagmatic pyroclastic flows constructed a large tuff cone that filled the old caldera, cutting it off from  
 287 the sea. In Phase 4, eruption of hot pyroclastic flows took place from multiple subaerial vents, associated with  
 288 caldera collapse that enlarged and deepened the ancient caldera (Nomikou et al., 2016).

289 For science popularization and communication, the VR reconstruction of Metaxa mine is being used in a  
 290 UNESCO Geosciences Programme project (IGCP project 692 “Geoheritage for Geohazard Resilience”) to  
 291 raise awareness in the geological community and in the more general public about the value of this site, which  
 292 is in urgent need of protection and development as a unique heritage demonstration of the powerful volcanic  
 293 eruptions of Santorini. Moreover, this site has great value in regards to the relations between volcanic activity  
 294 and humans: this mine is part of Santorini history, especially in relation to the economic development of local

295 populations, who in difficult times were able to find income opportunities thanks to the extraction of pumice  
 296 materials. The Metaxa mine is not only a site of international scientific relevance, but also an industrial heritage  
 297 site that, as every monument, deserves special attention. The VR model has also been presented at Santorini  
 298 administrations in order to explain in a more effective way the features present in the field. Finally, in regards  
 299 to teaching, our VR model has been used to train Msc and PhD students of different European countries during  
 300 a series of International Summer Schools organized in the framework of the 2018-2020 project Erasmus+ KA2  
 301 “3DTeLC: Bringing the 3D-world into the classroom: a new approach to Teaching, Learning and  
 302 Communicating the science of geohazards in terrestrial and marine environments”.  
 303



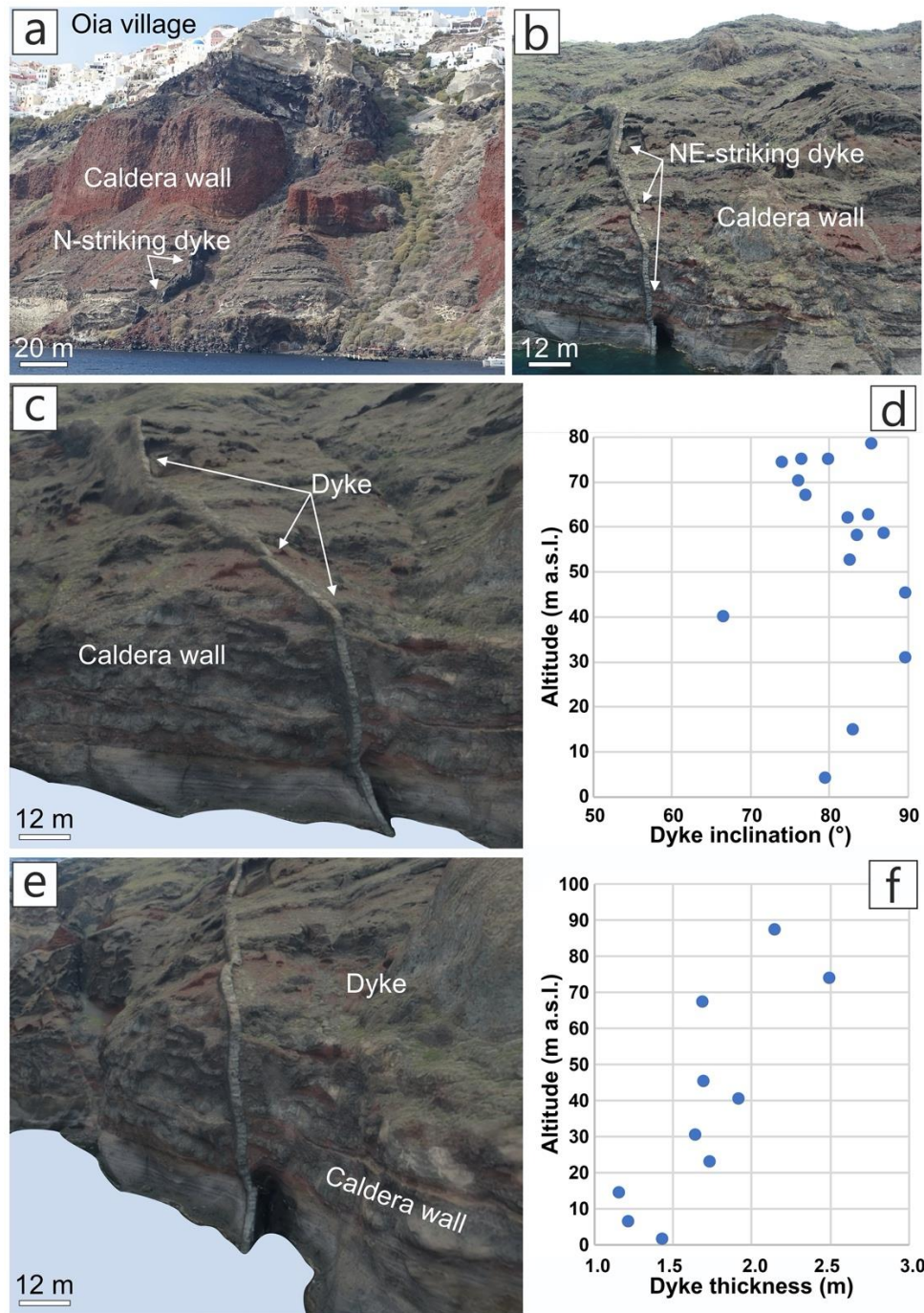
304  
 305 **Figure 3.** Metaxa mine example: a) Location in Santorini island. b) Location of the reconstructed outcrop used  
 306 in this example. c) 3D view of the “Famous section” showing the main strata of the various Minoan eruptive  
 307 phases and measured thickness in immersive VR. d) and e) Examples of measurement of lithic clasts at vertical  
 308 outcrops by VR. f) Field-panoramic view of the “Famous section” (modified after Antoniou et al., 2019).  
 309



