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

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| Abstract: | <p>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.</p> | |
| Response to Reviewers: | I have corrected the paper and figures as suggested by the Editor Taddeucci. | |
| Author Comments: | 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). | |

[Click here to view linked References](#)

1 **Real world-based immersive Virtual Reality for research, teaching** 2 **and communication in volcanology**

3
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15

16 ***Abstract***

17 Direct outcrop observation and field data collection are key techniques in research, teaching and outreach
18 activities in volcanic areas. However, very often outcrops are of difficult or impossible access, such as in areas
19 with active volcanoes or steep cliffs. Classical remote-sensing surveys by satellites or airplanes are expensive,
20 rarely reach sufficient resolution to allow high quality 3D visualisation of volcanic features, and do not
21 facilitate mapping of vertical cliffs. We describe a novel approach that uses immersive Virtual Reality (VR)
22 based on real world 3D Digital Outcrop Models (DOMs) from images surveyed by “unoccupied aerial system”
23 (UAS). 3D DOMs are built up using the Structure-from-Motion (SfM) photogrammetry technique, and a VR
24 scene is created using game engine technologies. Immersive real-time exploration of the environment is
25 possible through a head-mounted display, e.g. Oculus Rift. Tools embedded in the VR environment allow the
26 user to map polygons, lines and point features. Tools also allow to measure orientation, dip, inclination,
27 azimuth, area, thickness and even take virtual photographs. Using three examples of volcanic areas with
28 different geological features, we demonstrate the potential of our approach to allow users to be able to virtually
29 map and measure remotely, and to collect data for research and teaching. Our approach is of paramount
30 importance also for outreach, as it allows non-specialist audiences (e.g. common citizens) to experience and
31 appreciate highly complex volcanic features through customised, hands-on immersive VR tools.
32

33 **Key words:** Volcanology, Teaching & Scientific Communication, Immersive Virtual Reality, Head-
34 Mounted Displays
35

36 **Introduction**

37 Research activity, teaching and learning in volcanological sciences need the collection and observation of data
38 in the field, which typically constitute the backbone of any applied study in petrography, geochemistry,
39 geohazard, and many other areas. Outcrops can often be difficult to access for logistical reasons, or even
40 impossible to inspect, e.g. in the case of steep or vertical cliffs. Data collection can also be dangerous, as in
41 active volcanic areas with explosions, gas, hot fumes, etc., or other areas prone to geological hazards. Also,
42 teaching and learning is classically based on 2D images, although geological objects are 3D; to overcome this
1

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

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

58 Remote or dangerous volcanic areas have been classically studied by aerial or satellite remotely-sensed images,
59 which have several limitations: 1) high-resolution data are very expensive to cover large-scale geological
60 objects and the resolution can be poor for some targets, 2) it can be challenging to plan a specific survey by an
61 airplane, due to high costs or remoteness of the site, 3) it is impossible to map steep to vertical slopes by images
62 acquired in vertical nadir, and 4) images are mostly 2D. Recently, unoccupied aerial systems (UASs), due to
63 their high imaging capabilities, have been used to study volcanic eruption sites (Müller et al., 2017), dykes
64 (Dering et al., 2019), volcano-tectonic relations (Walter et al., 2018; Bonali et al., 2019) and active faults in
65 volcanic areas (Rust and Whitworth, 2019), as well as faults and landslides in non-volcanic environment
66 (Rathje and Franke, 2016; Gao et al., 2017). UASs are also known as drones, aerial photography systems and
67 unmanned aerial vehicles. Recently, some studies have used the Structure from Motion (SfM) technique to
68 create 3D Digital Outcrop Models (DOMs) of UAS-mapped areas (Benassi et al., 2017; Burns and Delparte,
69 2017; Cook, 2017; Pavlis and Mason, 2017), but none of these approaches has fully exploited the 3D nature
70 of the modelled structures to allow the user to interact with the full 3D geometry of the model for measurement
71 and mapping purposes. An attempt in this sense has been done by Gonzaga et al. (2017), although their
72 approach is just focused on single, limited outcrops.

