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THIS DOCUMENT CONTAINS THE LETTER TO THE EDITOR AND THE DETAILED REPLIES TO THE REVIEWERS

Lisbon, 25 April 2021

Dear Dr Jens Klump,

We are now submitting the revised version of the manuscript "Very high-resolution terrain surveys of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde)". The first version of the manuscript was reviewed by 4 referees (Drs S. Thiele, B. Wagner, M. Kirsch and P.J. Gonzalez) and received also comments from Dr G. Stuck de Quay. We have submitted the detailed review at the closing of the public discussion and we are now submitting the revised version and also revised replies to each of the referees.
We have conducted very substantial modifications in the manuscript, addressing the questions, comments and suggestions posed by the detailed revision by the referees. We think that this version answers all the issues raised and that it is now a much more solid contribution than the original manuscript. Since the public discussion, we have again improved the figures that had been submitted in the replies to the reviewers and created new ones, so the figures included now, should be the ones to be evaluated.
The main modifications that we have implemented in the manuscript were following:

- The title was modified in order to make clear the type of survey and the use of UAV.
- The abstract was improved to clarify the methods and the objectives, as well as the potential applications of the data set.
- The introduction is now shorter and more focussed on the significance of the dataset, supported by a clearer motivation and objectives. A very brief review of the applications of UAV-based surveys is presented. We have completely removed the previous section 2 on the applications of UAVs to volcanic areas, as suggested by several referees.
- The section 2 (Study area) is more concise now.
- A new section 3 on the volcanic activity of 2014-15 and previous digital elevation models was added. This section includes a more concise review of the last eruptive event and a more detailed review of the existing DEMs and their characteristics, as requested.
- The section 4 (Methods) was substantially improved with a more detailed description of the procedures and inclusion of tables with data and a new figure with the workflow. We have also improved the description of the procedures followed to generate the point cloud and the DSM. The

figures were improved and several new ones with the inclusion of survey details, have been added. We have clarified the procedures used to evaluate the model accuracy, including the ones based on the visual inspection of the DSM to delineate its quality zones. A better description of the lava flow delineation procedure was also included, supported by an example in a figure.

- The section 5 (Results) presents more details on the evaluation of the quality of the data set, with a much more in depth analysis of the quality of the point cloud, as well as with quantitative measures of DSM quality.
- The figures throughout the manuscript were significantly improved and some were removed, following suggestions by referees. New figures allowing to improve the data set characterization and the evaluation of its accuracy have been added.
- The dataset made available in Zenodo now includes all the aerial photos, as well as the 10 cm DSM and orthomosaic, as required by some reviewers.

Below, we present separate replies to the questions by the referees.

We expect that with this new version, the manuscript and data set are now in good conditions to be accepted for publication in ESSD.

Thank you very much.

Sincerely,

Gonçalo Vieira

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REPLY TO REVIEWER 1

Dear Dr Samuel Thiele,

Thank you very much for the detailed review, comments and suggestions of our manuscript on the "Very high-resolution terrain surveys of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde) submitted to ESSD.

We hope that with the significant changes we have made to the manuscript, following your comments, but also integrating the comments from other three reviewers and from the public discussion, the manuscript is now in good shape to be accepted for publication in ESSD.

We have included the suggestions you have proposed in the RC1-supplement file and the comments are in in the pdf. The version with track changes, as well as the clean manuscript are included.

The manuscript has been substantially edited and the main changes were the following:

- The title was modified in order to make clear the type of survey and the use of UAV.
- The abstract was improved to clarify the methods and the objectives, as well as the potential applications of the data set.
- The introduction is now shorter and more focussed on the significance of the dataset, supported by a clearer motivation and objectives. A very brief review of the applications of UAV-based surveys is presented. We have completely removed the previous section 2 on the applications of UAVs to volcanic areas, as suggested by several referees.
- The section 2 (Study area) is more concise now.
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- The section 4 (Methods) was substantially improved with a more detailed description of the procedures and inclusion of tables with data and a new figure with the workflow. We have also improved the description of the procedures followed to generate the point cloud and the DSM. The figures were improved and several new ones with the inclusion of survey details, have been added. We have clarified the procedures used to evaluate the model accuracy, including the ones based on the visual inspection of the DSM to delineate its quality zones. A better description of the lava flow delineation procedure was also included, supported by an example in a figure.

- The section 5 (Results) presents more details on the evaluation of the quality of the data set, with a much more in depth analysis of the quality of the point cloud, as well as with quantitative measures of DSM quality.
- The figures throughout the manuscript were significantly improved and some were removed, following suggestions by referees. New figures allowing to improve the data set characterization and the evaluation of its accuracy have been added.
- The dataset made available in Zenodo now includes all the aerial photos, as well as the 10 cm DSM and orthomosaic, as required by some reviewers.

Below you find the answers to your detailed comments, as well as the ones to the generic commentary. Thanks again for the time you have put into this review.

Sincerely,

Gonçalo Vieira

Reply to the general comments (essd-2020-289-RC1.pdf):

1) We have added a clearer message on the broader scope of the dataset, both in the abstract and in the manuscript.
2) We have done significant shortening of the text explaining the application of UAV surveys and modified the order of some paragraphs, such as the case of former line 170, as suggested. We have also significantly modified and shortened the introduction.
3) We have clarified the aims of the surveys in the paragraph starting in line 205, describing that we aimed at a survey with a resolution better than 50 cm. We made sure we followed the protocols outlined by Dering et al. (2019) and by James et al (2017). We have also improved the description of the existing DEMs, which support the motivation for our surveys.
4) We thank for the suggestion concerning the sensitivity analysis by James et al (2017, 2019). However, we did not apply the methods proposed by James et al. (2017) since that would imply a fully new approach to the data processing. We consider that using independent ground control points to evaluate model accuracy provides a satisfactory evaluation of the data set quality. In order to improve this component, we have also improved the description of the procedure to generate the point cloud and DSM and made available more data for the assessment of the accuracy of both. We have added an evaluation of the DSM accuracy by comparing the elevation with GCPs, in a similar approach as the one conducted by Bagnardi et al. (2016). The discussion of the quality of the results has been improved.
5) We have made the whole data set publicly available at Zenodo, including the aerial images, the dense point clouds and the 10 cm orthomosaics, DSM and 2014-15 lava flow, as suggested.
6) We have reviewed the manuscript with care and expect that we have improved its readability.

Reply to the detailed comments typed in the pdf manuscript (essd-2020-289-RC1-supplement.pdf):

- The suggested corrections were implemented and several improvements in the text following the remarks were conducted.
- Figure 1 was improved following the suggestions.
- Figure 3 was significantly improved accounting for flight details, including take-off/landing locations, GCPs and base station locations.
- Former figure 4 showing the ground control point collection procedure was deleted.
- A new figure 5 showing the location of ground control points, check points and manual tie points was created. The ground control point coordinates were made available in the public repository.
- Former line 290. The date for the surveys was wrong here. It was 2016. The collection of the extra-GCPs was in 2017.
- Section 3.3 was completely rewritten to clarify the procedure followed for generating the models. Figure 4 showing the general workflow was added. We have also addressed your questions relating to the methods used in PIX4D and clarified those whenever possible. However, the detailed algorithms are not made available by the company. Küng et al. (2011) describe the procedure and we have referenced that paper. We do not present a table for each individual flight, since the georeferencing and the identification of manual tie points was done after the merge of the full flights and these steps were essential to improve the final model results and even matches inside the same flights. This is because we have used a very large number of manual tie points.
- The selection of the surface smoothing with the sharp option in the interpolation of the DSM was made to reduce the effects of outliers in the point cloud in areas with worst quality. The designation “sharp” may induce mistakes in the interpretation, since in fact it is a filter that aims at preserving sharps areas, such as corners. The visual inspection of the hill shade DSM showed a good quality of the generated surface. Since we have made available the full dense point cloud in the dataset, it will be straightforward for the community to produce new DSMs using different interpolation methods, according to the needs.
- We do not calculate the lava volume, since the pre-eruption model is of very low resolution when compared to the new survey and this was not a goal of this study.

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Very high-resolution terrain surveys of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde)

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Abstract. Fogo in the Cape Verde archipelago off Western Africa is one of the most prominent and active ocean island volcanoes on Earth, posing an important hazard to both local populations and at a regional level. The last eruption took place between 23 November 2014 and 8 February 2015 in the Chã das Caldeiras area at an elevation close to 1,800 m above sea level The eruptive episode gave origin to extensive lava flows that almost fully destroyed the settlements of Bangaeira, Portela and Ilhéu de Losna. In December 2016 a survey of the Chã das Caldeiras area was conducted using a fixed-wing unmanned aerial vehicle and RTK GNSS, with the objective of improving the mapping accuracy derived from satellite platforms. The main result is an ultra-high resolution 3D point cloud with a Root Mean Square Error of 0.08 m in X, 0.11 m in Y and 0.12 m in Z, which provides unprecedented accuracy. The survey covers an area of 23. 9 km2 and used 2909 calibrated images with an average ground sampling distance of 7.2 cm. A digital surface model and an orthomosaic with 25 cm resolution are provided, together with ~~elevation con~~ ~~with an equidistance of 50 cm~~ and a 3D texture mesh for visualization purposes. The delineation of the 2014-15 lava flows ~~s~~ an area of 4.53 km2 by lava, which is smaller but more accurate than the previous estimates from 4.8 to 4.97 km2. The difference in the calculated area, when compared to previously reported values, is due to a more detailed mapping of flow geometry and the exclusion of the areas corresponding to kīpukas. Our study provides an ultra high-resolution dataset of the areas affected by Fogo's latest eruption – crucial for local planning – and provides a case study to determine the advantages of ultra high-resolution UAV surveys in disaster-prone areas. The dataset is available for download at http://doi.org/10.5281/zenodo.4035038 (Vieira et al., 2020).

1. Introduction

Detailed knowledge on volcanic eruptions, their products, evolution and impacts is of paramount importance for volcanic hazard assessments and to advance our capability to forecast the likely behaviour of future eruptions. Volcanic eruptions may ~~incur~~ in considerable loss of life and lasting damage to infrastructures, particularly on Small Developi and States

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like Cape Verde, where volcanic eruptions are likely to have disproportionate impacts, on account of their more limited resources and geographical isolation (Komorowski et al., 2016). Accordingly, ~~solid and~~ realistic volcanic hazard assessments in such areas, ~~more than in any other settings, greatly benefit~~ very-high resolution datasets from which detailed volcanological, geophysical, and environmental parameters can be inferred. In particular, very high-resolution digital terrain datasets of recently erupted lava-flow fields, may provide rapidly produced topographical d s that can also be used to plan mitigation and reconstruction strategies, as well as the opening of vital new communication infrastructures. The usefulness of such datasets is greatly enhanced when these datasets are freely available to governmental agencies, decision-making bodies and the scientific community alike. In line with this vision, in this paper we report and make available a recently acquired very high-resolution digital surface model and orthomosaic of the lava flow-flow field created during the 2014-15 eruption of Fogo volcano in Cape Verde.

Fogo in the Cape Verde Archipelago off Western Africa is one of the most prominent and active ocean island volcanoes on Earth, posing an important hazard to both local populations and at a regional level (Day et al., 1999; Heleno da Silva et al., 1999; Ramalho et al., 2015; Eisele et al., 2015; Jenkins et al. 2017). Crucially, Fogo is the site of recurring volcanic activity, with a record of at least 27 historical eruptions since the island was discovered in the mid-fifteenth century, yielding a mean recurrence interval between eruptions of approximately years, with individual intervals ranging from 1 to 94 years (Ribeiro, 1954; Torres et al., 1998; Day et al., 1999; Mata et al., 2017). The latest events occurred in 1995 and in 2014-15, both of which e ed extensive lava flow fields at the Chã das Caldeiras, a summit depression lying at an elevation of approximately 1800 m above mean sea level. ~~Effectively,~~ the settlements of Bangaeira, Portela and Ilhéu de Losna located in Chã das Caldeiras were almost fully destroyed in the 2014-15 eruption (Fig. 1). With a population of about 1200 inhabitants prior to the eruption, the local economy was based in agriculture (mainly wine and fruit orchards), grazing, and tourism. Fortunately, there were no casualties.

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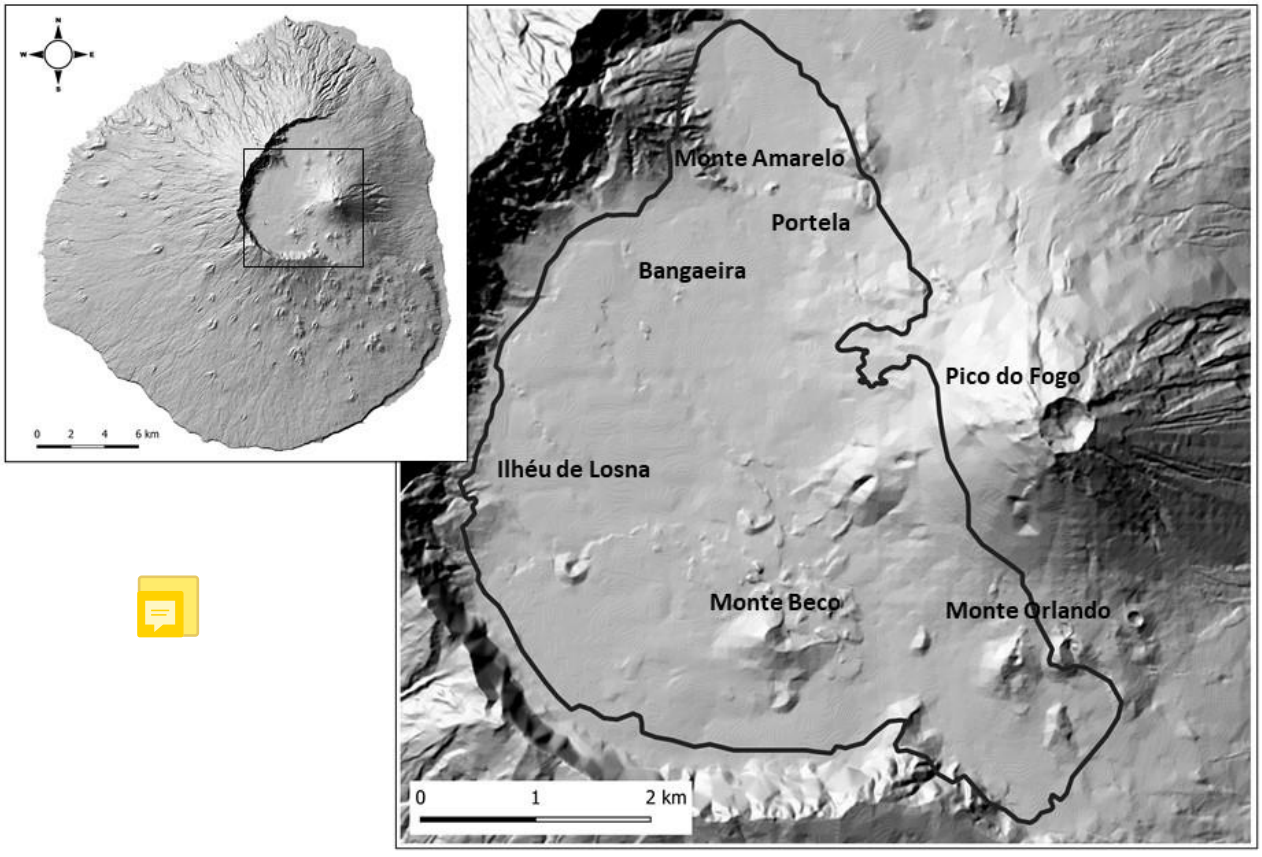

Figure 1 – Location of the Chã das Caldeiras and of the surveyed area (black line) in Fogo Island (Cape Verde). Shaded relief derived from the DEMFI (2010) 5 m DEM.

The latest eruption started on the 23rd November 2014 and lasted until the 8th February 2015, with magma ~~being~~ erupted from a 700 m-long NE–SW trending eruptive fissure ~~located~~ on ¬the SE flank of the previous 1995 crater row, on the SW flank of Pico do Fogo (Vieira et al., 2016; Mata et al., 2017). Reportedly, the eruption started with vigorous fire-fountain activity, which quickly evolved to a more explosive strombolian style, forming a crater row roughly parallel to the 1995 fissure. Later, the eruption was characterized by simultaneous or alternating hawaiian, strombolian and vulcanian eruptive styles (from the different craters of the fissure) lasting for several days, and by an almost constant emission of lava flows from the lowermost terminus of the vent (Mata et al., 2017). These formed two initial thick ‘a'ā flow lobes: the first advanced towards the southwest and eventually stalled after 1.7 km, at the foot of the caldera wall; the second progressed intermittently 3 km to the northeast, towards the village of Portela, razing a large portion of this settlement (Mata et al. 2017; Jenkins et al., 2017). During the later stages of the eruption, ~~however,~~ this flow lobe was reactivated, producing more fluid

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ʻa'ā and pāhoehoe breakouts to the west and north, the latter of which destroyed most of what was left of the Portela settlement and descended to the village of Bangaeira, causing widespread destruction there (Mata et al. 2017; Jenkins et al., 2017). The resulting lava flow field affected an area of ci. 4.8 km2, with extruded volumes estimated at ~45 × 106 m3 (Bagnardi et al., 2016; Richter et al., 2016; Cappello et al. 2016).