311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344

**Outstanding dykes along the Santorini's caldera wall, Greece**

Santorini is a unique place where it is possible to study outstanding feeder and non-feeder dykes (e.g. Figs. 4a-b), cropping out along the northern part of the caldera wall. Their study is of paramount importance for better understanding processes related to the propagation paths of fractures/dykes through layers with dissimilar mechanical properties, since they are emplaced in a highly heterogeneous and anisotropic host rock. Their mapping could provide valuable insights on the topic. In fact, Browning et al. (2015) started this work collecting detailed measurements of dykes at the sea level in some accessible sites. The problem is that most dykes crop out along inaccessible vertical cliffs (up to 300 m high) or dangerous areas with hard logistic conditions (continuous rockfalls), and thus their characterisation can only be done very locally, at the sea level, and cannot be measured along their whole outcropping range. We give here an example to illustrate how it is possible to overcome such difficulties. We also emphasize that this is just an example, but a full study of the whole cliff is underway by VR and will be published in another paper. This represents measurements at a site that was previously inaccessible. We reconstructed a text-book case of a dyke (Figs. 4c-e) using UAS-collected pictures and SfM processing, obtaining a model with a texture resolution of 4 cm/pixel. Pictures have been collected with oblique orientation of the camera using a quadcopter equipped with a 20 MPX camera. It has been manually driven, at a constant velocity of 3 m/s and capturing pictures every 2 seconds (equal time interval mode), flying between the sea level and a maximum height of 130 m. Regarding the processing, photo alignment has been processed with high quality setting and both using Generic and Reference preselection. The dense cloud has been built up using medium quality, and a set of 5 GCPs have been included in order to co-register the 3D model to the World Geodetic System (WGS84) (Smith et al., 2016; Esposito et al., 2017). The resulting 3D DOM is as large as about 1000 x 340 m. Different from the two examples described before, in this case quantitative data have been collected flying in front and around the dyke, instead of walking within the 3D DOM. Using the measurement tools, we collected dyke inclination and thickness from the sea level up to an altitude of 100 m, providing unique and new data (Figs. d-e). The selected dyke is characterised by a dip angle of about 80° at the sea level, with a NW dip, becoming vertical between 30-50 m a.s.l. Between 50-90 m a.s.l., its inclination decreases to 70-80°. The thickness is between 1.0-1.5 m from sea level to an altitude of 20 m, and increases up to 2-2.5 m at 80-90 m a.s.l. These results demonstrate that the immersive VR we developed has a great potential to fully study the dyke swarm emplaced in the Santorini volcano, as well as any other magma plumbing system exposed at vertical cliffs. Even though field studies are vital for mapping and understanding the geological processes on Earth, in several cases, like the one here shown, classical surveys are impossible, whereas our approach represents a solution.