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

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

85

86 **3D modelling and data input (Part I)**

87 Our approach consists of creating immersive VR that provides scientists and students with virtual ways to
88 study rock outcrops and collect measurements (e.g. Fig. 1b), replicating classical field activity. The first step
89 consists of creating a high-resolution 3D DOM, which is based off a real world scene, with UAS surveys
90 planned at a scale suitable for the research purposes and using the SfM workflow (e.g. James and Robson,
91 2014; James et al., 2017; Bonali et al., 2019). We would like to remark that 3D DOM can be also referred as
92 “Virtual Outcrops (VO)” (Xu et al., 1999; Tavani et al., 2014) that, with our approach, can be studied in first
93 person. A Wavefront Object File (OBJ) - in the form of a Tiled model - was selected to store the 3D geometry
94 and texture, based on the UAS-collected high-resolution images, as it can be easily imported and managed in
95 the Unity game engine (Unity is a cross-platform game engine developed by Unity Technologies, and a game
96 engine is a software-development environment designed for people to build video games) (Krokos et al., 2019).
97 The resolution and accuracy of the resulting model depends on the UAS camera resolution, UAS distance to
98 target during photo acquisition, number of established ground control points and level of quality during SfM
99 processing (details in Westboy et al., 2012; Bonali et al., 2019). For example, when flying about 25 m above
100 the target, we achieve a resolution of 8 mm/pixel, as shown in our example of the Greek Metaxa mine that will
101 be described below. All surveys in the present work have been done using a quadcopter equipped with a 20
102 MPX camera, including EXIF (Exchangeable Image file Format) information and GPS coordinates, provided
103 by the integrated Satellite Positioning Systems GPS/GLONASS (referred to the WGS84 datum). Thanks to a
104 built-in high precision 3-axis gimbal, flights are smooth, and the image collection is steady. The model we
105 used provides constantly stable flights thanks to the integrated GPS system, including position holding, altitude
106 lock and stable hovering. Hereunder we summarise the overall steps to produce a high-resolution 3D DOM
107 (Part I of the overall workflow shown in Figure 1c).

108 The first step is to define the area to be surveyed, the UAS flight missions, including paths orientations and
109 flight height, that can be planned and managed using dedicated software, particularly for pictures acquired in
110 nadir orientation. The UAS has been manually driven to collect pictures with oblique orientation of the camera
111 and to detail vertical cliffs. Photo overlap has also to be defined, as suggested by Gerloni et al. (2018), Bonali
112 et al. (2019), Krokos et al. (2019) and Antoniou et al. (2019). In fact, it is recommended that UAS-captured
113 photos should have an overlap of 90% along the path and 80% in lateral direction, in order to obtain a greater
114 alignment of images and to reduce the distortions on the resulting texture. The photos have been captured every
115 2 seconds (equal time interval mode), with a constant velocity of 3 m/s (low speed) and in optimal light
116 conditions suitable for the camera ISO range (100-1600) (Bonali et al., 2019).