Remote sensing techniques have been used by several authors to study the Fogo eruption of 2014-15. Capello et al. (2016) used the HOTSAT satellite thermal monitoring system for the analysis of MODIS and SEVIRI dat the location of the hotspot, lava thermal flux, and effusion rate estimation. To st lava flow hazards during the 2014-15 Fogo eruption they used the MAGFLOW model. Validation of numerical simulations was done using Landsat 8 OLI and EO-1 ALI images and field observations. Bargnardi et al. (2016) used very high-resolution tri-stereo optical imagery acquired by the Pleiades-1 satellite constellation and generated a 1 m resolution digital elevation model (DEM) of the Fogo Volcano. From the Pleiades-1 post-eruption topography they subtracted the heights from a pre-eruption DEM, that was obtained using spaceborne synthetic aperture radar (SAR) data from the TanDEM-X mission. To measure the subsidence of the lava flow field, they used Sentinel-1 for interferometry. Height differences between the post-eruptive Pleiades-1 DEM and the pre-eruptive topography from TanDEM-X show a lava volume of 45.83 ± 0.02 × 106 m3, emplaced over an area of 4.8 km2 at a mean rate of 6.8 m3/s. Richter et al. (2016) did lava flow simulations based on field topographic mapping and satellite remote sensing analysis. They produced a topographic model of the 2014-15 lava flows from combined Terrestrial Laser Scanner (TLS) and photogrammetric data. The pre-eruptive DEM used was 5 m/pixel and was generated from the contours based on photogrammetric data. They estimated a lava flow volume of 43.7 ± 5.2 x 106 m3. TerraSAR-X imagery was used to access the lava flow model performance. The authors po t the need of having up-to-date topographic information because lava flow hazards change as result of topography modifications.

More r Bignami et al. (2020) used a combined method of 21 images from Sentinel-1, COSMO-SkyMed, Landsat 8, and Earth-Observing-1 missions from November 2014 to January 2015, to retrieve lava flow patterns. They applied an automatic change detection technique for estimating the lava field and its temporal evolution, combining the SAR intensity and the interferometric SAR coherence. Results showed a SW-NE oriented dyke, located inside Chã das Caldeiras, SW of the Pico do Fogo, as reported by Gonzalez et al. (2015). The area coverage of the lava flow obtained by visual analysis (L8 and EO-1) was estimated at 4.97 km2 as in Cappello et al. (2016), very close to the 4.8 km2 estimated by Bagnardi et al. (2016), and the 4.85 km2 estimated using Terrestrial Laser Scanner (TLS) combined with structure from motion data by Richter et al. (2016).

Several papers have been published on the latest eruption of the Fogo volcano, e.g. focusing on the variation of land surface temperatures during the eruption (Vieira et al., 2016), on lava geochemistry and small-scale mantle heterogeneity (Mata et al., 2017), mineralogy and geochemistry of incrustations (Silva et al., 2019), conduit dynamics and surface deformation (Gonzalez et al. 2015), on lava flow mapping and volume estimates (Bargnardi et al. 2016; Bignami et al., 2020), and lava flow hazards (Richter et al., 2016; Cappello et al. 2016; Jenkins et al., 2017).

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In the remit of the project FIRE (Fogo Island volcano: multidisciplinary Research on 2014/15 Eruption, funded by FCT-Portugal), an extensive survey using a survey-grade unmanned aerial vehicle (UAV) was conducted in December 2016 with the purpose of generating a very high resolution digital elevation model (DEM) and orthomosaic of the lava field to be used as baseline data for assessment of the eruption impacts, support to geological mapping and studies of the lava flow field, as well as for modelling lava flow dynamics. A study commissioned by the United Nations Development Program in Cape Verde stresses that an improvement in the assessment of hazards on the island of Fogo can only be achieved from a detailed analysis and the modelling of the lava flow (Fonseca et al., 2014). The data presented here is the result of that campaign and is the most detailed and updated survey of the area, with an ultra-high resolution digital surface model (DSM) that is essentially a DEM in most of the area due to the overall lack of vegetation and scarce number of buildings, and a digital orthomosaic.

2. Application of UAVs to volcanic areas

Digital elevation models and the dissemination of Geographical Information Systems have changed the way the terrain is characterized, analysed, monitored and modelled, especially since the 1990's. DEMs have been produced from dense collections of topographical points, manned aircraft photogrammetry, digitizing of topographic maps (Stevens et al., 1999), satellite remote sensing (Baldi et al., 2002; Kerle, 2002; Diefenbach et al., 2013), light detection and ranging - LiDAR (Mouginis-Mark and Garbeil, 2005; Mazzarini et al., 2007; Favalli et al., 2009; Fornaciai et al., 2010), radar interferometry (InSAR) (Rowland et al., 1999; Poland, 2014). Since the mid-2010's, with the technological developments and decreasing cost of unmanned aerial vehicles, accompanied by the development of photogrammetry software and computing power, a revolution took place. Very accurate and high quality DEMs became increasing available, leading to the possibility to easily achieve centimetric to decimetric resolution, even for large areas. The number of UAV-based surveys have been increasing steadily but many of them stay stored in the producers or client computers and are not of open-access.

UAVs have had various applications, such as for wildlife recognition (e.g. Christiansen et al., 2014; Wang et al., 2019), agriculture (e.g. Hassan-Esfahani et al., 2015, Kattenborn et al. 2014; Hasseler and Baysal-Gurel, 2019), urban and civil engineering (Westfeld et al., 2015), archaeology (Campana 2017; Risbøl and Gustavsen 2018), coastal dynamics (Chikhradze et al 2015; Brunier et al 2016; Turner et al 2017; Long et al 2016), climatology (Lindgren et al 2015; Bühler et al 2016), geomorphology (Lucieer, et al 2014; Dabski et al. 2020), vegetation in Polar regions (Mora et al 2015, Miranda et al 2020), glacier monitoring (Benoit et al 2019; Jouvet et al 2020) or for monitoring volcanic systems (Chio and Lin, 2017; Thiele et al., 2017).

Applications of UAV surveys to research in the Earth and Atmosphere sciences are relatively recent, having begun to emerge with greater expression from 2014 (Colomina and Molina 2014; Pajares 2015). Since then the number of publications has grown rapidly and spread across research fields, developing into a technique allowing fast and low-cost access to high spatial resolution data (Gomez and Purdie, 2016). The high versatility and possibilities of surveying even

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rough terrains of difficult access, such as the situation of volcanic eruptions, make UAVs a powerful tool to acquire real-time or near-real-time data on processes that often cannot be observed by naked eye (Di Felice et al 2018). Hence UAVs are increasingly used in situations of risk where it is essential to make the rapid terrain recognition following natural disasters (Gomez and Purdie 2016). Software and computing power have evolved very fast in last decade and the application of advanced photogrammetry algorithms involving image matching and structure from motion started to allow facilitated production of high-quality digital surface models and orthophoto maps. The collection of accurate GNSS ground control points allows to generate these products with centimetre resolution and accuracy (Favalli et al 2018). The recent development of RTK UAVs allows for even faster workflows in the terrain and to produce highly accurate models.

Photogrammetry techniques have been widely applied to study detailed changes in the morphology and structures of volcanos, like Mount St. Helens, the Colima and the Merapi (Major et al., 2009; Walter et al., 2013; Salzer et al., 2016). Optical and thermal cameras transported on UAVs have been used for identifying meter to sub-meter topography changes and for the detection of thermal anomalies (Nakano et al., 2014; Thiele et al., 2017; Nakano et al., 2014; Müller et al., 2017; Amici et al., 2013; Di Felice et al 2018). In addition, specific payload sensors are being used for measuring volcanic gas fluxes (McGonigle et al., 2008; Liu et al. 2019; de Moor et al., 2019), gas sampling (Mori et al., 2016; Rüdiger et al., 2018; Stix et al., 2018) and sediment sampling (Yajima et al., 2014).

Various studies have shown the potential of UAV-based surveying in volcanic terrains. These show the potential of the survey produced at Fogo, not only for characterizing post-eruption changes, but also for providing baseline data for analysing the dy ~~es~~ of the lava flow fields cooling, ~~soil erosion and even human reoccupation of the area.~~ As examples of UAV-based mapping, at the Nishinoshima Volcano, Nakano et al (2014) have acquired visible imagery to produce 3D maps allowing to monitor the evolution of the volcano. Darmawan et al. (2018) studied morphological and structural changes from 2012 to 2015 at the Merapi lava dome having identified the locations of steam-driven explosions. Felice et al. (2018) surveyed the erupting crater of Indonesian Lusi mud eruption was sp ~~;~~ boiling mud, water, ~~aqueous vapour,~~ CO2, CH4. Favalli et al. (2018) generated a high spatial resolution digital terrain model and orthomosaic of Mount Etna's January–February 1974 lava flow field, allowing the analysis of the morphology of sub-meter features, such as folds, blocks, and cracks, over kilometre-scale areas. The 3-cm orthomosaic allowed the analysis of centimetre-scale grain size distribution of the lava surface. Müller et al. (2017) studied the 2014-15 fissure eruptions of the Holuhraun to investigate the link between magma dikes at depth and the association with elastic and inelastic surface deformation. Turner et al (2017) during the 2014–15 Pāhoa crisis, used a UAV to monitor the front of a slowly advancing pāhoehoe lava flow. UAV surveys allowed Bonali et al. (2019) to study volcano-tectonics and tectonic features in an active Icelandic rift with unprecedent detail in extended areas in a much faster way and much lesser funds with respect to traditional field activity. One of the first UAV surveys during an ongoing eruption was performed by De Beni et al. (2019) in the 27 February–02 March 2017 event of Mt. Etna, which allowed improving the monitoring quality of the lava flow in terms of timeliness and detail. The independent acquisition of both visible and thermal infrared imagery by a pair of UAV in Stromboli allowed Wakeford et al. (2019) to build a 3D photogrammetric model of an active volcano. Finally, a recent summary about the use of small UAV

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for collecting immediate and real-time aerial data in volcanic environments during and after an eruption is provided by Jordan (2019), highlighting its advantages for mapping, sample collection, thermal imaging, magnetic surveys, slope stability studies, and also as platforms for carrying outgassing measurement sensors.

3. The study area and the volcanic activity of 2014-15

The island of Fogo is one of ten islands of Cape Verde, an archipelago located off the west African coast, about 600 km from Senegal. The Cape Verdes are regarded as the type-example of a volcanic archipelago formed in a stationary plate environment relatively to its hotspot, which probably explains the arcuate distribution of its islands (Burke & Wilson 1972; Lodge and Helffrich, 2006; Ramalho et al., 2010a, 2010b, 2010c; Ramalho, 2011). In more detail, this arcuate geometry is defined by two island chains: a "northern", from São Nicolau to Santo Antão, and a "eastern-to-southern", from Sal to Brava. There is no evident hotspot track but there is a morphological suggestion of an age progression in the "eastern-to-southern chain", from east (oldest islands) to west (youngest islands), which is supported by ages of the oldest exposed lithologies (see Ramalho, 2011). Fogo is located close to the southern terminus of this latter chain and is the only island in the archipelago with historical (i.e. last 500 years) eruptions (Bebiano, 1932; Ribeiro, 1954; Machado, 1965; Day et al., 1999; Faria and Fonseca, 2014).

Fogo is a large ocean island volcano showing a conical shape with a diameter of about 30 km (at sea level) and rising to an elevation of 2829 m, approximately 7 km above the surrounding seafloor. Structurally, the island is a compound volcano, featuring a "somma-vesuvio" association, with a younger stratovolcano – Pico do Fogo – rising from the central depression – Chã das Caldeiras – of an older collapsed volcano, sometimes referred as Monte Amarelo (Ribeiro, 1954; Day et al., 1999). This depression, however, is open to the east, being limited in the remaining three sides by a horseshoe shaped steep rock wall, over 1,000 m high, called Bordeira. This morphology, in turn, is either interpreted as a gravitational collapse headwall (Day et al., 1999; Paris et al., 2011) or as volcanic caldera walls, whose eastern portion later experienced a gravitational flank failure (Torres et al., 1998; Brum da Silveira et al., 1997a, 1997b; Madeira et al., 2008). Notwithstanding the different interpretations for the origins of this summit depression, it is clear that the opening to the east resulted from a massive flank failure of the flank of the volcano. Effectively, marine geophysical surveys undertaken off Fogo revealed the presence of voluminous submarine debris avalanche deposits extending offshore into the channel between Fogo and Santiago, and into the seafloor south and north of these islands, thus attesting the occurrence of this collapse (Le Bas et al., 2007; Masson et al., 2008; Barrett et al., 2019b). Moreover, field evidence attesting to the impact of a megatsunami triggered by Fogo's flank failure has been documented in the neighbouring islands of Santiago (Paris et al., 2011, 2018; Ramalho et al., 2015) and Maio (Madeira et al., 2020), confirming the catastrophic nature of the collapse and suggesting a 65-84 ka age for this event.

Pico do Fogo, currently the highest point in the island (2829 m in elevation), is a large and roughly symmetrical strato-cone that grew on top of the collapse scar, partially infilling this feature (Ribeiro, 1954; Torres et al., 1997; Brum da Silveira et al., 1997a, 1997b; Day et al., 1999). The sheer volume of this volcanic edifice is a testimony to the vigorous eruptive activity

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taking place at Fogo Island. There have been suggestions that Pico do Fogo experienced summit eruptions as late as the 18th century (Day et al., 1999), however this seems to be contradicted by the stratigraphic sequence at the summit, which exhibits mostly altered volcanic successions. Effectively, historical records suggest that all historic eruptions were extruded from ~~adventitious~~ vents ~~localised~~ at the base and lower flanks of Pico do Fogo, or at Chã das Caldeiras and the eastern flank of the island, in the periphery of this strato-cone (Ribeiro, 1954; Torres et al., 1997; Brum da Silveira et al., 1997a, 1997b). This is the case of the 1951, 1995, and 2014-15 eruptions, which vents were located in the NW, SW and S flanks of Pico do Fogo, close to its base at Chã das Caldeiras.

Chã das Caldeiras (Fig. 2) is thus a lava-infilled high-altitude summit depression, which resulted from the gradual accumulation and ponding of lava flows (and pyroclasts) erupted from Pico do Fogo and its ~~adventitious/~~satellite cones, against the vertical walls of Bordeira. Morphologically, Chã can be divided in two large semi-circular sectors: a southern, larger, with approximately 3 km of radius, and with an elevation of 1780 m, and a northern, with a shorter radius of approximately 1 km, and with a mean elevation of 1650 m. These two sectors, which are roughly separated by the prominent Monte Amarelo spur, have been interpreted as two coalescent volcanic calderas by Torres et al. (1997), Brum da Silveira et al. (1997a, 1997b), and Madeira et al. (2008). Chã das Caldeiras is a generally flat landscape, punctuated by a few volcanic cones and extensively covered by ‘a'ā and pāhoehoe lava flows and ash and lapilli deposits, which make it very irregular in detail and a challenging terrain for mapping. In particular, the extensive ‘a'ā lava flow lobes of the 2014-15, 1995 and 1951 eruptions covered large portions of Chã, resulting in large swaths of ~~virtually~~ inaccessible rocky surfaces~~, given their extreme roughness~~. Hummocky landscapes also exist, generally corresponding to older ‘a'ā lava flow fields with scattered large rafted blocks of spatter sequences in its surface (resulting from the gravitational collapse of strombolian cones and subsequent transport by lava flows), which are now partially buried under a blanket of lapilli and ash that smoothed the surface. A good example of such surfaces can be found to the east and particular to the west of the Monte Beco cone, being genetically associated to this vent. The foot and slopes of Pico do Fogo, in contrast, are extensively covered by a thick blanket of lapilli and ash, conferring a very smooth and uniform conical surface. Despite this cover, fanned leveed channelled morphologies can also be recognized at the foot of Pico do Fogo, corresponding to buried lava flow fans and alluvial fans. Overall, vegetation is scarce and is mostly confined to the surfaces of talus accumulated at the foot of Bordeira, where a thin soil exists, or to some scattered vineyards along some ash-covered slopes.

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Figure 2 – The Chã das Caldeiras and Pico do Fogo during the 2014-15 eruption. View towards the southeast with the ‘a'ā lava flows of 2014-15 in the foreground.

Human settlement at Chã das Caldeiras started towards the end of the 19th century (Ribeiro, 1954). Chã, as a high-altitude depression, is cooler and more humid than the rest of the island, with frequent fog condensation and occasional frosts, providing ideal conditions for the planting of orchards and vineyards. Attracted by the prospect of a more prosperous agriculture, people gradually settled Chã, mostly in the vicinities of Monte Amarelo, where some water springs and enhanced but ephemeral flow (from the larger canyons draining Bordeira) allowed easier access to water. Here they established the settlements of Portela, Boca Fonte, and later Bangaeira, which slowly and gradually grew in size until the 1995 eruption, when Boca Fonte was all but destroyed and the main access road to these settlements was blocked by the advancing flows (the 1951 eruption, although of a higher magnitude, had a lower impact in these settlements; Jenkins et al., 2016). After the 1995 eruption, however, the prospect of an additional income provided by a burgeoning wine industry and the rapidly growing flow of tourists that came to see the volcano, fuelled the rapid growth of Portela and Bangaeira, with population reaching as much as ~1500 resident inhabitants by 2014 (Fonseca et al., 2014; Jenkins et al., 2016). The 2014/2015 eruption, ~~in contrast,~~ had a profound impact in these villages, ~~g~~ ~~hat~~ the advancing lava flows either razed or

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buried up to 90% of the existing buildings, as as covered large swaths of the adjacent agricultural land. Gradually, however, reconstruction is taking place, either through new constructions over the recent lava flows, or by the painstaking reclamation of lava-buried but structurally intact buildings.

3. Methods

3.1 UAV Surveying

The field campaign was conducted about 20 months after the end of the eruption of 2014-15, when the lava flows had already cooled substantially, but with the occupation of the few houses existing at the Chã das Caldeiras, being forbidden and still hazardous, mainly due to gas emissions. Hence, the field team stayed at the village of São Filipe and travelled daily to the survey area. The expertise of the team on local conditions, geology and logistics and cooperation with the Cape Verde authorities, greatly facilitated the success of the mission.

The main challenges to overcome were i. the weather, which in December frequently shows high winds and low visibility (clouds) in the Chã das Caldeiras, ii. finding good landing sites for the UAV, iii. coping with the 1000 m high vertical rock wall of the Bordeira and with its possible influence on the positioning and communications system of the UAV, and iv. collecting enough high-quality ground control points.

The survey of the Chã das Caldeiras area was conducted from 12 to 16 December 2016 with a field team of 4 members. Two members focussed on conducting the UAV flights and the other two on the collecting ground control points. Communications among team members were done using VHF radios.

The weather during the campaign was excellent with clear skies and no wind in the first days, but deteriorated towards the end of the week, with clouds entering the survey area and affecting initially the illumination conditions and even limiting the flights in the last two days. This has affected the quality of the orthomosaic, which shows illumination artefacts in the northern part of the Chã das Caldeiras.