**Figure 4.** a) Boat-collected picture of a vertical dyke outcropping along the NW part of the caldera wall, in correspondence of the Oia village; houses for scale, the location is provided in Figure 3a. b) UAS-collected picture of a mostly vertical NE-striking dyke, outcropping in the NE part of the caldera wall, location is marked in Figure 4a (picture courtesy of Luca Fallati). c) and e) show the same dyke of Figure 4b but the pictures have been collected in immersive VR, as well as all measurements regarding dyke inclination and thickness presented in figures d) and f).

## Discussion

Volcanic areas are of high interest for scientific and economic reasons, such as minerals, soil fertility and tourism. In the case of active volcanoes, they can pose significant threats to large populations and infrastructures, and the latter can be temporarily or permanently interrupted with significant repercussions for economic and social stability. Volcanic areas can also have spectacular features that attract the attention of the

358 wider public, who is keen to experience and know more about them, but that is also a risk if people go close  
359 to hazardous sites. Therefore, the reconnaissance, mapping, quantification and understanding of volcanic areas  
360 is increasingly important, together with the communication of volcanic hazards.

361 To date, the study of volcanic areas has relied largely upon standard field data collection techniques, but these  
362 can be affected by logistic and time constraints or difficulties in accessing dangerous sites. For example, an  
363 impending eruption requires immediate data collection or observations of the crater zone, which can be  
364 inaccessible or extremely dangerous to approach. Similarly, very rugged terrains and steep slopes represent  
365 hard logistic conditions. The approach described here links together geoscience, remote sensing and game  
366 engine technologies with an innovative, integrated software solution to create opportunities to collect data in  
367 remote areas or dangerous zones, using a fully immersive VR environment.

368 The three case sites presented, show how important and useful our approach can be. We have focused here on  
369 onshore examples, but we stress that our approach can also be applied to offshore environments. The Dallol  
370 Volcano shows a case where several complex characteristics can be detected and measured in an extremely  
371 inhospitable environment. The magma and karst paths of the volcano are now 3D objects that stand out from  
372 a highly dissected landscape. The approach here allows careful measurement of dyke thickness, length, strike,  
373 and dip angle, allowing a complete reconstruction of the karst and volcanic plumbing system. It is also possible  
374 to immediately calculate the area of exposures from these various outcrops, and to inspect inaccessible cliffs  
375 and deep hollows, allowing other 3D objects, such as sink holes to be explored and measured. The Dallol  
376 example also shows how visually attractive such an experience can be for engaging with the greater public.  
377 This is particularly true in the case of spectacular natural features that otherwise would be impossible to visit.

378 The Metaxa mine provides exposure of the Minoan eruption and illustrates how detailed measurements can be  
379 obtained along inaccessible vertical cliff sections. It has been possible to measure bed thickness and  
380 dimensions of single cm-size lithic clasts hosted in the volcanic strata. Furthermore, this example shows that  
381 our approach can be used to demonstrate the value of the site and the need for its protection and future  
382 development. VR acts as a motor for a wider appreciation of this site, and can be used in political and  
383 administrative meetings to effectively communicate with decision makers.

384 The Santorini dyke we presented (Fig. 4) is part of a large dyke swarm affecting the northern part of the caldera  
385 where it is mostly impossible to collect quantitative measures to characterize dyke geometry and thickness,  
386 except for near the sea level. This is due to the continuous rock falling and the absence of safe paths to reach  
387 the dykes along the 300-m-high caldera wall. Using the immersive VR, we provided, for the first time,  
388 measurements characterizing dyke thickness and geometry with continuity from the sea level upwards. We  
389 demonstrated that this approach is fundamental to fully study the dyke swarm and to provide new outcomes  
390 related to diking process in highly heterogeneous and anisotropic host rock, a topic of paramount importance  
391 for volcanic hazard assessment (Gudmundsson, 2006).

392 The three cases of 3D rendering in immersive VR are also examples of how this approach can be used for  
393 outreach purposes; for example, a Santorini committee is currently using the model as part of its proposal to  
394 classify the mine as a unique example of the Minoan eruption, serving as an open-air museum. This 3D model

records important scientific and cultural heritage and will virtually preserve the integrity of the site. This permanent record of the site will allow future scientists to interact with the original outcrops, and inform a non-academic audience about the historical and volcanological aspects of this site that provides a unique window of the Minoan eruption (Antoniou et al., 2019). Equally, the Dallol example is being used to communicate the unknown and un-valued nature of the site to both locals, authorities and tourists, in order to protect this natural heritage (Vereb et al., 2019). Santorini dyke swarm is a unique example to popularize the concept of magmatic intrusions, feeder and non-feeder dyke and volcanic eruptions. This showcases how a volcano interior is.