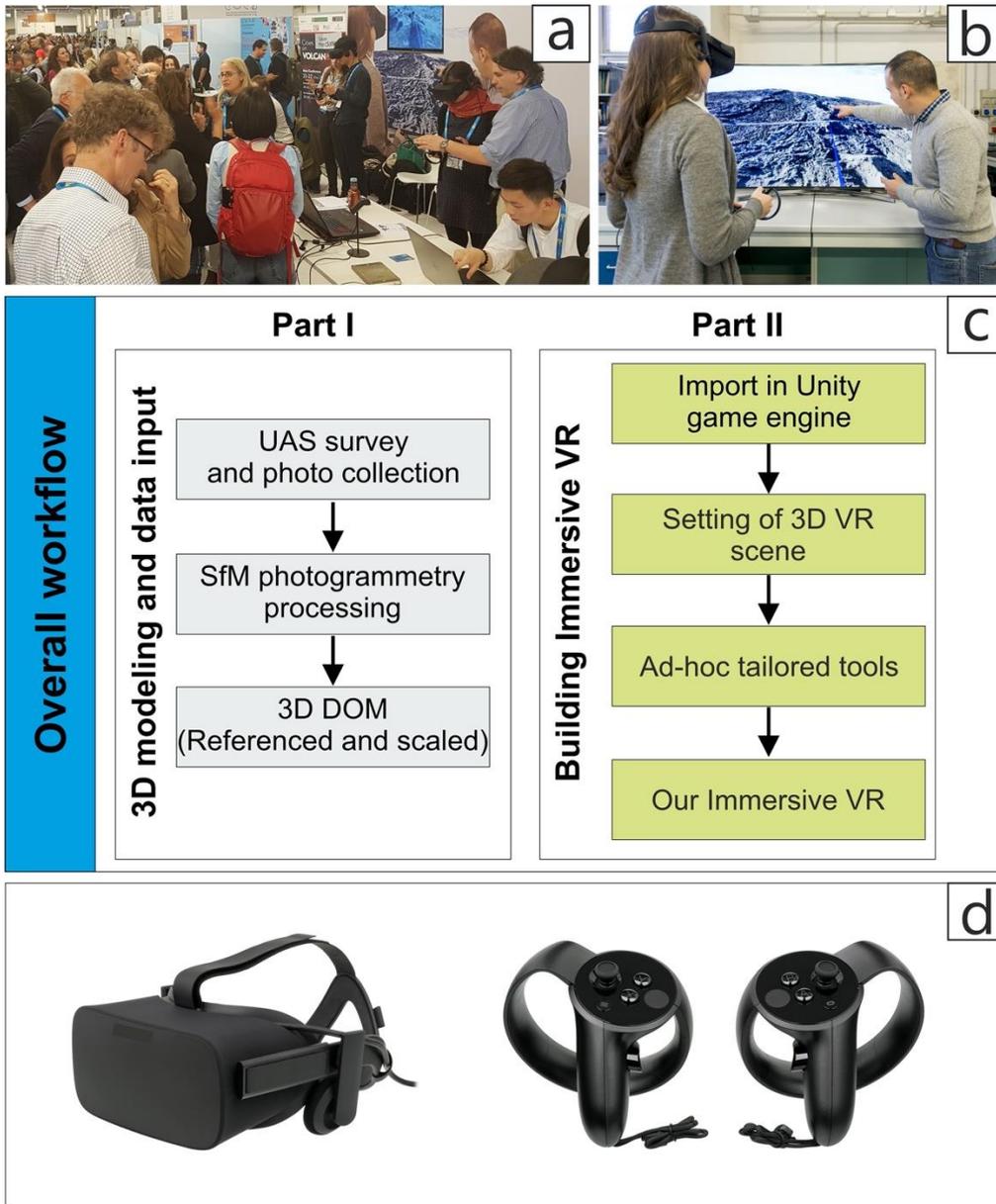
117 In order to allow for the co-registration of datasets and the calibration of models resulting from SfM processing
118 (e.g. Orthomosaics and DSMs), World Geodetic System (WGS84) coordinates of, at least, four artificial
119 Ground Control Points (GCPs) must be established near each corner within 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.

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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.

156 **Building Immersive VR (Part II)**

157 The target of our approach is to comprehensively simulate field experiences and observational behaviours of
158 geoscientists using high-resolution datasets and models. Our approach provides interaction experiences
159 realising navigation/exploration workflows that may not even be possible in the actual field, thus giving unique
160 spatial awareness insights in comprehending complex volcanological processes. An example can be the
161 monitoring of a steep slope on an active volcano, where uprising magma, intrusions, or earthquake shaking
162 can destabilise the slope with the possibility of slope failure. These multiple hazards create a complex scenario
163 that requires field inspection and collection of reliable field measures, but this can be impossible for the
164 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, 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).