The survey was conducted using a professional survey-grade fixed-wing UAV SenseFly eBee classic, which has a structure of expanded polypropylene (EPP) foam, with carbon and composite parts. It has a 96 cm wingspan and under 0.7 kg take-off weight, which when disassembled allows for lightweight packing. This model allows for flights with wind speeds up to 45 km/h, flight durations of up to 50 min and a radio link distance up to 3 km. Two cameras were used: a Canon G9X 16MP in the initial flights, which had a critical failure, and a backup Canon IXUS 12 MP which was used subsequently.

Take-off with the eBee is performed by hand, which facilitates selecting the location, but landing is done normally in fully automatic mode needing several tens of meters of approach area, and a smooth landing surface in order not to damage the EPP UAV body. This was a significant limitation to the survey, since the area of the Chã das Caldeiras is mostly covered by very rough lava surfaces, with scarce smooth ash and lapilli cover sites, which are normally far apart. Given these constraints, five sites allowing for good landing conditions were selected: (i) 14.[illegible]77º N, 24.35407º W, (ii) 14.928092º N,

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24.353165º W, (iii) 14.92339º N, 24.356605º W, (iv) 14.9334999º N, 24.3722831º W and, (v) 14.962204º N, 24.3690256º W.

The survey consisted of 20 flights that do not show the ideal spatial setup nor homogenous illumination conditions in the resulting aerial photos, but it was the best solution given the logistical constraints. This was due to the following problems: sparse location of the take-off and landing sites, changes in wind-speed affecting power consumption, unexpected cloud advection and low visibility during some days, duration of daylight, fast changing shadowing effect from the Bordeira rock wall and by Pico do Fogo, battery limitations (due to heat, high risk of damaging the UAV in case of a need to crash land over lava flow, we decided not to conduct flight of over 30 min), long-distances to move between landing sites, these resulting on the need for constant on-site modifications of the original flight planning. The average flight elevation above the ground was 190 m, resulting on an average ground sampling distance of 6 cm, over 2,900 aerial photos and a total surveyed area of 24 km2 (Fig. 3).

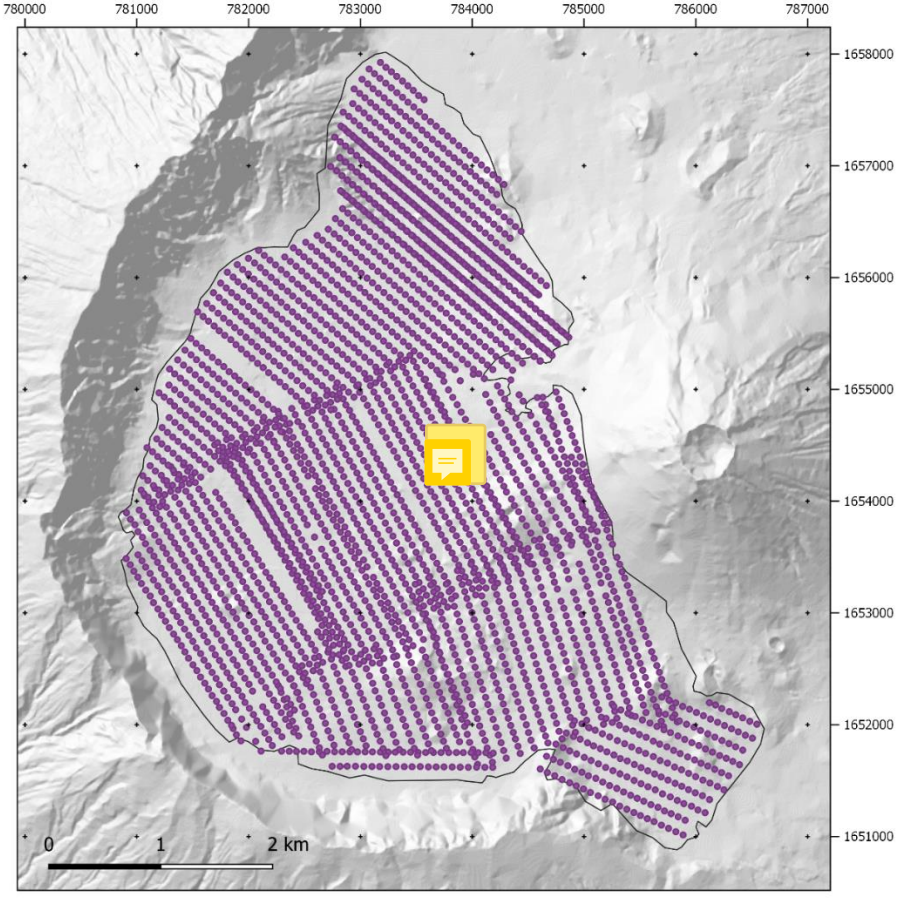

Figure 3 – Aerial survey of the Chã das Caldeiras with the geolocation of the photographs, Shaded relief derived from the DEMFI (2010) 5 m DEM.

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3.2 Ground control points

Coordinates of ground control points (GCPs) were measured at markers distributed in the field prior to the survey and at easy identifiable points, such as large boulders and building edges. The measurements were obtained using a Leica Viva (GS08) GNSS with base stations located at known coordinate sites (Monte Beco and Monte Amarelo) and a rover for surveying in RTK mode during the field surveys in December 2018. Extra GCPs were collected in February in small boulders selected in the preliminary orthophoto mosaic, in order to improve georeferencing quality. The accuracy of the GCP coordinates is of about 3 cm.

Figure 4 – Ground control point collection with RTK GNSS. A. Using markers, B. Using existing points.

3.3 Point cloud, orthophoto mosaic and digital surface model

Aerial image processing was done using Pix4Dmapper 4.5.6, a commercial software based on automatic feature detection, image matching and modelling using structure from motion (SfM) algorithms. This process developed in the 1990s, results from the application of algorithms by automatic feature-matching. The SfM operates according to the basic

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~~principles of stereoscopic photogrammetry, in which a 3D structure results from a series of 2D image overlays taken in motion to an object. The geom of the images, position and orientation of the camera are calculated automatically without the need for a priori indication. Decisions are made simultaneously based on an iterative adjustment of package images, and the structures are automatically extracted from several overlapping images and the points are searched from image to image allowing the estimation of the coordinates of the objects. The 3D point clouds are generated in an image-space coordinate system and are transformed into an absolute real-world object-space coordinate system. The transformation is achieved by using 3D functions based on a relatively small number of GCPs (Westoby et al. 2012; Smith et al. 2016).~~

The models that we have developed ~~have~~ used 2909 calibrated images with an average ground sampling distance of 7.17 cm and a total area covered of 23.89 km2. The camera optimi resulted in a 0.35% difference between the initial and optimized internal camera parameters. The images showed a median of 49521 k nts per image and a median of 22632 matches per calibrated image. The large number of flights, large area and different illuminati onditions led us to do separate processing and georeferencing of flights, with iterative project merging until nal model was obtained. In this process, we have used a total of 37 3D and 3 2D GCPs measured in the terrain. In order to improve the matching, 696 manual tie points were included, especially in areas covered by pyroclasts (lapilli and ash).

The point cloud was processed using full image scale, matching of image pairs using the aerial grid/corridor model and geometrically verified matching using automatic ~~advanced~~ points extraction. The advanced camera calibration was done using the alter method, internal parameters optimization (all), external parameters optimization (all) and no automatic rematch. The point cloud densification was done using multiscale and half-image size, with an optimal point density and a minimum number of 3 matches. This option was selected after intensive testing with 4 and 5 matches, which generated large gaps in the point clouds, in areas which were well-resolved with 3 matches. The point cloud still shows sectors with no data in homogeneous fine ash and lapilli covers, but those areas are small as discussed below and always outside the recent lava fields (Fig. 5). Since the target of the 3D survey are the lava fields, we guarantee that those sectors are well represented with many accurate points in the cloud.

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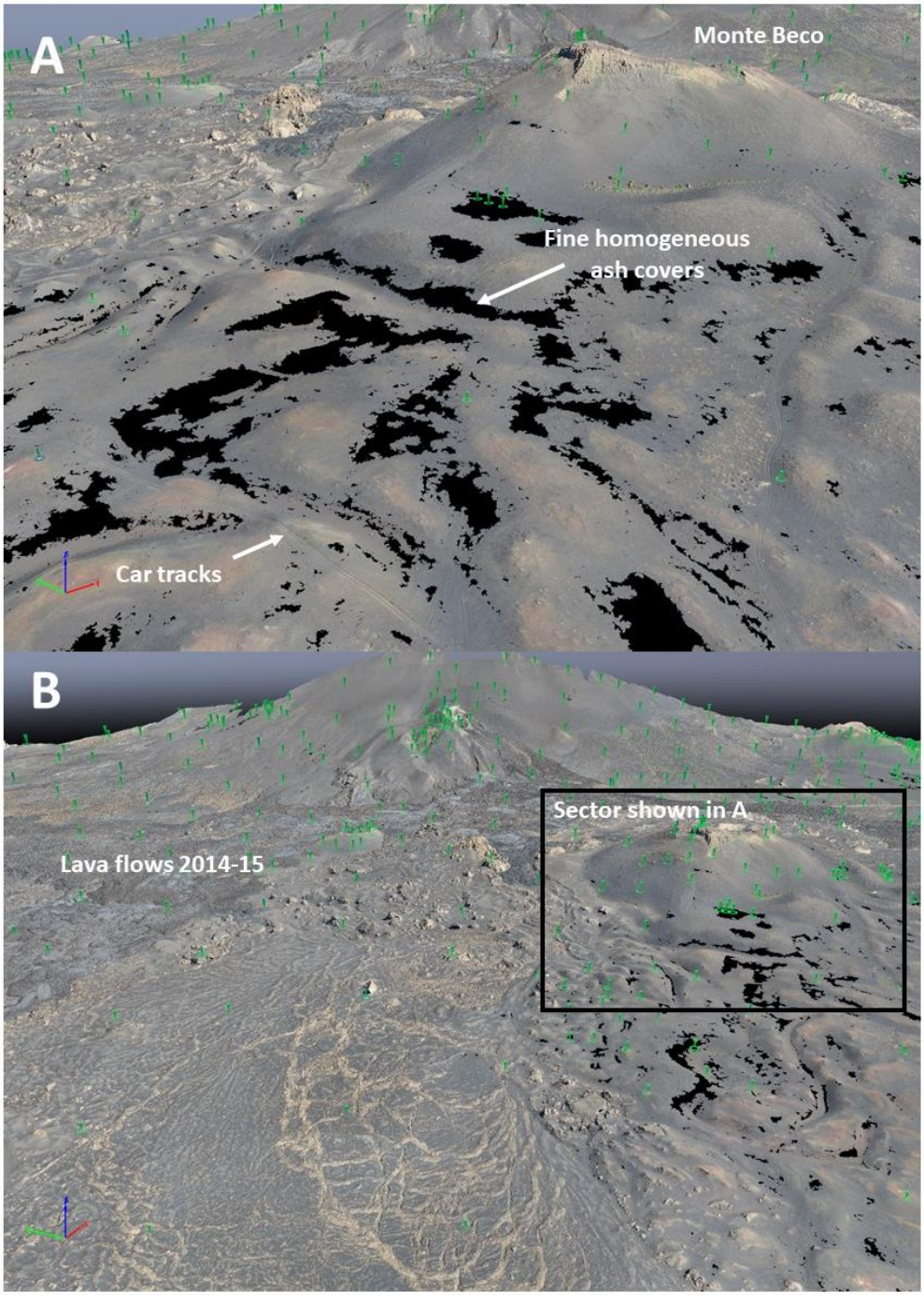

Figure 5 – Examples of areas without data in the 3D dense point cloud. A. Low quality areas in ash surfaces close to Monte Beco (car tracks pointed for scale), B. Most of the survey is of very high quality, with the figure showing the lava fields close to Monte Beco and the small areas with low quality. The green pins are manual tie points.

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The final digital surface model (DSM) and orthomosaic are presented with a resolution of 25 cm/pixel, which allow for maintaining the root mean square error (RMSE) well below pixel size. Noise filtering and sharp su smoothing were applied for the DSM, with interpolation using inverse distance weighting.

4. ~~Modelling~~ results and discussion

4.1 Point cloud

The point cloud model shows a RMSE of 0.08 m in X, 0.11 m in Y and 0.12 m in Z, evaluated using 13 independent check points (Table 1). Even after including several hundreds of manual tie points, it was not possible to obtain a good quality point cloud all over the survey area. Areas of homogeneous ash and pyroclasts covers lack 3D data, but they do not impact the overall mapping of the area, as is discussed below.

Table 1 – Location accuracy per ~~Ground~~ ~~rol Point~~ in X, Y and Z.

Check Point	ErrorX (m)	Error Y (m)	Error Z (m)	Projection Error (pixel)
beco03	-0.0218	-0.0110	0.0729	1.02
beco05	-0.1511	-0.1224	-0.0617	0.40
beco10	-0.0597	0.0347	0.2638	0.45
beco23	-0.0026	0.0791	0.0287	0.39
beco24	-0.0076	0.0844	0.1193	0.53
beco26	0.0286	0.1193	-0.0298	0.52
beco28	0.0671	0.0423	-0.0542	0.28
beco29	-0.0872	-0.0194	-0.1591	0.54
amarelo03	-0.0451	-0.1036	0.0280	0.41
amarelo05	-0.1162	-0.3011	0.2447	0.80
amarelo13	0.0567	0.0098	-0.1135	0.97
amarelo14	0.1900	0.0138	0.1076	0.74
amarelo16	-0.0011	0.1119	0.0940	0.60
Mean (m)	-0.0107	-0.0045	0.039	
RMSE (m)	0.082	0.107	0.125	

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4.2 Digital Surface Model

The DSM of the Chã das Caldeiras with 25 cm resolution shows unprecedented topographic detail and allows for excellent visualization and quantification of the terrain morphometry. The iterative improvement of the point cloud by a detailed visual analysis of the DSM shaded relief model followed by adding almost 700 manual tie points in the model and reprocessing, allowed to reach a very high-quality result (Fig. 6). The final model is the result of a resampling of the first model obtained with 10 cm resolution.

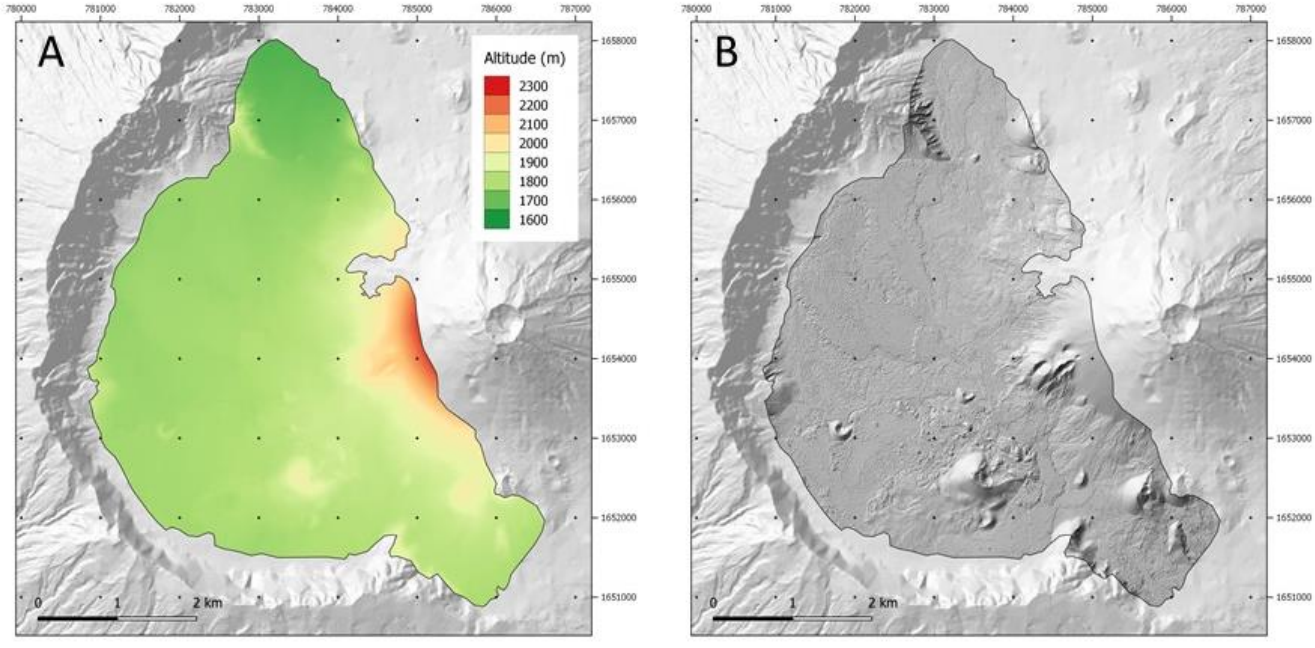

Figure 6 – Digital surface model of the Chã das Caldeiras (A) and DSM shaded relief model (B). The surveyed area is overlaying the DEMFI (2010) 5 m DEM.

In order to guarantee the quality of its use, the DSM was divided in three quality zones (Fig. 7). The zonation is available in the dataset as a shapefile that can be used to mask the DSM depending on user needs. The high resolution (10 cm) shaded relief model derived from the DSM, as well as the 50 cm equidistance contours interpolated from the DSM were used for the systematic visual analysis and for manual delineation of the areas with errors in the DSM.