In general, our approach enables anyone to create models based on real world images with unprecedented detail, georeferenced, and fully explorable. This allows the operator to take measurements in an immersive VR 3D environment. Moreover, since outcrops can also change over time, our approach allows to make a quick and direct comparison of the area development. For example, it is possible to quantitatively compare pre- and post-eruption craters. This approach allows collection of quantitative data similar to standard field data collection. This represents a scenario where the experience of the geologist/volcanologist, which is critical in carrying out the interpretation, can be fully exploited, and fully communicated to all end users. Of course, VR cannot substitute field survey where this is feasible (but it can contribute to collect more geometric data), and cannot replace field trips for students where they can also take samples and see finer rock textures and minerals.

412

## 413 **Conclusions**

Collecting in-situ data from field localities is essential in geological and volcanological sciences for teaching and research. We proposed an approach that ensures that studies can be as effective as possible even where areas are difficult or impossible to access (e.g. active volcanic areas or vertical slopes). We combine existing technologies of remote sensing, UAS, SfM, game engines and gaming headsets (e.g. Oculus Rift) with new software that allows real-time navigation in real world-based immersive VR and quantitative measurements using specially designed tools for typical geological mapping. This method has been showcased using three sites with different volcanological and volcanotectonic features to illustrate how relevant quantitative field data can be collected in inaccessible areas using VR. The results indicate significant potential for recording sites for virtual research and also for educational purposes and exploration by future generations. There is a high potential for improving communication between scientists and the public about the shared experience of natural objects; “bringing” the field in a room through immersive VR means that non-scientists can have a real perception of natural phenomena. This is scientific awareness and understanding of the ongoing volcanological processes in a way that previously was not possible, an essential step for making informed choices and behaviours.

428

## 429 **Acknowledgements**

We greatly appreciated the useful comments on an early version of the manuscript of the Editor, Jacopo Taddeucci, and two anonymous reviewers. The UAS survey of the Dallol volcano was made in collaboration with Olivier Grunewald (<https://www.oliviergrunewald.com/>). Funded by project ACPR15T4\_00098



433 “Agreement between the University of Milan Bicocca and the Cometa Consortium for the experimentation of  
 434 cutting-edge interactive technologies for the improvement of science teaching and dissemination” of Italian  
 435 Ministry of Education, University and Research (coordinated by A. Tibaldi), and project Erasmus+ Key Action  
 436 2 2017-1-UK01-KA203-036719 "3DTeLC - Bringing the 3D-world into the classroom: a new approach to  
 437 Teaching, Learning and Communicating the science of geohazards in terrestrial and marine environments"  
 438 (coordinated by M. Whitworth). The examples are integrated into the UNESCO International Geosciences  
 439 Program project 692 “Geoheritage for Geohazard Resilience” (coordinated by B. van Wyk de Vries). This  
 440 article is also an outcome of Project MIUR – Dipartimenti di Eccellenza 2018–2022 and ILP Task Force II.  
 441 Agisoft Metashape is acknowledge for photogrammetric data processing.  
 442