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

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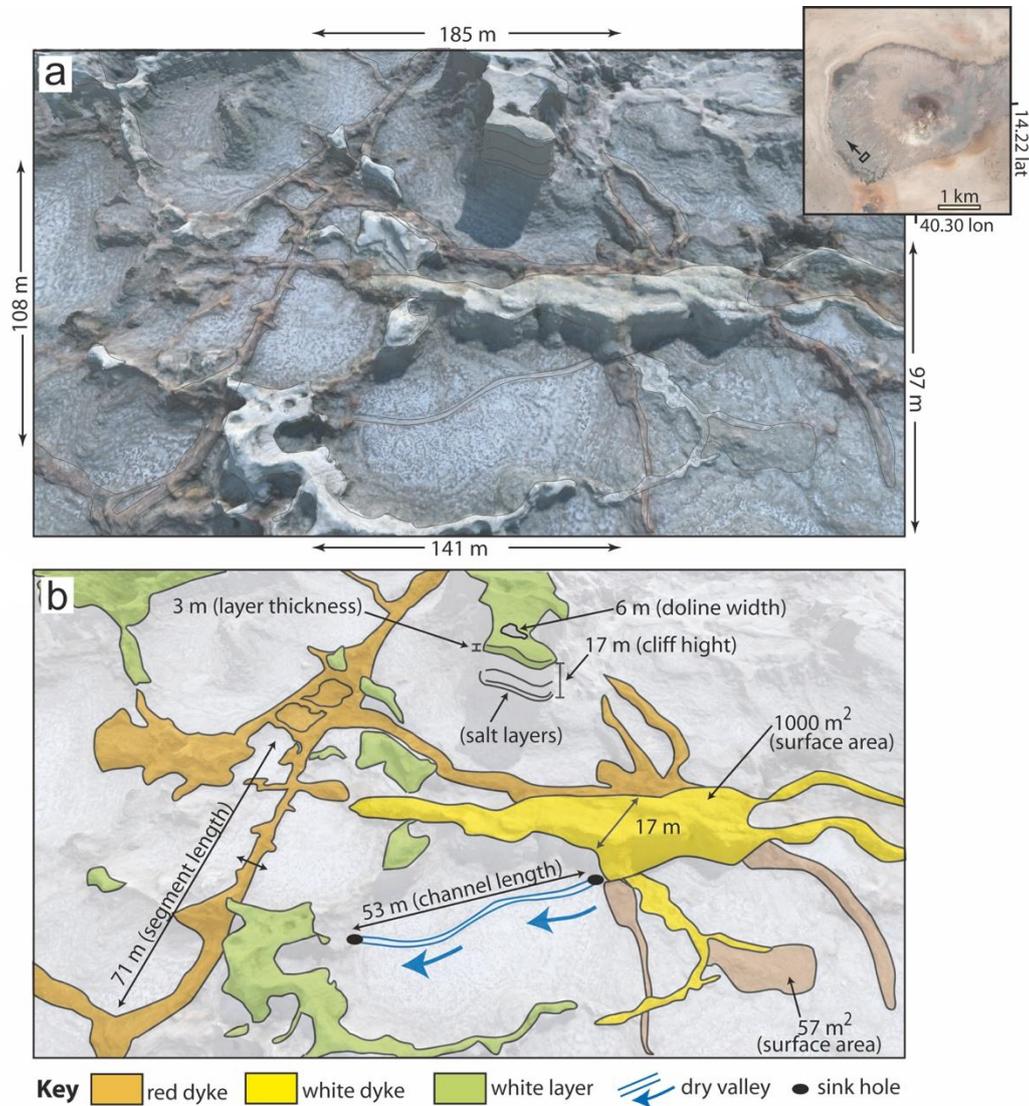
218 **Case studies**