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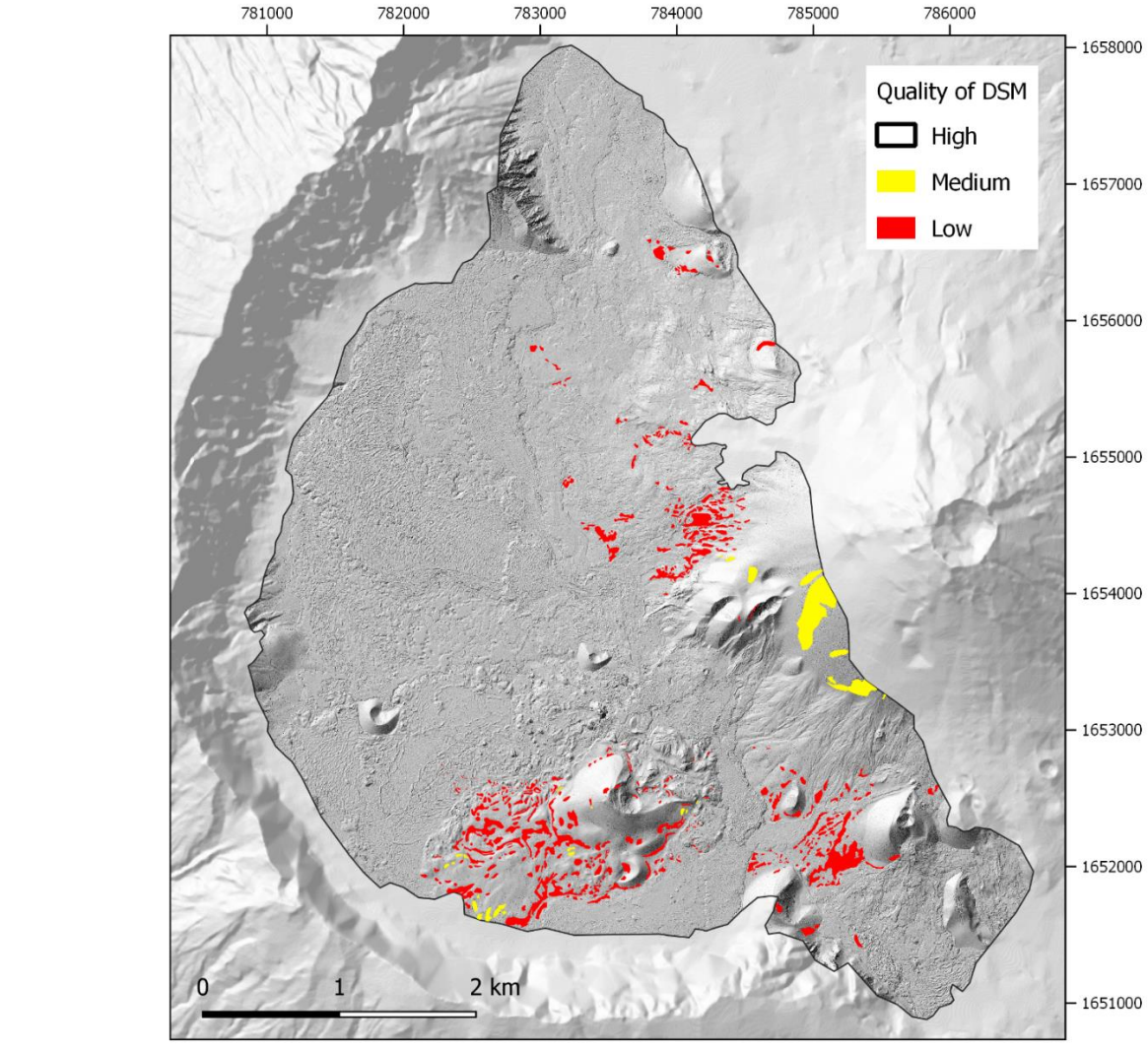

Figure 7 – Quality of the digital surface model in the Chã das Caldeiras. Shaded relief outside the surveyed area derived from the DEMFI (2010) 5 m DEM.

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The high-quality zones cover 96.8% of the ~~entire~~ survey and coincide with areas of rough surfaces with numerous automatic and manual tie points, where the morphology is very accurate, and the point cloud model has high resolution. Figure 8 shows some selected examples of the types of surface present in the survey area, which allow to visually assess the quality of the model:

370 - The 'a'ā lava flow fields are characterized by high rugosity and numerous features which are easily matched between aerial photogra[illegible]including blocks, frequent sharp slope changes and pressure ridges (Figs. 8-A and 8-B).

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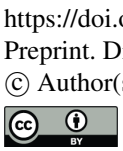

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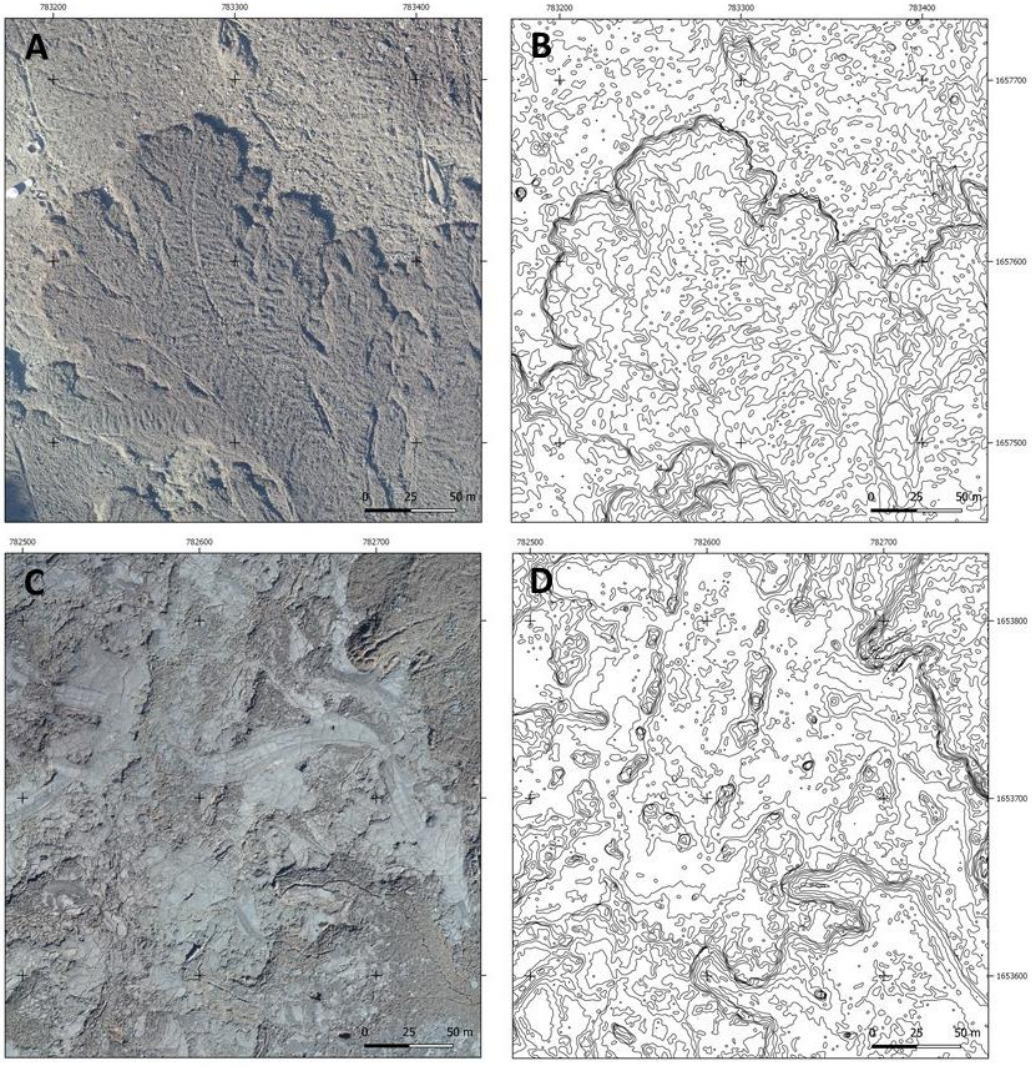
- Pāhoehoe lava flows show a much smoother and homogeneous surface, but they have frequent fractures and lineaments. They occupy generally small sectors of the orthomosaic and are bound by very rough a'ā lavas, facilitating point matching (Figs. 8-C and 8-D).

375 - Small volcanic cones with rough surfaces (e.g. boulders, footpaths, lava outcrops) show very high-quality results (Figs. 9-A and 9-B).

- Infrastructure, such as non-paved roads and houses show numerous matches and provide very accurate results. Cultivated areas occupy small sectors of the surveyed area, but the small holes dug to cultivate vines, as well as other small trees, are also very well represented in the DSM (Figs. 9-C and 9-D).



380 **Figure 8 – Examples of surfaces in the Chã das Caldeiras with high-quality results for the digital surface model, with orthomosaic for visualization (10 cm resolution) and contour lines derived from the digital surface model (50 cm equidistance). Note the good quality of the elevation contours. A and B. 'a'ā lava flows, C and D. Pāhoehoe lava field.**

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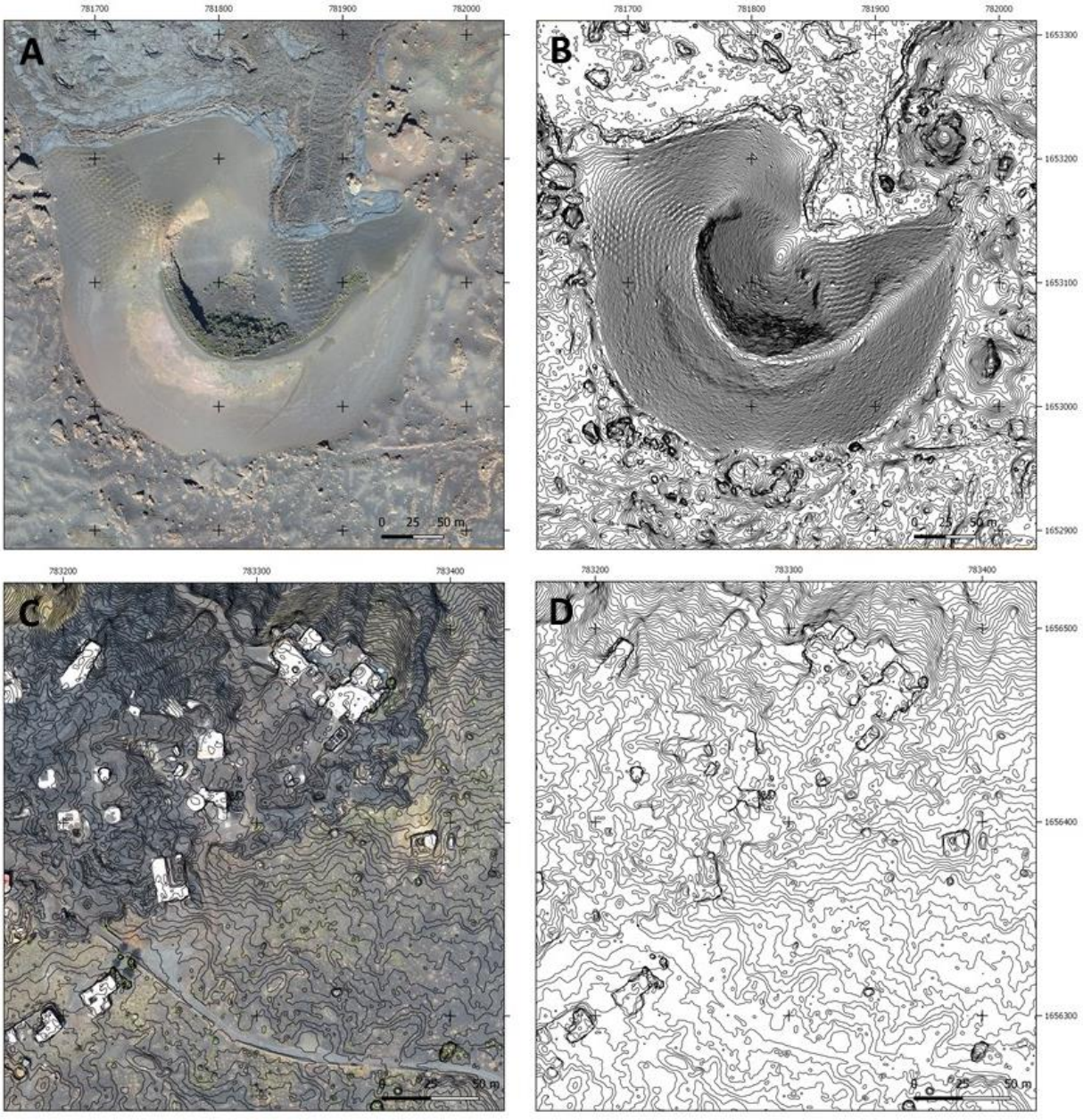

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Figure 9 – Examples of surfaces in the Chã das Caldeiras with high-quality results for the digital surface model, with orthomosaic for visualization (10 cm resolution) and contour lines derived from the digital surface model (50 cm equidistance). Note the good quality of the elevation contours. A and B. Volcanic cone with cultivated areas inside the crater, C and D. Lava field with buildings and a road.

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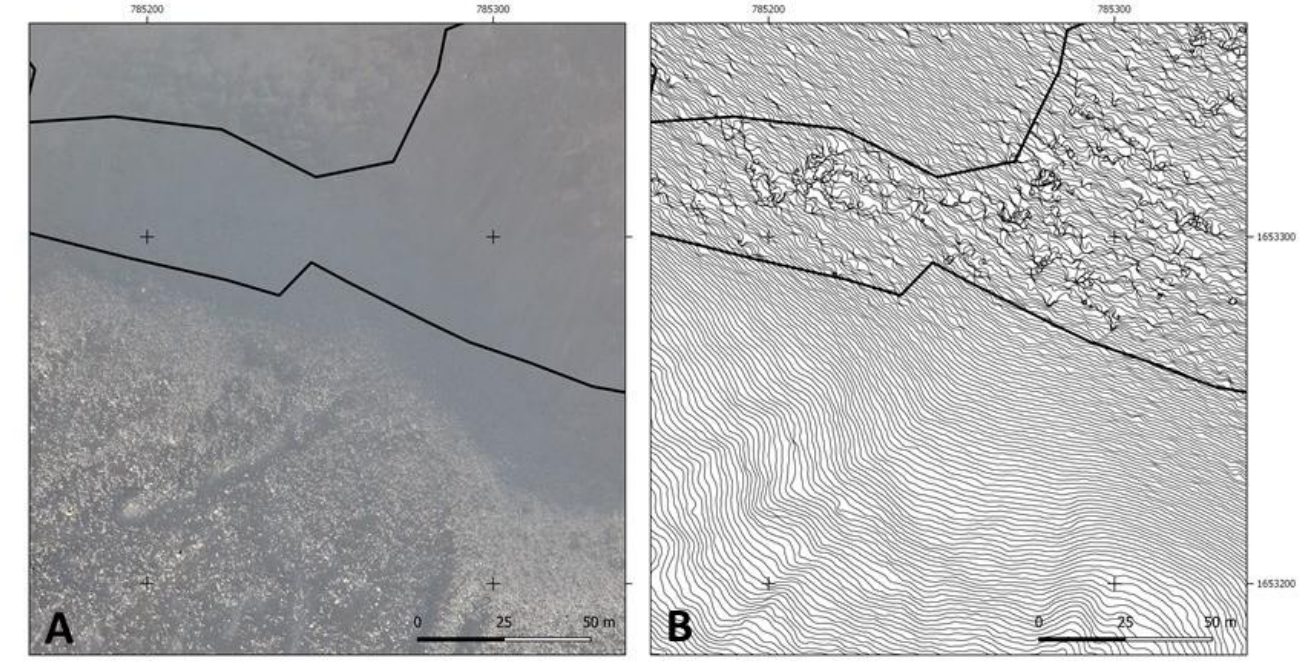

Figure 10 – Steep slope covered with ash in the Chã das Caldeiras with medium-quality results for the digital surface model. A. orthomosaic (10 cm resolution), and B. contour lines derived from the digital surface model (50 cm equidistance). The black line shows the boundary of the medium-quality area. The contours are very irregular in detail, but the overall slope at a coarse resolution is maintained. The area where the deposits are coarser provide a good DSM.

The medium-quality zones are sectors dominated by ash and lapilli, where sporadic 3D errors occur and occupy 0.6% of the survey. These areas, which in general can be used for visualization purposes and even for quantification, but with special care. Most errors in these zones are very small (dm scale) and can be smoothed by resampling, for example to 1-2 m resolution (Fig. 10).

The low-quality zones correspond to patches where the point cloud was poorly resolved, having numerous artefacts in the DSM (Fig. 11). These areas cannot be used for quantification purposes and their visualization shows errors, which sometimes are significant. The low-quality zones only occupy 2.6% of the survey area. These cases occur in very smooth surfaces of ash and lapilli or in sectors where a small number of overlapping aerial photos exists. They are located mainly in the base of some slopes, concave areas and also in the top of Monte Beco, due to the lack of photo overlapping.

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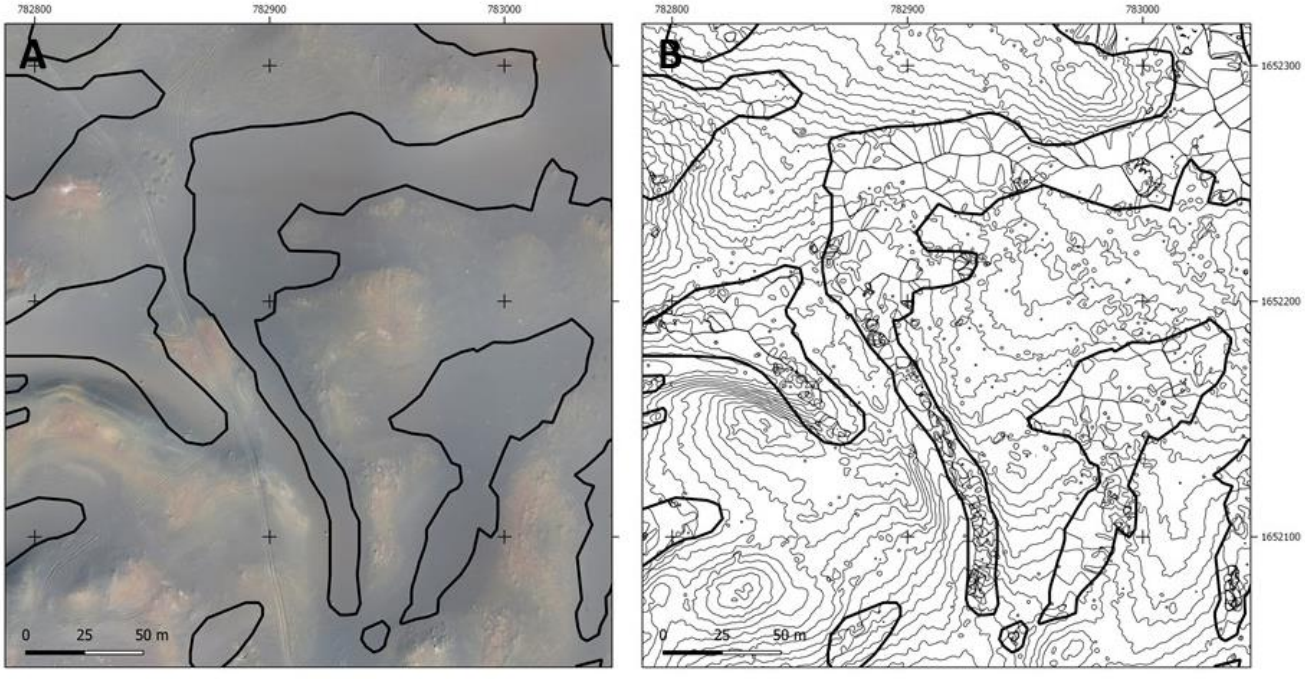

Figure 11 – Irregular surfaces with linear depressions covered with ash in the Chã das Caldeiras with poor-quality results for the digital surface model. A. orthomosaic for visualization (10 cm resolution), and B. contour lines derived from the digital surface model (50 cm equidistance). The black line shows the boundary of the low-quality area. The contours are very irregular and show numerous errors. The border with the good quality areas is sharp with good topography where the ground surface is coarser.