## 443 References

- 444 Andrade, A., 2015. Game Engines: A Survey, EAI Endorsed Transactions on Serious Games, 2 (6),150615,  
 445 DOI: 10.4108/eai.5-11-2015.150615.
- 446 Antoniou, V., Nomikou, P., Bardouli, P., Sorotou, P., Bonali, F., Ragia, L. and Metaxas, A., 2019. The story  
 447 map for Metaxa Mine (Santorini, Greece): A unique site where history and volcanology meet each other.  
 448 In: Proceedings of the 5th International Conference on Geographical Information Systems Theory,  
 449 Applications and Management, 1, 212-219. DOI: 10.5220/0007715602120219
- 450 Benassi, F., Dall'Asta, E., Diotri, F., Forlani, G., Cella, U.M. di, Roncella, R., Santise, M., 2017. Testing  
 451 accuracy and repeatability of UAV blocks oriented with gnss-supported aerial triangulation. Rem. Sens., 9  
 452 (2), 172.
- 453 Bonali, F.L., Tibaldi, A., Marchese, F., Fallati, L., Russo, E., Corselli, C., Savini, A., 2019. UAV-based  
 454 surveying in volcano-tectonics: An example from the Iceland rift. Journal of Structural Geology, 121, 46-  
 455 64.
- 456 Bond, A. & Sparks, R.S.J. (1976). The Minoan eruption of Santorini, Greece, Journal of the Geological  
 457 Society, London, 132, 1–16.
- 458 Burns, J.H.R., Delparte, D., 2017. Comparison of commercial structure-from-motion photogrammetry software  
 459 used for underwater three-dimensional modeling of coral reef environments. In: International Archives of  
 460 the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42. 127–131.
- 461 Browning, J., Drymoni, K., Gudmundsson, A., 2015. Forecasting magma-chamber rupture at Santorini  
 462 volcano, Greece. Scientific reports, 5, 15785.
- 463 Christopoulou, E., and Xinogalos, S., 2017. Overview and Comparative Analysis of Game Engines for  
 464 Desktop and Mobile Devices. International Journal of Serious Games, 4(4), DOI:  
 465 <https://doi.org/10.17083/ijsg.v4i4.194>.
- 466 Cook, K.L., 2017. An evaluation of the effectiveness of low-cost UAVs and structure from motion for  
 467 geomorphic change detection. Geomorphology 278, 195–208.
- 468 Dering, G.M., Micklethwaite, S., Thiele, S.T., Vollgger, S.A., Cruden, A.R., 2019. Review of drones,  
 469 photogrammetry and emerging sensor technology for the study of dykes: Best practises and future potential.  
 470 Journal of Volcanology and Geothermal Research, 373, 148-166.
- 471 Druitt, T.H., 2014. New insights into the initiation and venting of the Bronze-Age eruption of Santorini  
 472 (Greece), from component analysis. B. Volcanol, 76 (2), 794.
- 473 Druitt, T. H., Edwards, L., Mellors, R., 1999. Santorini volcano. Geol. Soc. Lond. Mem. 19, 1–165.
- 474 Esposito, G., Mastrorocco, G., Salvini, R., Oliveti, M. and Starita, P. (2017). Application of UAV  
 475 photogrammetry for the multi-temporal estimation of surface extent and volumetric excavation in the Sa  
 476 Pigada Bianca open-pit mine, Sardinia, Italy. Environmental Earth Sciences, 76(3), p.103.
- 477 Friedrich, W. L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T. and Talamo, S., 2006. Santorini  
 478 eruption radiocarbon dated to 1627-1600 BC. Science, 312(5773), 548-548.
- 479 Gao, M., Xu, X., Klinger, Y., van der Woerd, J., Tapponnier, P., 2017. High-resolution mapping based on an  
 480 Unmanned Aerial Vehicle (UAV) to capture paleoseismic offsets along the Altyn-Tagh fault, China. Sci.  
 481 Rep., 7 (1), 8281.
- 482 Gerloni I.G., V. Carchiolo, F.R. Vitello, E. Sciacca, U. Becciani, A. Costa, S. Riggi, F.L. Bonali, E. Russo, L.  
 483 Fallati, F. Marchese, A. Tibaldi, 2018. Immersive Virtual Reality for Earth Sciences. Proceedings of the  
 484 Federated Conference on Computer Science and Information Systems, 15, 527–534, DOI:  
 485 10.15439/2018F139.
- 486 Gonzaga, L., Veronez, M.R., Alves, D.N., Bordin, F., Kannenberg, G.L., Marson, F.P., Tognoli F.M.W.,  
 487 Inocencio, L.C., 2017. MOSIS - Multi-outcrop sharing & interpretation system. In 2017 IEEE International

Geoscience and Remote Sensing Symposium (IGARSS), 5209-5212), DOI: 10.1109/IGARSS.2017.8128175.

Granshaw, F. D., & Duggan-Haas, D. (2012). Virtual fieldwork in geoscience teacher education: Issues, techniques, and models. *Geological Society of America Special Papers*, 492, 285-303.

Gudmundsson, A. (2006). How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes. *Earth-Science Reviews*, 79(1-2), 1-31.

Heiken, G., McCoy, F., 1990. Precursory activity to the Minoan eruption, Thera, Greece. In: Hardy D.A. (ed.) *Thera and the Aegean World III*, vol 2. Thera Foundation, London, 13–18.

James, M.R., Robson, S., 2014. Mitigating systematic error in topographic models derived from UAV and ground-based image networks. *Earth Surf. Process. Landforms* 39 (10), 1413–1420.