219 **The Dallol Volcano, Ethiopia**

220 The active Dallol Volcano was one of the most inaccessible places on Earth, but recently has opened up due
221 to a new road, and there is rapid increase of tourists visiting the incredible geothermal manifestations. This has
222 led to increased risk from multiple geohazards and from the extreme climate. Assessing hazards requires
223 detailed topographic and geologic information, but the area is dangerous and hard to access. Thus, the area
224 was surveyed by UAS and data was processed following our approach (Fig. 2a). Particularly, the 3D DOM is
225 based on 229 pictures acquired with nadir camera orientation, at a flight height of 113 m, obtaining a texture
226 resolution of 2.87 cm/pixel over an area of 0.176 km². Photo alignment has been processed with high quality
227 setting and using Generic and Reference preselection. The dense cloud has also been built up using high
228 quality, whereas GCPs have been not collected in the field due to hard logistic condition. In the VR
229 environment, we have been able to access areas impossible in the field, making measurements and observing
230 features. We have detected different types of dykes and found erupted products (Fig. 2b). We have also
231 characterized and quantified salt karst structures, to start integrating measurements into a hydrogeological–
232 volcanological model. Tower morphologies are topped by a 3-m thick white eruption deposit. A tower of salt
233 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
234 a 17-m high cliff. Dykes of red clay, possibly filled karst pathways, from Dallol’s central hydrothermal area,
235 are mapped and selected measurements shown. A white dyke, made of salt and magma is up to 17 m wide
236 outcropping over 1000 m². A small dry river channel between source and sink holes is 53 m long.

237 This Dallol reconstruction has already been shown in Ethiopia and internationally, and has been used to get
238 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.
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 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

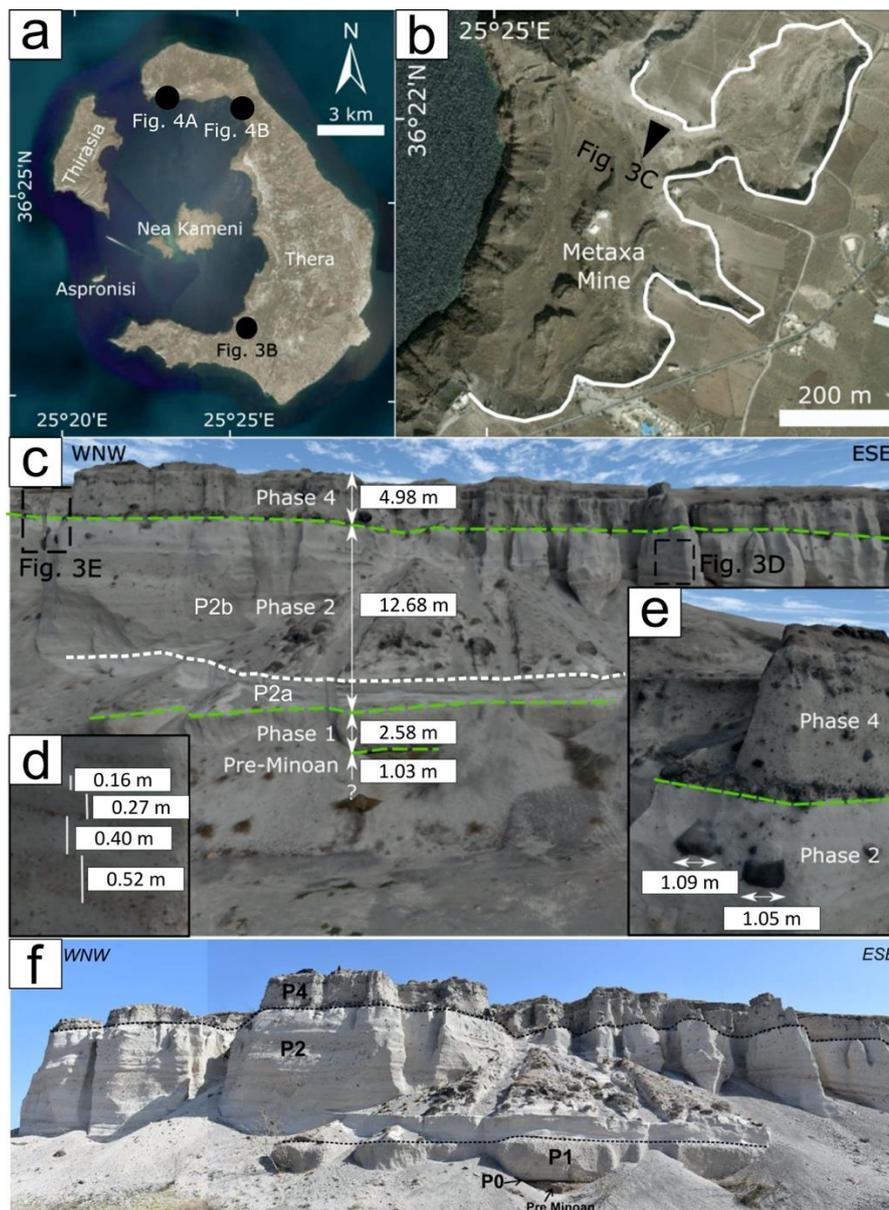
253 The Metaxa Mine is a unique geotope of Santorini volcano (Greece) where the pumice layers of the famous
 254 Late Bronze Age (LBA) (well-known also as Minoan) eruption are exposed (see supplemental video 3). It is
 255 nowadays abandoned and it is located in the central part of Santorini island, overlooking the famous Santorini
 256 caldera (Figs. 3a, b). The latter was created after the catastrophic Minoan eruption (Friedrich et al., 2006;
 257 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 m³ were excavated in the early years of mining. A total of 4.5 million m³ 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”.