4.3 Orthophoto mosaic

The digital orthophoto mosaic that shows a resolution of 25 cm (Fig. 12), but the high accuracy of the survey allowed to make a mosaic with a resolution of 10 cm. This product may be delivered upon request. The mosaic shows an overall high graphic quality, with few problems relating to shadow effects close to the Bordeira wall in the south of the Chã das Caldeiras, and with varying illumination conditions in the lava flows of the northwest part of the survey, where ~~stri~~ g occurs. The sectors with medium quality in the DSM do not affect the overall quality of the ortho mosaic, but the interpolation may result in geometrical inaccuracies in the orthophoto mosaic in the areas of low quality in the DSM.

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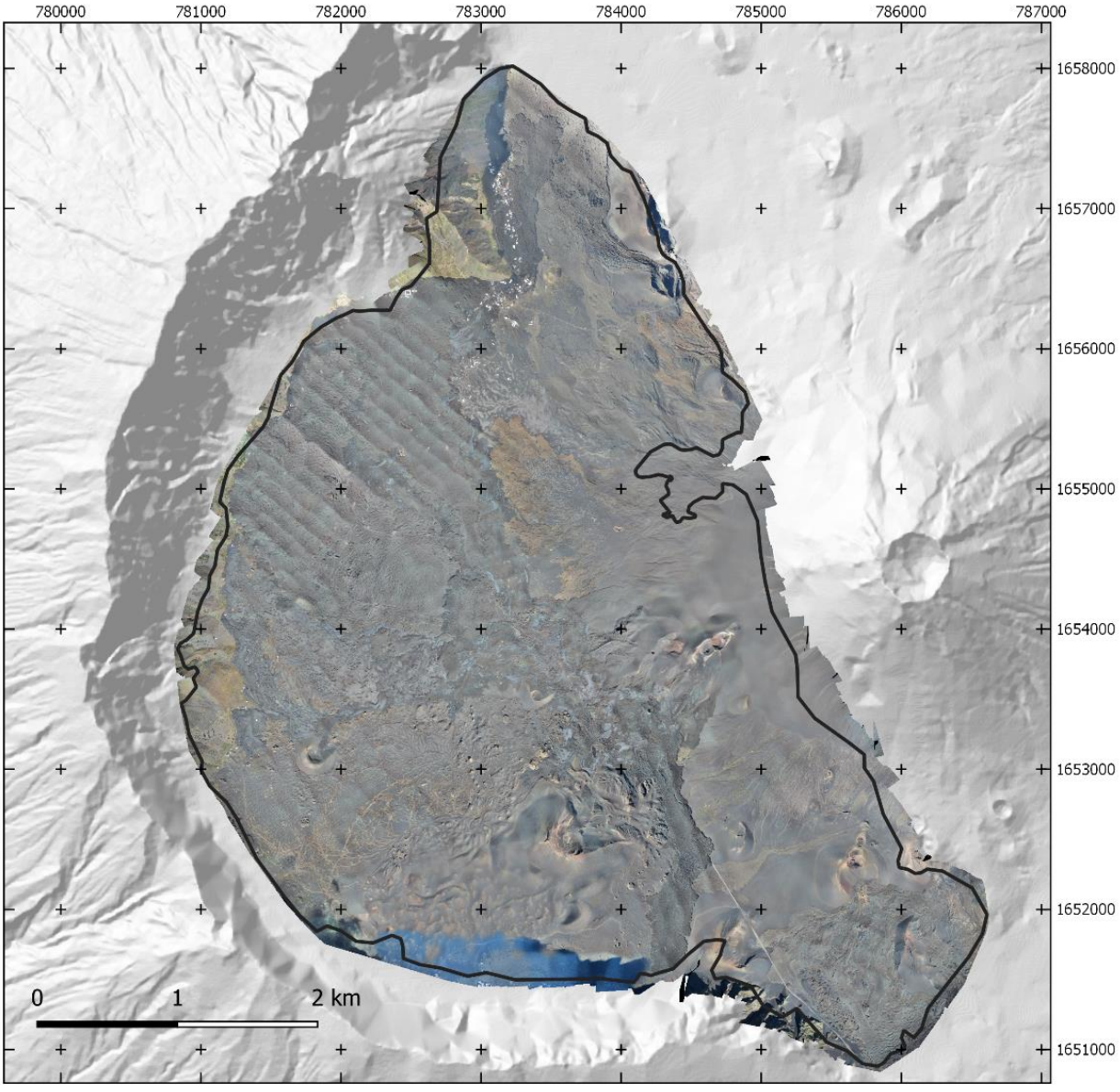

Figure 12 – Digital orthophoto mosaic with 25 cm resolution of the Chã das Caldeiras. Shaded relief outside the surveyed area derived from the DEMFI (2010) 5 m DEM.

4.4 3D models for visualization

A 3D texture mesh (.fbx) was produced for visualization purposes, allowing for the accurate visualization of the whole surveyed area (Fig. 13).

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Figure 13 – 3D visualization of the texture mesh of the Chã das Caldeiras.

4.5 New estimates of the 2014-15 lava flow field area

The lava flow field of the 2014-15 eruption was digitized manually using the orthomosaic and DSM. Unfortunately, our survey missed a small area of the lava flow with 0.007 km2 in the northwest sector of Chã das Caldeiras, close to Monte Amarelo and that sector had to be digitised using very high-resolution Google Earth imagery. The accuracy of the present survey allowed to calculate a new area for the 2014-15 lava flow field, which is 4.53 km2, a number smaller than the areas calculated by other authors using coarser resolution imagery, that varied from 4.8 to 4.97 km2 (5.8% to 8.9%). This discrepancy can be explained by the higher spatial resolution of our dataset that allows more accurate delineations, identifying in addition several kīpukas, i.e. small 'islands' (interior elevations surrounded by lava during the 2014-15 eruption) and also to a spatial variation effect (Chen, 1999) that results from the computation of the same areas in products with different spatial resolutions.

5. Data availability

The data is available at Zenodo: Vieira, Gonçalo, Mora, Carla, Pina, Pedro, Ramalho, Ricardo, & Fernandes, Rui. (2020). Digital surface model and orthomosaic of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde, December 2016) (Version 1.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4035038.

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The dataset consists of the following files:

- cha_caldeiras_contours_50cm.zip: Compressed shapefile (shp) and auxiliary files. Contour lines of the Chã das Caldeiras in December 2016 with 50 cm equidistance, interpolated from the digital surface model. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N, elevation: ellipsoidal ITRF2014 (WGS84).
- cha_caldeiras_dsm_25cm.tif: Digital surface model of the Chã das Caldeiras in December 2016 with 25 cm resolution. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N, elevation: ellipsoidal ITRF2014 (WGS84).
- cha_caldeiras_error_assessment_areas.zip: Compressed shapefile (shp) and auxiliary files. Areas with errors in the point cloud obtained by visual analysis. 1. Low accuracy, 2. Moderate accuracy. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N.
- cha_caldeiras_ortho_25cm.tif: Orthomosaic RGB of the Chã das Caldeiras in December 2016 with 25 cm resolution. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N.
- cha_caldeiras_pix4d_report.pdf: Report of the processing of the aerial imagery in PIX4D.
- lava-2014-15.zip: C[illegible]essed shapefile (shp) and auxiliary files. Lava flows of the eruption of 2014-15 digitised from the original 10 cm resolution orthomosaic. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N.

6. Conclusions

The 23.9 km^2 very high-resolution digital surface model and orthophoto mosaic of the Chã das Caldeiras lava fields developed from UAV surveys of December 2016, show unprecedented detail and accuracy (resolution = 25 cm and RMSE = 0.103 m). 96.8% of the survey area has provided a very high-quality DSM, which due to the scarce vegetation and built areas may be used as a DEM. The areas with moderate problems occupy 0.6% of the survey, with only 2.6% of the area showing poor-quality. The sectors with problems in the point cloud and DSM are those associated to very homogeneous ash and lapilli deposits. These areas can be easily masked out of the DSM by using the shapefiles made available in the dataset. The rough surface ‘a'ā lavas and the smooth pāhoehoe flows are very accurately determined, as well as the volcanic cones. The resulting DSM and orthomosaic constitute base datasets of unprecedent detail of high-value for geological research and for lava flow modelling with a high potential for applications in risk mitigation. These products allow delineating accurately the borders between different surfaces (lava types and other classes) and perceiving sub-meter surface features, which is less accurate or not achievable at all at meter scale, over an area of several square kilometres. These morphometrics features include pressure ridges, tumuli, flow channels, levées, dragged blocks and remains of human structures, among other smaller features.

Finally, we consider that these highly detailed products can play a relevant role in [illegible]ssessment of volcanic hazards and related research and whose importance is surely excelled by becoming open access.

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Author contributions

GV, CM, PP and RR prepared the UAV survey planning and wrote the manuscript. GV and CM conducted the UAV surveys. PP and RR conducted the GNSS GCP collection. GV and CM conducted the modelling. RR digitised the lava flows. RF coordinated the GNSS activities. All authors contributed to discussion and review of the manuscript.

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REPLY TO REVIEWER 2

Dear Dr Bianca Wagner,

Thank you very much for the detailed review, comments and suggestions of our manuscript on the "Very high-resolution terrain surveys of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde) submitted to ESSD.

We hope that with the significant changes we have made to the manuscript, following your comments, but also integrating the comments from other three reviewers and from the public discussion, the manuscript is now in good shape to be accepted for publication in ESSD.

We have attached the RC2-supplement file with our replies to your questions in the discussion and you may see them implemented in the .doc file with the track changes.

The manuscript has been substantially edited and the main changes were the following:

- The title was modified in order to make clear the type of survey and the use of UAV.
- The abstract was improved to clarify the methods and the objectives, as well as the potential applications of the data set.
- The introduction is now shorter and more focussed on the significance of the dataset, supported by a clearer motivation and objectives. A very brief review of the applications of UAV-based surveys is presented. We have completely removed the previous section 2 on the applications of UAVs to volcanic areas, as suggested by several referees.
- The section 2 (Study area) is more concise now.
- A new section 3 on the volcanic activity of 2014-15 and previous digital elevation models was added. This section includes a more concise review of the last eruptive event and a more detailed review of the existing DEMs and their characteristics, as requested.
- The section 4 (Methods) was substantially improved with a more detailed description of the procedures and inclusion of tables with data and a new figure with the workflow. We have also improved the description of the procedures followed to generate the point cloud and the DSM. The figures were improved and several new ones with the inclusion of survey details, have been added. We have clarified the procedures used to evaluate the model accuracy, including the ones based on the visual inspection of the DSM to delineate its quality zones. A better description of the lava flow delineation procedure was also included, supported by an example in a figure.

- The section 5 (Results) presents more details on the evaluation of the quality of the data set, with a much more in depth analysis of the quality of the point cloud, as well as with quantitative measures of DSM quality.
- The figures throughout the manuscript were significantly improved and some were removed, following suggestions by referees. New figures allowing to improve the data set characterization and the evaluation of its accuracy have been added.
- The dataset made available in Zenodo now includes all the aerial photos, as well as the 10 cm DSM and orthomosaic, as required by some reviewers.

Our sincere thanks for the time you have put into this review.

Best wishes,

Gonçalo Vieira

Review of "Very high-resolution terrain surveys of the Cha das Caldeiras lava fields (Fogo Island, Cape Verde)" by Vieira et al.

Bianca Wagner, Geoscience Centre, University of Göttingen, Germany

January 26, 2021

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1 Data

1.1 Data representation and accessibility

Is the data presented readily and accessible for inspection and analysis?

Yes, the data is readily available on ZENODO. The authors used standard file formats, such as shp, tiff and pdf.

Is the data set accessible via the given identifier?

No, the data set can not be accessed via "http://doi.org/10.5281/zenodo.40350338" from a standard browser and has therefore be searched manually in ZENODO. Why was no other more discipline-specific repository chosen, such as PANGAEA or OpenTopography to make the data more visible within the community ? Some data are provided on request, but such information is not given for the mesh (*.fbx) file. An explanation for this particular case would be helpful.

1.2 Data quality

Is the data set itself of high quality?

The quality of the DSM and the orthoimage mosaic is high due to the very high resolution. But the data set has some limitations (varying quality , blur), resulting from gaps in the original point cloud. Furthermore, the authors did not describe, why the provided products cover just a part of the volcano or the volcanic island. The overall accuracy of the DSM in z-direction might not be sufficient enough to analyse small changes in elevation due to shrinking, erosion or compaction in the range of mm to cm.

Does the claimed findings and its factors - individually and as a whole - are plausible and do not contain detectable faults?

Yes, the claimed findings are plausible. More details about the results would be helpful, such as the number of points of the point cloud or the spatial distribution of the point density.

Are there any inconsistencies within these, implausible assertions or data, or noticeable problems which would suggest the data are erroneous (or worse).

No, there are no inconsistencies, just missing information (see 3.1) *Are error estimates and sources of errors given (and discussed in the article)?*

Yes, there is an error estimation of the GCP accuracy provided in the article and some further details in the supplemented report. *If possible, apply tests (e.g. statistics)?*

The values in the table were checked visually.

Unusual formats or other circumstances which impede such tests in your discipline may raise suspicion.

There are no unusual formats.

1.3 Uniqueness

Are the data presented new?

Yes, the data are new for this particular region, but a lot of other investigations dealing with spatial analysis and remote sensing were performed in the same region. An overview map showing the outline of the former investigation areas would be extremely helpful for future users. Beside this, a simple, but well-structured table could be used to present the various details given between lines 71 and 94

Is it possible to replicate the experiment or observation on a routine basis?

It would not be possible to replicate exactly this data set on a routine base due to the unique weather and illumination conditions as well as the time efforts and costs.

Is a variable of the data set supposed or suspected to reflect changes in the Earth system?

Yes, the data set reflects the changes of the flank of the volcano. *Is it a cost-intensive data set which will not be replicated due to financial reasons?*

Yes, it is cost-intensive in terms of human resources, accessibility and weather conditions.

1.4 Usefulness

Is the data set usable in its current format and size?

Yes, the data set is usable in the provided format and size. *Is there any potential of the data being useful in the future?*

Yes, the data set could be used for morphological studies and for the comparison of different volcanic land forms, for mass estimations and for teaching purposes. Beside this, it could be utilized for the technical/ methodological comparison of different UAV approaches or photogrammetry software packages.

Would you be able to understand and (re-)use the data set in the future?

Yes, the data are easily to understand, because the main outcome is the well-known representation of elevation data (DSM). *It is plausible that the data, alone or in combination with other data sets, can be used in future interpretations, for the comparison to model output or to verify other experiments or observations?*

Yes, there are several opportunities to use the data alone or with other data sets. *Are other possible uses mentioned by the authors that can be considered?*
Yes, there are some applications mentioned, especially in the field of volcanology.

1.5 Completeness

Is the data set complete?

The answer of this questions depends on the definition of completeness. The file themselves are complete. But the mentioned UAV images, the point cloud (raw, ...) as well as the textured mesh(es) are not provided.

Does the data set contain all data, thus can be reviewed without unnecessary increase of workload for reuse in another context?

The currently available data set can be easily reused for several applications. In case of more quantitative or qualitative studies, further metadata about the processing steps and/or some of the other results are necessary.

Is the data set or collection split intentionally, for example, to increase the possible number of publications?

There are no obvious signs of intentional splitting of the data set.

1.6 Reproducibility

1.7 General comments

Is the data set significant - unique, useful, and complete?

The data set has a medium significance, is unique for this particular region and is useful for a number of applications. It can be rated as complete for more general studies, if just the DSM and the ortho-image mosaic are needed (visual morphological interpretations).

2 Standards and Metadata

Are the formal metadata appropriate?

There are no formal metadata provided. *Are common standards used for comparison?*

There are a few standards used, such as file formats.

3 Methods

3.1 Uniqueness

Is the method rated as new or improved?

In general, the described methods are not new. But the application of these methods in this region can be rated as new.

Are methods and materials described in sufficient detail?

No,whether methods nor materials are described in sufficient detail for these reasons:

- Please include a more clear description of the settings and steps performed for point cloud-generation as in the text just a lot of software-specific terms are listed.
- How did you avoid the bowl effect?
- Please replace the story-like writing style in some paragraphs
- Why are many important numbers and facts hidden in the text and not presented in tables or figures)
- Was the UAV equipped with an internal GPS?
- Which exact weather conditions occur per day and/or per flight?
- Which flight planning software was used?
- How large was the image overlap in both directions?
- Which coordinate system was used (just mentioned at the end of the publication)?
- Which reference services were used for the RTK?
- Why were the GCPs measured in 2017 and 2018, but not in 2016?
- Which pre-processing steps were performed on the images? (such us color correction, sharpening, selection)
- What is the total number of images? Could all images be used for the point-cloud creation?
- If yes, which selection criteria were applied?
- Was the point cloud clipped, cleaned, noise-reduced?
- What is the definition of a 2D and a 3D GCP?
- Which camera calibration was used?
- How did the authors fill the gaps of the point cloud or mesh?
- What about the 10cm DSM? It is just mentioned in the text, but seems to be one major outcome. How was it generated?