James, M.R., Robson, S., d'Oleire-Oltmanns, S., Niethammer, U., 2017. Optimising UAV topographic surveys processed with structure-from-motion: ground control quality, quantity and bundle adjustment. *Geomorphology*, 280, 51–66.

Krokos, M., Bonali, F.L., Vitello, F., Antoniou, V., Becciani, U., Russo, E., Marchese, F., Fallati, L., Nomikou, P., Kearl, M., Sciacca, E., Whitworth, M., 2019. Workflows for virtual reality visualisation and navigation scenarios in earth sciences. 5th International Conference on Geographical Information Systems Theory, Applications and Management: GISTAM 2019, SciTePress.

Lawson, E., 2015. Game Engine Analysis ([www.gamesparks.com/blog/gameengine-analysis/](http://www.gamesparks.com/blog/gameengine-analysis/)).

McClelland, E., Thomas, R., 1990. A palaeomagnetic study of Minoan age tephra from Thera. In: Hardy, D.A. (ed.) *Thera and the Aegean World III*, Vol. 2 Earth Sciences, Thera Foundation, London, 129–138.

Müller D., Walter T.R., Schöpa A., Witt T., Steinke B., Gudmundsson M.T., Dürig T., 2017. High-resolution digital elevation modeling from TLS and UAV campaign reveals structural complexity at the 2014/2015 Holuhraun eruption site, Iceland. *Front. Earth Sci.*, 5:59, doi: 10.3389/feart.2017.00059.

Nomikou, P., Druitt, T. H., Hübscher, C., Mather, T.A, Paulatto, M., Kalnins, L.M., Kelfoun, K., Papanikolaou, D., Bejelou, K., Lampridou, D., Pyle, D.M., Carey, S., Watts A.B , Weiß, B. & Parks, M.M., 2016. Post-eruptive flooding of Santorini caldera and implications for tsunami generation, *Nature Communication*.

Pavlis, T.L., Mason, K.A., 2017. The new world of 3D geologic mapping. *GSA Today*, 27 (9), 4-10.

Rathje, E.M., Franke, K., 2016. Remote sensing for geotechnical earthquake reconnaissance. *Soil Dynamics and Earthquake Engineering*, 91, 304-316.

Rust, D. and Whitworth, M., 2019. A unique 12 ka subaerial record of rift-transform triple-junction tectonics, N.E. Iceland. *Scientific Reports*, 9:9669. <https://doi.org/10.1038/s41598-019-45903-8>

Smith, M., Carrivick, J. and Quincey, D. (2016). Structure from motion photogrammetry in physical geography. *Progress in Physical Geography: Earth and Environment*, 40(2), pp.247-275.

Tavani, S., Granado, P., Corradetti, A., Girundo, M., Iannace, A., Arbués, P., Muñoz J.A., Mazzoli, S., 2014. Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran). *Computers & Geosciences*, 63, 44-53.

Trexler, C. C., Morelan, A. E., Oskin, M. E., & Kreylos, O. (2018). Surface slip from the 2014 South Napa earthquake measured with Structure from Motion and 3-D Virtual Reality. *Geophysical Research Letters*, 45(12), 5985-5991.

Vereb V., van Wyk de Vries, B., Hagos, M., 2019. Remote sensing monitoring and geosite assessment of Dallol, Ethiopia. Putting an isolated and deserted area on map with geoheritage and resilience *Geophysical Research Abstracts*, 21, EGU2019-5640.

VGRS, 2017, (<http://www.vrgeoscience.com>).

Walter, T.R., Jousset, P., Allahbakhshi, M., Witt, T., Gudmundsson, M.T., Hersir, G.P., 2018. Underwater and drone based photogrammetry reveals structural control at Geysir geothermal field in Iceland. *J. Volcanol. Geother. Res.*, doi.org/10.1016/j.jvolgeores.2018.01.010.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179, 300-314.

Xu, X., Aiken, C. L., & Nielsen, K. C., 1999. Real time and the virtual outcrop improve geological field mapping. *Eos, Transactions American Geophysical Union*, 80(29), 317-324.

Zhao, J., Wallgrün, J. O., LaFemina, P. C., Normandeau, J., & Klippel, A. (2019). Harnessing the power of immersive virtual reality-visualization and analysis of 3D Earth science data sets. *Geo-spatial Information Science*, 1-14.