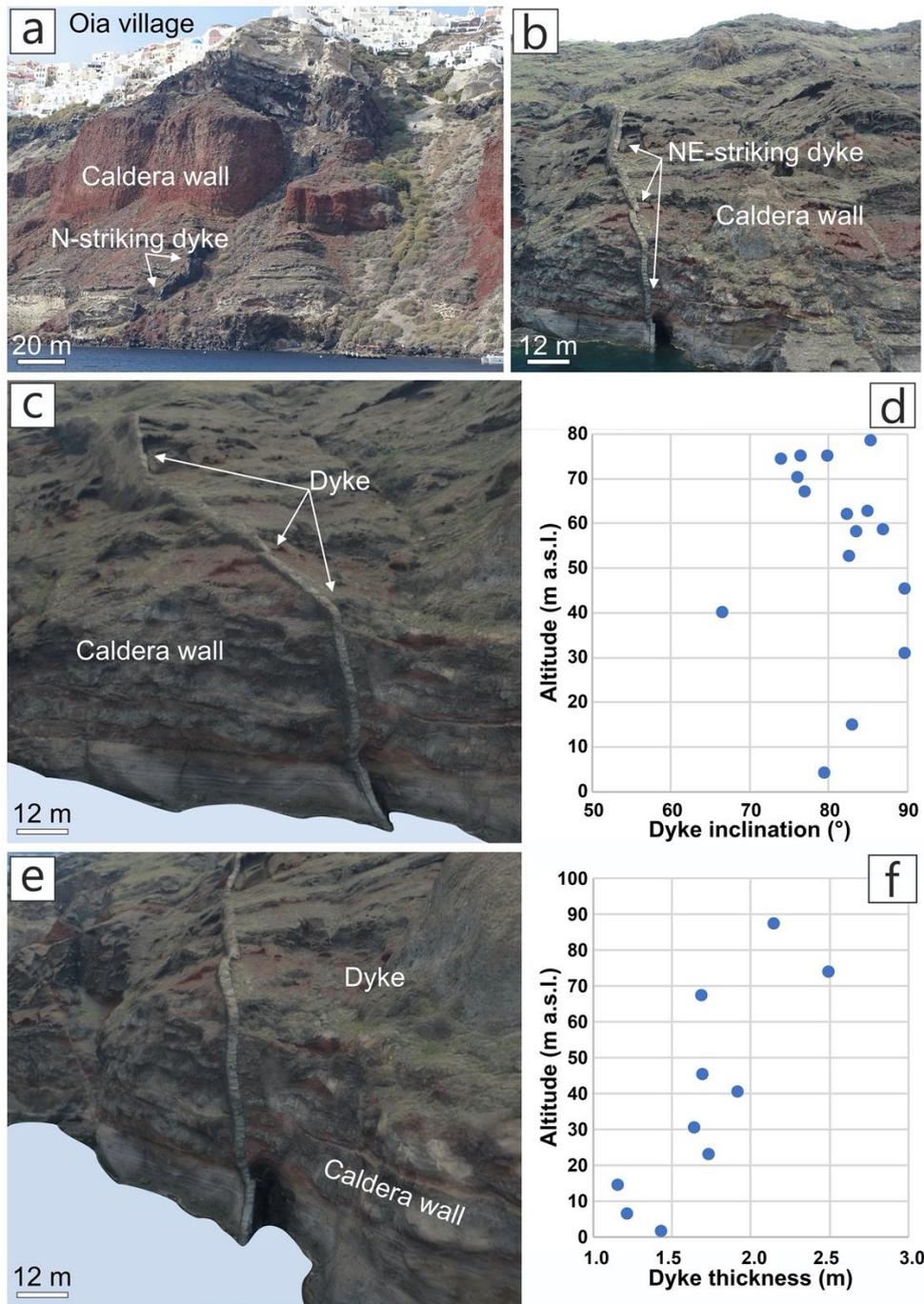
304
 305 **Figure 3.** Metaxa mine example: a) Location in Santorini island. b) Location of the reconstructed outcrop used
 306 in this example. c) 3D view of the “Famous section” showing the main strata of the various Minoan eruptive
 307 phases and measured thickness in immersive VR. d) and e) Examples 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).