Are the accuracy, calibration, processing, etc. state of the art?

the description is not detailed enough to evaluate this question satisfactorily.

Does its claimed accuracy, the instrumentation employed, and methods of processing reflect the "state of the art" or "best practice"?

Yes, in general reflects the deployment of a fixed-wing UAV in concert with the PIX4D software one best practice option. *Are all theses claims and factors mutually consistent?*

Yes.

4 Publication

Is the article itself appropriate to support the publication of a data set?

In general, the article itself is appropriate to support the publication of the data set, but has some limitations. For instance, the authors did not mention possible disadvantages and potential errors of UAV surveys. This information could support the decisions of future users to select the best data set for their investigations. Furthermore, the text gives the impression that UAV surveys are a synonym for air-borne photogrammetry, which is not the case. The authors should differentiate in more detail, if the UAV campaigns in the cited publications were used for VIS photogrammetry or for other kinds of surveys, such as laser scanning or ash sampling. There is an ambiguity between the term "very high-resolution" in the title and the term "ultra high-resolution" in the text. Are these terms synonyms? Could just one be used? Parallel to this, the title is ambiguous. The phrase "terrain surveys" could describe any kind of spatial data acquisition in the field and describes two surveys. Why is the term UAV not mentioned?

In the abstract, the final products that are uploaded on ZENODO, are not clearly mentioned. Therefore, the abstract as well as the title give the impression that the 3D point-cloud, the textured 3D mesh and the images are available, too.

Very important details about the methods and the workflow are listed in the supplemented pdf-document. But this information should be the major content of a data publication. Otherwise, the future reader has to read at least two documents to gather all the relevant details.

*Does the article express clearly **what** has been found, **where**, **when**, and **how**?*

The description of the results (what), the location (where) and the timing (when) are sufficient, but there is information about the methods (how) missing (see other answers).

Is the overall structure of the article well structured and clear?

Most sections and paragraphs show a clear and common structure, apart from from those:

- Section 1: The introductory part on page 4 is a mixture of technical description and geological observations and facts. It makes it hard for the reader to separate the information and to compare or evaluate the mentioned campaigns
- Section 2:
  - The relevance of line 120 to 128 is not obvious.
- Section 3:
  - The paragraph starting with line 205 should be placed behind line 194 to merge the information about the depression.
- Section 3.1:

  - 249-250 - transfer to acknowledgments
  - 258-261 - redundant to 251-254
  - 274-282 - redundancy to previous paragraphs

- Section 3.3:
  - 298-305 - move to introduction

- Section 4.2:
  - 345-348 - transfer to methods
  - 354-357 - transfer to methods
  - It has in general a poor structure, which is a mixture of technical results and volcanic interpretation.
  - The definition of "quality zones" is still questionable.

- Section 4.5:
  - 431-433 - move to methods

Check the publication: Is the length of the article appropriate?

There is an imbalance between the general geographic, geologic and volcanic information on the one hand side and the description of the data and methods on the other side. Although the latter are the core information of the paper, it's not complete. Furthermore:

- Sections 1 and sections 2 are quite long.
- Section 4 (especially 4.1) is very short in comparison with other parts of the text. As the main outcome of the study - the point cloud - is the object of this part, more information should be provided.

Is the language consistent and precise?

In most parts of the text the language is consistent. There are just some typing mistakes (vulcanic - line 68, flow flow - line 41) and repeated usage of the same verb (conducted: 246-263). The word "kipukas" is mentioned at the beginning of the paragraph, but not explained. There are some "story-like" sentences, especially in 246-257 and 267-271 that could be expressed more formal.

Are figures and tables correct and of high quality?

The quality of the figures can be rated between good and medium. The coordinates of the maps are too small and hard to read. Some scales are not recognizable, and some maps could be enlarged to show more details. A lot of space is covered by quite large, but unimportant photographs. These recommendations could be used to improve the figures:

- Figure 1:
  - The space in the lower left corner is wasted.
  - There are no coordinates.
  - The outline of the mentioned eruption could be shown.
  - The resolution of the scales is poor.
  - Major locations (Bordaira, Boca Fonte) or geological features that are mentioned in the text are not presented, such as "the fissure", vents (line 204) or the depression itself.
  - The ocean around the island is invisible. Therefore, the reader needs an additional map to understand the investigation area fully.
  - I would like to recommend to replace figure 1 by two new maps - one that contains all the major geographical and technical locations and objects (and a small overview map with all Cap Verde islands) and a second one that shows the geology and the mentioned features.

- Figure 2:
  - The figure is not very helpful (too large, blurry).
  - It could be removed or improved by adding some explanatory lines and labels.
- Figure 3:
  - Add starting and landing points.
  - Colourize flights by days or weather conditions.
  - Add a legend to explain black line and points.
  - The figure could be the base for a technical map.
  - Add reference stations.
  - Add the GCPs listed in table 1.
  - Increase the size of the figure.
- Figure 4:
  - The figure is not very useful, because it includes just large pictures of men holding a pole.
- Figure 5:
  - The image is of low quality.
  - The location of this figure in a larger map is not clear (e.g. Figure 7).
  - Switch off the tie points for better visibility.
  - Provide some information about distances and dimensions.
- Figure 6:
  - The figure is quite small.
  - The sub figure B is not very informative.
- Figure 7:
  - Include the locations of figures 8, 9, 10, 11.
- Figure 8:
  - The contour lines are not very useful.
- Figure 9:
  - There are different representations of the sub figures, e.g. in B: contour lines and DSM, others just with contour lines.
  - The scale is hard to detect.
  - The sub figure C would be better without contour lines.
- Figure 10:
  - The figure is not very useful.
  - There are different representations of the sub figures of figures 8, 9, 10, 11, e.g. in B: contour lines and DSM.
- Figure 11:
  - Which areas are of low quality? Please mark them.
- Figure 12:
  - Please give explanations for the stripes in NW-SE direction.
  - Please add reasons for blurry patches (similar to low-quality areas?).

- Figure 13:
  - Some information about the direction could be added
  - Some points, places, features for reader's orientation would help a lot.
- Ideas and suggestions for additional or updated figures:
  - Add a schematic workflow showing the major processing steps.
  - Add an additional map: see details in paragraph 1.2.
  - Add a map of the interpreted, mapped lava types (could be included in a geological map).
  - Add some more technical figures from the report (pdf-document) or provide more references to the report.
- Tables:
  - The layout of the table is poor.
  - The landing positions on page 10 (number in text) could be added to a table or to figure 3.
  - Further comments see details in paragraph 1.2 (additional figure).

Are mathematical formulae, abbreviations, and units correctly defined and used?

The units should be presented in a correct way (km^2 instead of km2). The differences in the number of decimal places of the same quantity imply different levels of accuracy. The style of the larger numbers (with or without separation) is not homogeneous (e.g. in line 181 versus line 185).

Are any references/citations to other data sets or articles missing or inappropriate?

In the cited publication of Richter et al. (2016), TLS and photogrammetry was used. Did those authors produce comparable products? Further details are missing to compare those results with the recent ones (quality, resolution?).

4.1 General comments

Is the data set publication, as submitted of high quality?

The current version of the publication is rated as "medium", as several details of the methods and workflow are missing and the quality of figures and tables needs to be improved. At the moment, the reader needs time to compile all relevant data for a comprehensive comparison, evaluation and usage of the data.

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REPLY TO REVIEWER 3

Dear Dr Moritz Kirsch,

Thank you very much for the detailed review, comments and suggestions of our manuscript on the "Very high-resolution terrain surveys of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde) submitted to ESSD.

We hope that with the significant changes we have made to the manuscript, following your comments, but also integrating the comments from other three reviewers and from the public discussion, the manuscript is now in good shape to be accepted for publication in ESSD.

The manuscript has been substantially edited and the main changes were the following:

- The title was modified in order to make clear the type of survey and the use of UAV.
- The abstract was improved to clarify the methods and the objectives, as well as the potential applications of the data set.
- The introduction is now shorter and more focussed on the significance of the dataset, supported by a clearer motivation and objectives. A very brief review of the applications of UAV-based surveys is presented. We have completely removed the previous section 2 on the applications of UAVs to volcanic areas, as suggested by several referees.
- The section 2 (Study area) is more concise now.
- A new section 3 on the volcanic activity of 2014-15 and previous digital elevation models was added. This section includes a more concise review of the last eruptive event and a more detailed review of the existing DEMs and their characteristics, as requested.
- The section 4 (Methods) was substantially improved with a more detailed description of the procedures and inclusion of tables with data and a new figure with the workflow. We have also improved the description of the procedures followed to generate the point cloud and the DSM. The figures were improved and several new ones with the inclusion of survey details, have been added. We have clarified the procedures used to evaluate the model accuracy, including the ones based on the visual inspection of the DSM to delineate its quality zones. A better description of the lava flow delineation procedure was also included, supported by an example in a figure.
- The section 5 (Results) presents more details on the evaluation of the quality of the data set, with a much more in depth analysis of the quality of the point cloud, as well as with quantitative measures of DSM quality.

- The figures throughout the manuscript were significantly improved and some were removed, following suggestions by referees. New figures allowing to improve the data set characterization and the evaluation of its accuracy have been added.
- The dataset made available in Zenodo now includes all the aerial photos, as well as the 10 cm DSM and orthomosaic, as required by some reviewers.

In what concerns to your overview of the manuscript, our revision of the text includes now details on the objectives, which are the identification of small-scale geomorphic features below c. 50 cm, as well as improving the existing 1 m pixel DEM. The section 3 on the methods was fully rewritten and provides more details. In section 4, we have clarified issues associated with the evaluation of point cloud and DSM quality, also following several of your suggestions, after also revisiting James' et al papers. A better description of the lava flow delineation procedure was included in section 3.5. We have also made available the full data set, very high resolution point cloud, 10 and 25 cm DSM and orthomosaic and have included all the aerial photos, as well as GCP coordinates.
Finally, we have also introduced your suggestions and replied accordingly in the the RC3-supplement-commentGV.pdf file made available in the public discussion. You may also find the new version of the manuscript attached, as well as one with track changes.

Our sincere thanks for the time you have put into this review.

Best wishes,

Gonçalo Vieira

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Open Access Earth System Science Data Discussions

Very high-resolution terrain surveys of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde)

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Abstract. Fogo in the Cape Verde archipelago off Western Africa is one of the most prominent and active ocean island volcanoes on Earth, posing an important hazard to both local populations and at a regional level. The last eruption took place between 23 November 2014 and 8 February 2015 in the Chã das Caldeiras area at an elevation close to 1,800 m above sea level The eruptive episode gave origin to extensive lava flows that almost fully destroyed the settlements of Bangaeira, Portela and Ilhéu de Losna. In December 2016 a survey of the Chã das Caldeiras area was conducted using a fixed-wing unmanned aerial vehicle and RTK GNSS, with the objective of improving the mapping accuracy derived from satellite platforms. The main result is an ultra-high resolution 3D point cloud with a Root Mean Square Error of 0.08 m in X, 0.11 m in Y and 0.12 m in Z, which provides unprecedented accuracy. The survey covers an area of 23. 9 km2 and used 2909 calibrated images with an average ground sampling distance of 7.2 cm. A digital surface model and an orthomosaic with 25 cm resolution are provided, together with elevation contours with an equidistance of 50 cm and a 3D texture mesh for visualization purposes. The delineation of the 2014-15 lava flows shows an area of 4.53 km2 by lava, which is smaller but more accurate than the previous estimates from 4.8 to 4.97 km2. The difference in the calculated area, when compared to previously reported values, is due to a more detailed mapping of flow geometry and the exclusion of the areas corresponding to kīpukas. Our study provides an ultra high-resolution dataset of the areas affected by Fogo's latest eruption – crucial for local planning – and provides a case study to determine the advantages of ultra high-resolution UAV surveys in disaster-prone areas. The dataset is available for download at http://doi.org/10.5281/zenodo.4035038 (Vieira et al., 2020).

1. Introduction

Detailed knowledge on volcanic eruptions, their products, evolution and impacts is of paramount importance for volcanic hazard assessments and to advance our capability to forecast the likely behaviour of future eruptions. Volcanic eruptions may incur in considerable loss of life and lasting damage to infrastructures, particularly on Small Developing Island States

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like Cape Verde, where volcanic eruptions are likely to have disproportionate impacts, on account of their more limited resources and geographical isolation (Komorowski et al., 2016). Accordingly, solid and realistic volcanic hazard assessments in such areas, more than in any other settings, greatly benefit from very-high resolution datasets from which detailed volcanological, geophysical, and environmental parameters can be inferred. In particular, very high-resolution digital terrain datasets of recently erupted lava-flow fields, may provide rapidly produced topographical datasets that can also be used to plan mitigation and reconstruction strategies, as well as the opening of vital new communication infrastructures. The usefulness of such datasets is greatly enhanced when these datasets are freely available to governmental agencies, decision-making bodies and the scientific community alike. In line with this vision, in this paper we report and make available a recently acquired very high-resolution digital surface model and orthomosaic of the lava flow-flow field created during the 2014-15 eruption of Fogo volcano in Cape Verde.

Fogo in the Cape Verde Archipelago off Western Africa is one of the most prominent and active ocean island volcanoes on Earth, posing an important hazard to both local populations and at a regional level (Day et al., 1999; Heleno da Silva et al., 1999; Ramalho et al., 2015; Eisele et al., 2015; Jenkins et al. 2017). Crucially, Fogo is the site of recurring volcanic activity, with a record of at least 27 historical eruptions since the island was discovered in the mid-fifteenth century, yielding a mean recurrence interval between eruptions of approximately 19.8 years, with individual intervals ranging from 1 to 94 years (Ribeiro, 1954; Torres et al., 1998; Day et al., 1999; Mata et al., 2017). The latest events occurred in 1995 and in 2014-15, both of which extruded extensive lava flow fields at the Chã das Caldeiras, a summit depression lying at an elevation of approximately 1800 m above mean sea level. Effectively, the settlements of Bangaeira, Portela and Ilhéu de Losna located in Chã das Caldeiras were almost fully destroyed in the 2014-15 eruption (Fig. 1). With a population of about 1200 inhabitants prior to the eruption, the local economy was based in agriculture (mainly wine and fruit orchards), grazing, and tourism. Fortunately, there were no casualties.

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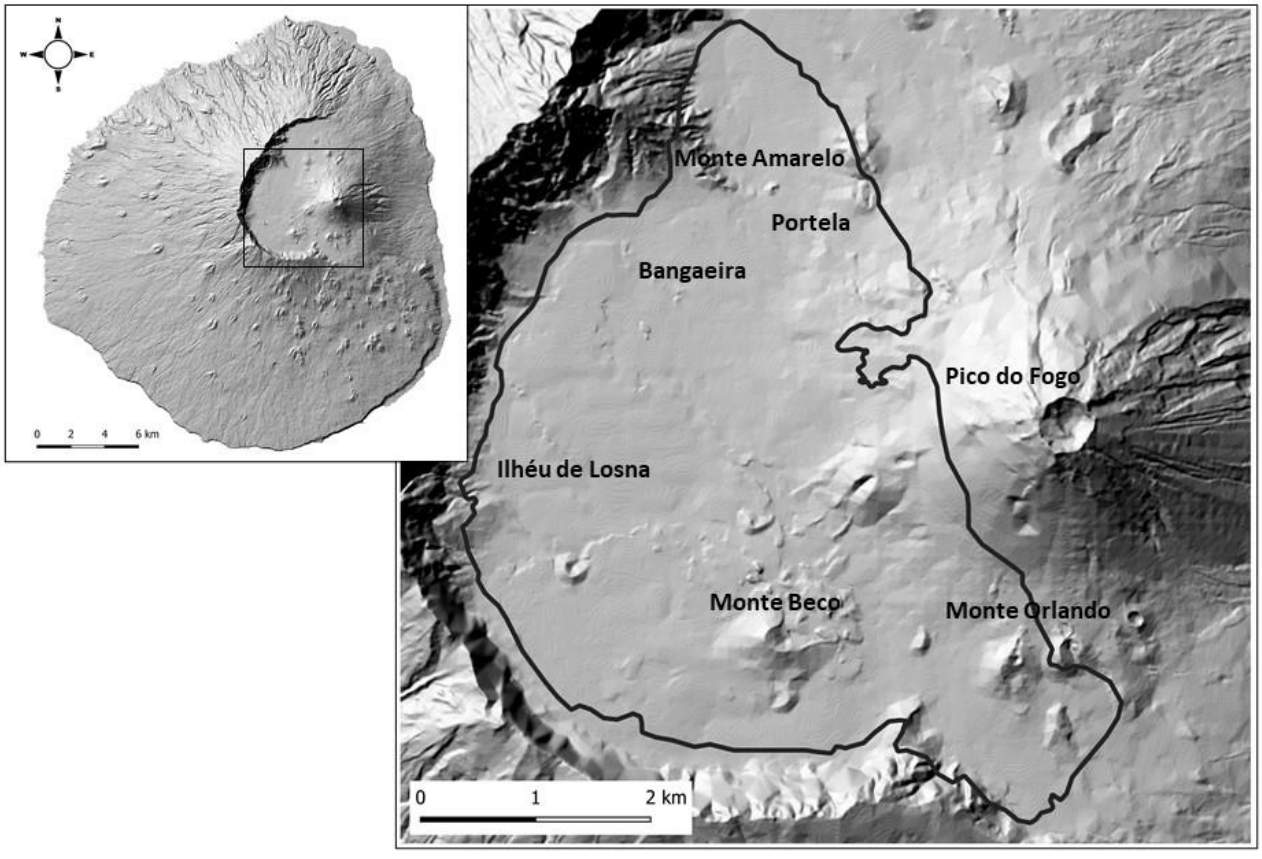

Figure 1 – Location of the Chã das Caldeiras and of the surveyed area (black line) in Fogo Island (Cape Verde). Shaded relief derived from the DEMFI (2010) 5 m DEM.

The latest eruption started on the 23rd November 2014 and lasted until the 8th February 2015, with magma being erupted from a 700 m-long NE–SW trending eruptive fissure located on the SE flank of the previous 1995 crater row, on the SW flank of Pico do Fogo (Vieira et al., 2016; Mata et al., 2017). Reportedly, the eruption started with vigorous fire-fountain activity, which quickly evolved to a more explosive strombolian style, forming a crater row roughly parallel to the 1995 fissure. Later, the eruption was characterized by simultaneous or alternating hawaiian, strombolian and vulcanian eruptive styles (from the different craters of the fissure) lasting for several days, and by an almost constant emission of lava flows from the lowermost terminus of the vent (Mata et al., 2017). These formed two initial thick ‘a'ā flow lobes: the first advanced towards the southwest and eventually stalled after 1.7 km, at the foot of the caldera wall; the second progressed intermittently 3 km to the northeast, towards the village of Portela, razing a large portion of this settlement (Mata et al. 2017; Jenkins et al., 2017). During the later stages of the eruption, however, this flow lobe was reactivated, producing more fluid

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ʻa'ā and pāhoehoe breakouts to the west and north, the latter of which destroyed most of what was left of the Portela settlement and descended to the village of Bangaeira, causing widespread destruction there (Mata et al. 2017; Jenkins et al., 2017). The resulting lava flow field affected an area of ci. 4.8 km2, with extruded volumes estimated at ~45 × 106 m3 (Bagnardi et al., 2016; Richter et al., 2016; Cappello et al. 2016).

Remote sensing techniques have been used by several authors to study the Fogo eruption of 2014-15. Capello et al. (2016) used the HOTSAT satellite thermal monitoring system for the analysis of MODIS and SEVIRI data for the location of the hotspot, lava thermal flux, and effusion rate estimation. To forecast lava flow hazards during the 2014-15 Fogo eruption they used the MAGFLOW model. Validation of numerical simulations was done using Landsat 8 OLI and EO-1 ALI images and field observations. Bargnardi et al. (2016) used very high-resolution tri-stereo optical imagery acquired by the Pleiades-1 satellite constellation and generated a 1 m resolution digital elevation model (DEM) of the Fogo Volcano. From the Pleiades-1 post-eruption topography they subtracted the heights from a pre-eruption DEM, that was obtained using spaceborne synthetic aperture radar (SAR) data from the TanDEM-X mission. To measure the subsidence of the lava flow field, they used Sentinel-1 for interferometry. Height differences between the post-eruptive Pleiades-1 DEM and the pre-eruptive topography from TanDEM-X show a lava volume of 45.83 ± 0.02 × 106 m3, emplaced over an area of 4.8 km2 at a mean rate of 6.8 m3/s. Richter et al. (2016) did lava flow simulations based on field topographic mapping and satellite remote sensing analysis. They produced a topographic model of the 2014-15 lava flows from combined Terrestrial Laser Scanner (TLS) and photogrammetric data. The pre-eruptive DEM used was 5 m/pixel and was generated from the contours based on photogrammetric data. They estimated a lava flow volume of 43.7 ± 5.2 x 106 m3. TerraSAR-X imagery was used to access the lava flow model performance. The authors point out the need of having up-to-date topographic information because lava flow hazards change as result of topography modifications.

More recent, Bignami et al. (2020) used a combined method of 21 images from Sentinel-1, COSMO-SkyMed, Landsat 8, and Earth-Observing-1 missions from November 2014 to January 2015, to retrieve lava flow patterns. They applied an automatic change detection technique for estimating the lava field and its temporal evolution, combining the SAR intensity and the interferometric SAR coherence. Results showed a SW-NE oriented dyke, located inside Chã das Caldeiras, SW of the Pico do Fogo, as reported by Gonzalez et al. (2015). The area coverage of the lava flow obtained by visual analysis (L8 and EO-1) was estimated at 4.97 km2 as in Cappello et al. (2016), very close to the 4.8 km2 estimated by Bagnardi et al. (2016), and the 4.85 km2 estimated using Terrestrial Laser Scanner (TLS) combined with structure from motion data by Richter et al. (2016).

Several papers have been published on the latest eruption of the Fogo volcano, e.g. focusing on the variation of land surface temperatures during the eruption (Vieira et al., 2016), on lava geochemistry and small-scale mantle heterogeneity (Mata et al., 2017), mineralogy and geochemistry of incrustations (Silva et al., 2019), conduit dynamics and surface deformation (Gonzalez et al. 2015), on lava flow mapping and volume estimates (Bargnardi et al. 2016; Bignami et al., 2020), and lava flow hazards (Richter et al., 2016; Cappello et al. 2016; Jenkins et al., 2017).

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In the remit of the project FIRE (Fogo Island volcano: multidisciplinary Research on 2014/15 Eruption, funded by FCT-Portugal), an extensive survey using a survey-grade unmanned aerial vehicle (UAV) was conducted in December 2016 with the purpose of generating a very high resolution digital elevation model (DEM) and orthomosaic of the lava field to be used as baseline data for assessment of the eruption impacts, support to geological mapping and studies of the lava flow field, as well as for modelling lava flow dynamics. A study commissioned by the United Nations Development Program in Cape Verde stresses that an improvement in the assessment of hazards on the island of Fogo can only be achieved from a detailed analysis and the modelling of the lava flow (Fonseca et al., 2014). The data presented here is the result of that campaign and is the most detailed and updated survey of the area, with an ultra-high resolution digital surface model (DSM) that is essentially a DEM in most of the area due to the overall lack of vegetation and scarce number of buildings, and a digital orthomosaic.

2. Application of UAVs to volcanic areas

Digital elevation models and the dissemination of Geographical Information Systems have changed the way the terrain is characterized, analysed, monitored and modelled, especially since the 1990's. DEMs have been produced from dense collections of topographical points, manned aircraft photogrammetry, digitizing of topographic maps (Stevens et al., 1999), satellite remote sensing (Baldi et al., 2002; Kerle, 2002; Diefenbach et al., 2013), light detection and ranging - LiDAR (Mouginis-Mark and Garbeil, 2005; Mazzarini et al., 2007; Favalli et al., 2009; Fornaciai et al., 2010), radar interferometry (InSAR) (Rowland et al., 1999; Poland, 2014). Since the mid-2010's, with the technological developments and decreasing cost of unmanned aerial vehicles, accompanied by the development of photogrammetry software and computing power, a revolution took place. Very accurate and high quality DEMs became increasing available, leading to the possibility to easily achieve centimetric to decimetric resolution, even in large areas. The number of UAV-based surveys have been increasing steadily but many of them stay stored in the producers or client computers and are not of open-access.

UAVs have had various applications, such as ~~for~~ wildlife recognition (e.g. Christiansen et al., 2014; Wang et al., 2019), agriculture (e.g. Hassan-Esfahani et al., 2015, Kattenborn et al. 2014; Hasseler and Baysal-Gurel, 2019), urban and civil engineering (Westfeld et al., 2015), archaeology (Campana 2017; Risbøl and Gustavsen 2018), coastal dynamics (Chikhradze et al 2015; Brunier et al 2016; Turner et al 2017; Long et al 2016), climatology (Lindgren et al 2015; Bühler et al 2016), geomorphology (Lucieer, et al 2014; Dabski et al. 2020), vegetation in Polar regions (Mora et al 2015, Miranda et al 2020), glacier monitoring (Benoit et al 2019; Jouvet et al 2020) or ~~for~~ monitoring volcanic systems (Chio and Lin, 2017; Thiele et al., 2017).

Applications of UAV surveys ~~to research~~ in the Earth and Atmosphere sciences are relatively recent, having begun to emerge with greater expression from 2014 (Colomina and Molina 2014; Pajares 2015). Since then the number of publications has grown rapidly and spread across research fields, developing into a technique allowing fast and low-cost access to high spatial resolution data (Gomez and Purdie, 2016). The high versatility and possibilities of surveying even

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rough terrains of difficult access, such as the situation of volcanic eruptions, make UAVs a powerful tool to acquire real-time or near-real-time data on processes that often cannot be observed by naked eye (Di Felice et al 2018). Hence UAVs are increasingly used in situations of risk where it is essential to make the rapid terrain recognition following natural disasters (Gomez and Purdie 2016). Software and computing power have evolved very fast in last decade and the application of advanced photogrammetry algorithms involving image matching and structure from motion started to allow facilitated production of high-quality digital surface models and orthophoto maps. The collection of accurate GNSS ground control points allows to generate these products with centimetre resolution and accuracy (Favalli et al 2018). The recent development of RTK UAVs allows for even faster workflows in the terrain and to produce highly accurate models.

Photogrammetry techniques have been widely applied to study detailed changes in the morphology and structures of volcanos, like Mount St. Helens, the Colima and the Merapi (Major et al., 2009; Walter et al., 2013; Salzer et al., 2016). Optical and thermal cameras transported on UAVs have been used for identifying meter to sub-meter topography changes and for the detection of thermal anomalies (Nakano et al., 2014; Thiele et al., 2017; Nakano et al., 2014; Müller et al., 2017; Amici et al., 2013; Di Felice et al 2018). In addition, specific payload sensors are being used for measuring volcanic gas fluxes (McGonigle et al., 2008; Liu et al. 2019; de Moor et al., 2019), gas sampling (Mori et al., 2016; Rüdiger et al., 2018; Stix et al., 2018) and sediment sampling (Yajima et al., 2014).

Various studies have shown the potential of UAV-based surveying in volcanic terrains. These show the potential of the survey produced at Fogo, not only for characterizing post-eruption changes, but also providing baseline data for analysing the dynamics of the lava flow fields upon cooling, or the soil erosion and even human reoccupation of the area. As examples of UAV-based mapping, at the Nishinoshima Volcano, Nakano et al (2014) have acquired visible imagery to produce 3D maps allowing to monitor the evolution of the volcano. Darmawan et al. (2018) studied morphological and structural changes from 2012 to 2015 at the Merapi lava dome having identified the locations of steam-driven explosions. Felice et al. (2018) surveyed the erupting crater of Indonesian Lusi mud eruption as is was spewing boiling mud, water, aqueous vapour, CO2, CH4. Favalli et al. (2018) generated a high spatial resolution digital terrain model and orthomosaic of Mount Etna's January–February 1974 lava flow field, allowing the analysis of the morphology of sub-meter features, such as folds, blocks, and cracks, over kilometre-scale areas. The 3-cm orthomosaic allowed the analysis of centimetre-scale grain size distribution of the lava surface. Müller et al. (2017) studied the 2014-15 fissure eruptions of the Holuhraun to investigate the link between magma dikes at depth and the association with elastic and inelastic surface deformation. Turner et al (2017) during the 2014–15 Pāhoa crisis, used a UAV to monitor the front of a slowly advancing pāhoehoe lava flow. UAV surveys allowed Bonali et al. (2019) to study volcano-tectonics and tectonic features in an active Icelandic rift with unprecedent detail in extended areas in a much faster way and much lesser funds with respect to traditional field activity. One of the first UAV surveys during an ongoing eruption was performed by De Beni et al. (2019) in the 27 February–02 March 2017 event of Mt. Etna, which allowed improving the monitoring quality of the lava flow in terms of timeliness and detail. The independent acquisition of both visible and thermal infrared imagery by a pair of UAV in Stromboli allowed Wakeford et al. (2019) to build a 3D photogrammetric model of an active volcano. Finally, a recent summary about the use of small UAV

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for collecting immediate and real-time aerial data in volcanic environments during and after an eruption is provided by Jordan (2019), highlighting its advantages for mapping, sample collection, thermal imaging, magnetic surveys, slope stability studies, and also as platforms for carrying outgassing measurement sensors.

3. The study area and the volcanic activity of 2014-15

The island of Fogo is one of ten islands of Cape Verde, an archipelago located off the west African coast, about 600 km from Senegal. The Cape Verdes are regarded as the type-example of a volcanic archipelago formed in a stationary plate environment relatively to its hotspot, which probably explains the arcuate distribution of its islands (Burke & Wilson 1972; Lodge and Helffrich, 2006; Ramalho et al., 2010a, 2010b, 2010c; Ramalho, 2011). In more detail, this arcuate geometry is defined by two island chains: a "northern", from São Nicolau to Santo Antão, and a "eastern-to-southern", from Sal to Brava. There is no evident hotspot track but there is a morphological suggestion of an age progression in the "eastern-to-southern chain", from east (oldest islands) to west (youngest islands), which is supported by ages of the oldest exposed lithologies (see Ramalho, 2011). Fogo is located close to the southern terminus of this latter chain and is the only island in the archipelago with historical (i.e. last 500 years) eruptions (Bebiano, 1932; Ribeiro, 1954; Machado, 1965; Day et al., 1999; Faria and Fonseca, 2014).

Fogo is a large ocean island volcano showing a conical shape with a diameter of about 30 km (at sea level) and rising to an elevation of 2829 m, approximately 7 km above the surrounding seafloor. Structurally, the island is a compound volcano, featuring a "somma-vesuvio" association, with a younger stratovolcano – Pico do Fogo – rising from the central depression – Chã das Caldeiras – of an older collapsed volcano, sometimes referred as Monte Amarelo (Ribeiro, 1954; Day et al., 1999). This depression, however, is open to the east, being limited in the remaining three sides by a horseshoe shaped steep rock wall, over 1,000 m high, called Bordeira. This morphology, in turn, is either interpreted as a gravitational collapse headwall (Day et al., 1999; Paris et al., 2011) or as volcanic caldera walls, whose eastern portion later experienced a gravitational flank failure (Torres et al., 1998; Brum da Silveira et al., 1997a, 1997b; Madeira et al., 2008). Notwithstanding the different interpretations for the origins of this summit depression, it is clear that the opening to the east resulted from a massive flank failure of the flank of the volcano. Effectively, marine geophysical surveys undertaken off Fogo revealed the presence of voluminous submarine debris avalanche deposits extending offshore into the channel between Fogo and Santiago, and into the seafloor south and north of these islands, thus attesting the occurrence of this collapse (Le Bas et al., 2007; Masson et al., 2008; Barrett et al., 2019b). Moreover, field evidence attesting to the impact of a megatsunami triggered by Fogo's flank failure has been documented in the neighbouring islands of Santiago (Paris et al., 2011, 2018; Ramalho et al., 2015) and Maio (Madeira et al., 2020), confirming the catastrophic nature of the collapse and suggesting a 65-84 ka age for this event.

Pico do Fogo, currently the highest point in the island (2829 m in elevation), is a large and roughly symmetrical strato-cone that grew on top of the collapse scar, partially infilling this feature (Ribeiro, 1954; Torres et al., 1997; Brum da Silveira et al., 1997a, 1997b; Day et al., 1999). The sheer volume of this volcanic edifice is a testimony to the vigorous eruptive activity

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taking place at Fogo Island. There have been suggestions that Pico do Fogo experienced summit eruptions as late as the 18th century (Day et al., 1999), however this seems to be contradicted by the stratigraphic sequence at the summit, which exhibits mostly altered volcanic successions. Effectively, historical records suggest that all historic eruptions were extruded from adventitious vents localised at the base and lower flanks of Pico do Fogo, or at Chã das Caldeiras and the eastern flank of the island, in the periphery of this strato-cone (Ribeiro, 1954; Torres et al., 1997; Brum da Silveira et al., 1997a, 1997b). This is the case of the 1951, 1995, and 2014-15 eruptions, which vents were located in the NW, SW and S flanks of Pico do Fogo, close to its base at Chã das Caldeiras.

Chã das Caldeiras (Fig. 2) is thus a lava-infilled high-altitude summit depression, which resulted from the gradual accumulation and ponding of lava flows (and pyroclasts) erupted from Pico do Fogo and its adventitious/satellite cones, against the vertical walls of Bordeira. Morphologically, Chã can be divided in two large semi-circular sectors: a southern, larger, with approximately 3 km of radius, and with an elevation of 1780 m, and a northern, with a shorter radius of approximately 1 km, and with a mean elevation of 1650 m. These two sectors, which are roughly separated by the prominent Monte Amarelo spur, have been interpreted as two coalescent volcanic calderas by Torres et al. (1997), Brum da Silveira et al. (1997a, 1997b), and Madeira et al. (2008). Chã das Caldeiras is a generally flat landscape, punctuated by a few volcanic cones and extensively covered by ‘a'ā and pāhoehoe lava flows and ash and lapilli deposits, which make it very irregular in detail and a challenging terrain for mapping. In particular, the extensive ‘a'ā lava flow lobes of the 2014-15, 1995 and 1951 eruptions covered large portions of Chã, resulting in large swaths of virtually inaccessible rocky surfaces, given their extreme roughness. Hummocky landscapes also exist, generally corresponding to older ‘a'ā lava flow fields with scattered large rafted blocks of spatter sequences in its surface (resulting from the gravitational collapse of strombolian cones and subsequent transport by lava flows), which are now partially buried under a blanket of lapilli and ash that smoothed the surface. A good example of such surfaces can be found to the east and particular to the west of the Monte Beco cone, being genetically associated to this vent. The foot and slopes of Pico do Fogo, in contrast, are extensively covered by a thick blanket of lapilli and ash, conferring a very smooth and uniform conical surface. Despite this cover, fanned leveed channelled morphologies can also be recognized at the foot of Pico do Fogo, corresponding to buried lava flow fans and alluvial fans. Overall, vegetation is scarce and is mostly confined to the surfaces of talus accumulated at the foot of Bordeira, where a thin soil exists, or to some scattered vineyards along some ash-covered slopes.

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Figure 2 – The Chã das Caldeiras and Pico do Fogo during the 2014-15 eruption. View towards the southeast with the ‘a'ā lava flows of 2014-15 in the foreground.