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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.



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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

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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

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

403 In general, our approach enables anyone to create models based on real world images with unprecedented
404 detail, georeferenced, and fully explorable. This allows the operator to take measurements in an immersive VR
405 3D environment. Moreover, since outcrops can also change over time, our approach allows to make a quick
406 and direct comparison of the area development. For example, it is possible to quantitatively compare pre- and
407 post-eruption craters. This approach allows collection of quantitative data similar to standard field data
408 collection. This represents a scenario where the experience of the geologist/volcanologist, which is critical in
409 carrying out the interpretation, can be fully exploited, and fully communicated to all end users. Of course, VR
410 cannot substitute field survey where this is feasible (but it can contribute to collect more geometric data), and
411 cannot replace field trips for students where they can also take samples and see finer rock textures and minerals.

412

413 **Conclusions**

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

428

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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

488 Geoscience and Remote Sensing Symposium (IGARSS), 5209-5212), DOI:
489 10.1109/IGARSS.2017.8128175.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

521 Tavani, S., Granado, P., Corradetti, A., Girundo, M., Iannace, A., Arbués, P., Muñozb J.A., Mazzoli, S., 2014.
522 Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth
523 via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran). *Computers & Geosciences*, 63,
524 44-53.

525 Trexler, C. C., Morelan, A. E., Oskin, M. E., & Kreylos, O. (2018). Surface slip from the 2014 South Napa
526 earthquake measured with Structure from Motion and 3-D Virtual Reality. *Geophysical Research Letters*,
527 45(12), 5985-5991.

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

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

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

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

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

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

542