Human settlement at Chã das Caldeiras started towards the end of the 19th century (Ribeiro, 1954). Chã, as a high-altitude depression, is cooler and more humid than the rest of the island, with frequent fog condensation and occasional frosts, providing ideal conditions for the planting of orchards and vineyards. Attracted by the prospect of a more prosperous agriculture, people gradually settled Chã, mostly in the vicinities of Monte Amarelo, where some water springs and enhanced but ephemeral flow (from the larger canyons draining Bordeira) allowed easier access to water. Here they established the settlements of Portela, Boca Fonte, and later Bangaeira, which slowly and gradually grew in size until the 1995 eruption, when Boca Fonte was all but destroyed and the main access road to these settlements was blocked by the advancing flows (the 1951 eruption, although of a higher magnitude, had a lower impact in these settlements; Jenkins et al., 2016). After the 1995 eruption, however, the prospect of an additional income provided by a burgeoning wine industry and the rapidly growing flow of tourists that came to see the volcano, fuelled the rapid growth of Portela and Bangaeira, with population reaching as much as ~1500 resident inhabitants by 2014 (Fonseca et al., 2014; Jenkins et al., 2016). The 2014/2015 eruption, in contrast, had a profound impact in these villages, given that the advancing lava flows either razed or

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buried up to 90% of the existing buildings, as well as covered large swaths of the adjacent agricultural land. Gradually, however, reconstruction is taking place, either through new constructions over the recent lava flows, or by the painstaking reclamation of lava-buried but structurally intact buildings.

3. Methods

3.1 UAV Surveying

The field campaign was conducted about 20 months after the end of the eruption of 2014-15, when the lava flows had already cooled substantially, but with the occupation of the few houses existing at the Chã das Caldeiras, being forbidden and still hazardous, mainly due to gas emissions. Hence, the field team stayed at the village of São Filipe and travelled daily to the survey area. The expertise of the team on local conditions, geology and logistics and cooperation with the Cape Verde authorities, greatly facilitated the success of the mission.

The main challenges to overcome were i. the weather, which in December frequently shows high winds and low visibility (clouds) in the Chã das Caldeiras, ii. finding good landing sites for the UAV, iii. coping with the 1000 m high vertical rock wall of the Bordeira and with its possible influence on the positioning and communications system of the UAV, and iv. collecting enough high-quality ground control points.

The survey of the Chã das Caldeiras area was conducted from 12 to 16 December 2016 with a field team of 4 members. Two members focussed on conducting the UAV flights and the other two on the collecting ground control points. Communications among team members were done using VHF radios.

The weather during the campaign was excellent with clear skies and no wind in the first days, but deteriorated towards the end of the week, with clouds entering the survey area and affecting initially the illumination conditions and even limiting the flights in the last two days. This has affected the quality of the orthomosaic, which shows illumination artefacts in the northern part of the Chã das Caldeiras.

The survey was conducted using a professional survey-grade fixed-wing UAV SenseFly eBee classic, which has a structure of expanded polypropylene (EPP) foam, with carbon and composite parts. It has a 96 cm wingspan and under 0.7 kg take-off weight, which when disassembled allows for lightweight packing. This model allows for flights with wind speeds up to 45 km/h, flight durations of up to 50 min and a radio link distance up to 3 km. Two cameras were used: a Canon G9X 16MP in the initial flights, which had a critical failure, and a backup Canon IXUS 12 MP which was used subsequently.

Take-off with the eBee is performed by hand, which facilitates selecting the location, but landing is done normally in fully automatic mode needing several tens of meters of approach area, and a smooth landing surface in order not to damage the EPP UAV body. This was a significant limitation to the survey, since the area of the Chã das Caldeiras is mostly covered by very rough lava surfaces, with scarce smooth ash and lapilli cover sites, which are normally far apart. Given these constraints, five sites allowing for good landing conditions were selected: (i) 14.93477º N, 24.35407º W, (ii) 14.928092º N,

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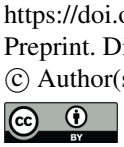

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24.353165º W, (iii) 14.92339º N, 24.356605º W, (iv) 14.9334999º N, 24.3722831º W and, (v) 14.962204º N, 24.3690256º W.

The survey consisted of 20 flights that do not show the ideal spatial setup nor homogenous illumination conditions in the resulting aerial photos, but it was the best solution given the logistical constraints. This was due to the following problems: sparse location of the take-off and landing sites, changes in wind-speed affecting power consumption, unexpected cloud advection and low visibility during some days, duration of daylight, fast changing shadowing effect from the Bordeira rock wall and by Pico do Fogo, battery limitations (due to heat, high risk of damaging the UAV in case of a need to crash land over lava flow, we decided not to conduct flight of over 30 min), long-distances to move between landing sites, these resulting on the need for constant on-site modifications of the original flight planning. The average flight elevation above the ground was 190 m, resulting on an average ground sampling distance of 6 cm, over 2,900 aerial photos and a total surveyed area of 24 km2 (Fig. 3).

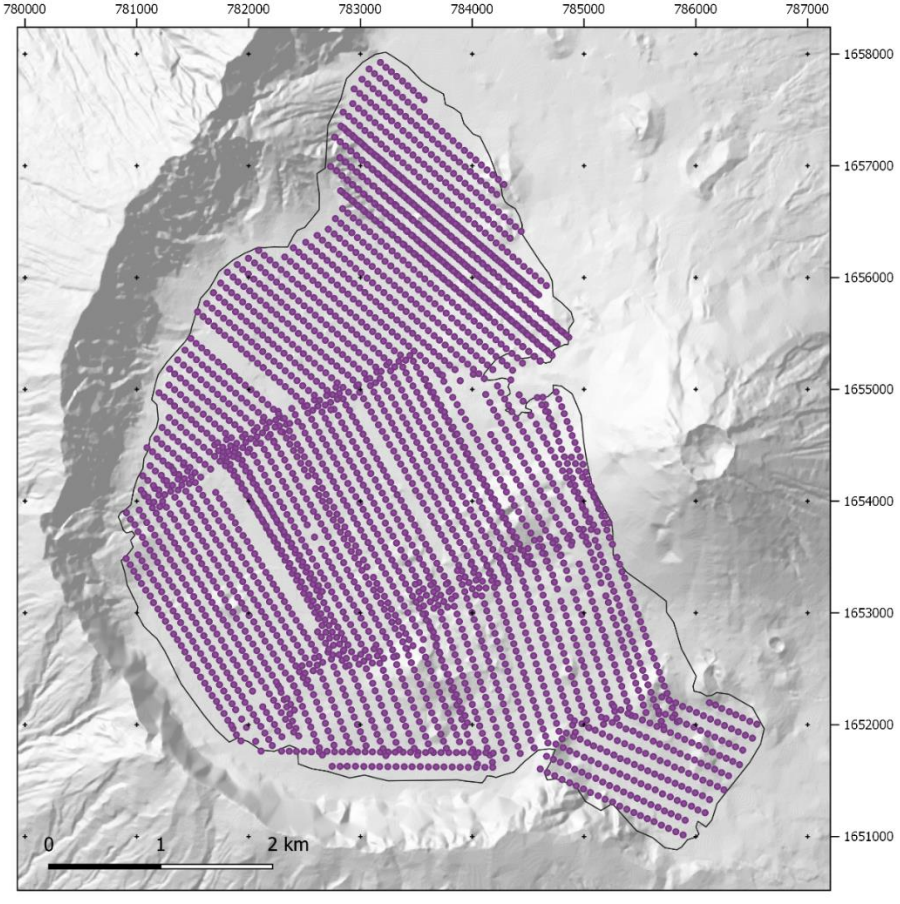

Figure 3 – Aerial survey of the Chã das Caldeiras with the geolocation of the photographs, Shaded relief derived from the DEMFI (2010) 5 m DEM.

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3.2 Ground control points

Coordinates of ground control points (GCPs) were measured at markers distributed in the field prior to the survey and at easy identifiable points, such as large boulders and building edges. The measurements were obtained using a Leica Viva (GS08) GNSS with base stations located at known coordinate sites (Monte Beco and Monte Amarelo) and a rover for surveying in RTK mode during the field surveys in December 2018. Extra GCPs were collected in February 2017 in small boulders selected in the preliminary orthophoto mosaic, in order to improve georeferencing quality. The accuracy of the GCP coordinates is of about 3 cm.

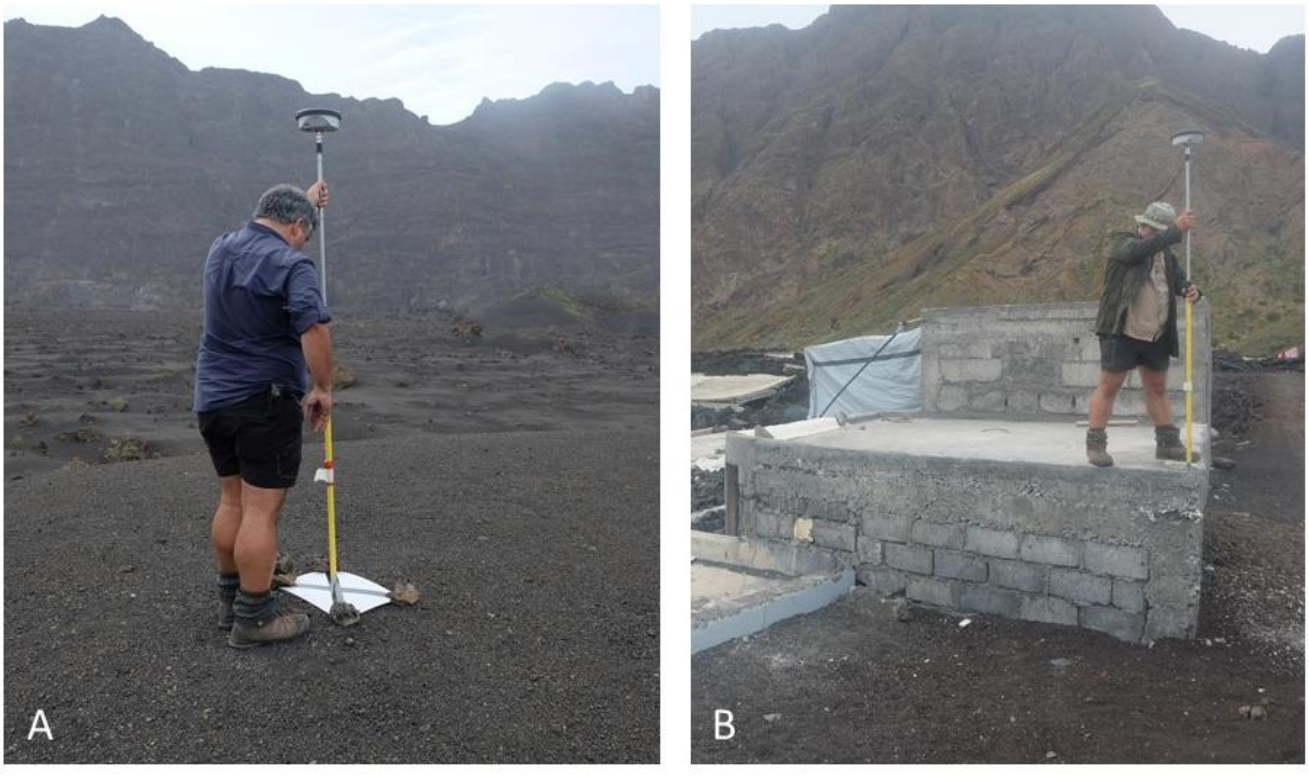

Figure 4 – Ground control point collection with RTK GNSS. A. Using markers, B. Using existing points.

3.3 Point cloud, orthophoto mosaic and digital surface model

Aerial image processing was done using Pix4Dmapper 4.5.6, a commercial software based on automatic feature detection, image matching and modelling using structure from motion (SfM) algorithms. This process developed in the 1990s, results from the application of algorithms by automatic feature-matching. The SfM operates according to the basic

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principles of stereoscopic photogrammetry, in which a 3D structure results from a series of 2D image overlays taken in motion to an object. The geometry of the images, position and orientation of the camera are calculated automatically without the need for a priori indication. Decisions are made simultaneously based on an iterative adjustment of package images, and the structures are automatically extracted from several overlapping images and the points are searched from image to image allowing the estimation of the coordinates of the objects. The 3D point clouds are generated in an image-space coordinate system and are transformed into an absolute real-world object-space coordinate system. The transformation is achieved by using 3D functions based on a relatively small number of GCPs (Westoby et al. 2012; Smith et al. 2016).

The models that we have developed have used 2909 calibrated images with an average ground sampling distance of 7.17 cm and a total area covered of 23.89 km². The camera optimization resulted in a 0.35% difference between the initial and optimized internal camera parameters. The images showed a median of 49521 key points per image and a median of 22632 matches per calibrated image. The large number of flights, large area and different illumination conditions led us to do separate processing and georeferencing of flights, with iterative project merging until the final model was obtained. In this process, we have used a total of 37 3D and 3 2D GCPs measured in the terrain. In order to improve the matching, 696 manual tie points were included, especially in areas covered by pyroclasts (lapilli and ash).

The point cloud was processed using full image scale, matching of image pairs using the aerial grid/corridor model and geometrically verified matching using automatic advanced key points extraction. The advanced camera calibration was done using the alternative method, internal parameters optimization (all), external parameters optimization (all) and no automatic rematch. The point cloud densification was done using multiscale and half-image size, with an optimal point density and a minimum number of 3 matches. This option was selected after intensive testing with 4 and 5 matches, which generated large gaps in the point clouds, in areas which were well-resolved with 3 matches. The point cloud still shows sectors with no data in homogeneous fine ash and lapilli covers, but those areas are small as discussed below and always outside the recent lava fields (Fig. 5). Since the target of the 3D survey are the lava fields, we guarantee that those sectors are well represented with many accurate points in the cloud.

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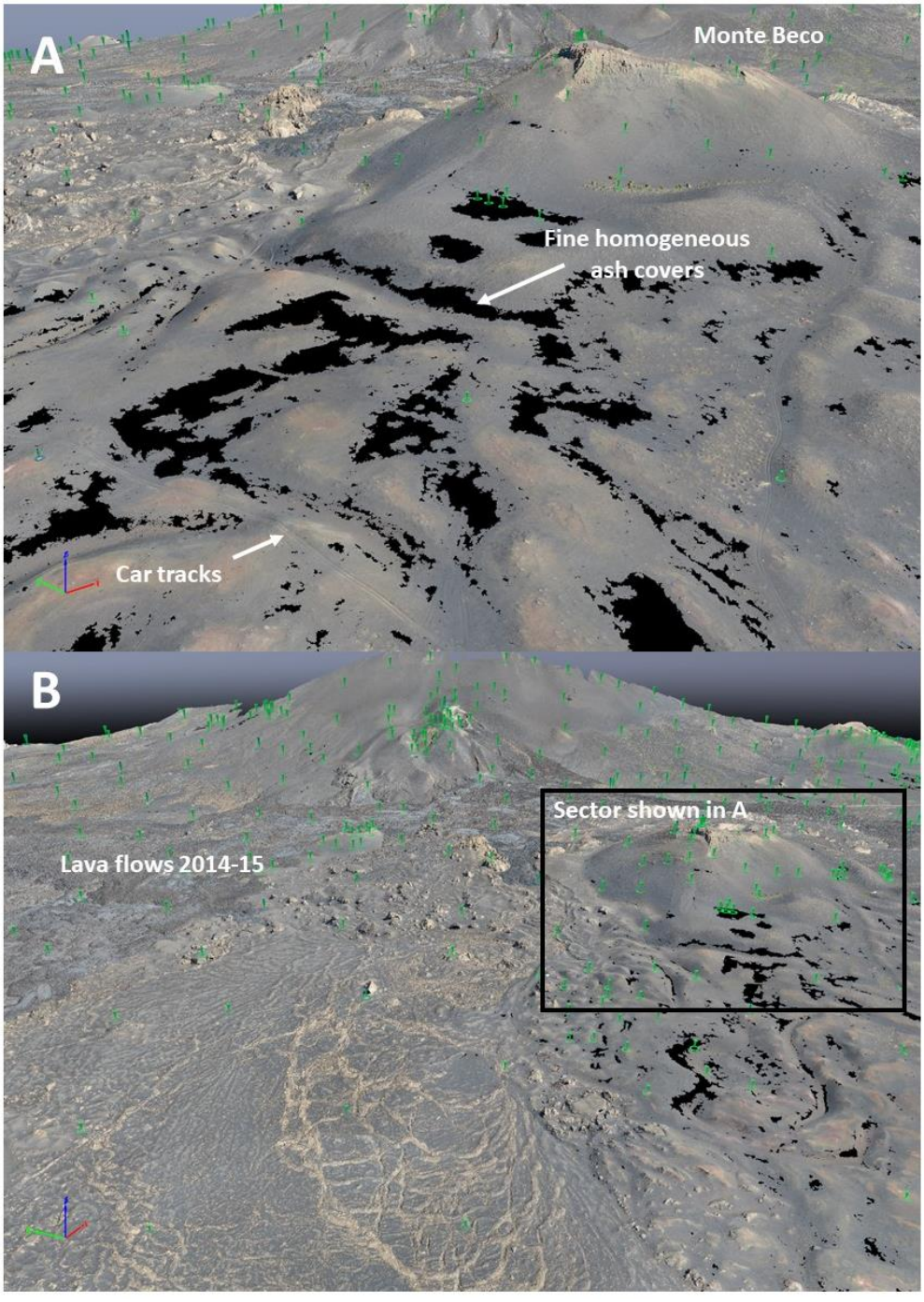

Figure 5 – Examples of areas without data in the 3D dense point cloud. A. Low quality areas in ash surfaces close to Monte Beco (car tracks pointed for scale), B. Most of the survey is of very high quality, with the figure showing the lava fields close to Monte Beco and the small areas with low quality. The green pins are manual tie points.

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The final digital surface model (DSM) and orthomosaic are presented with a resolution of 25 cm/pixel, which allow for maintaining the root mean square error (RMSE) well below pixel size. Noise filtering and sharp surface smoothing were applied for the DSM, with interpolation using inverse distance weighting.

4. Modelling results and discussion

4.1 Point cloud

The point cloud model shows a RMSE of 0.08 m in X, 0.11 m in Y and 0.12 m in Z, evaluated using 13 independent check points (Table 1). Even after including several hundreds of manual tie points, it was not possible to obtain a good quality point cloud all over the survey area. Areas of homogeneous ash and pyroclasts covers lack 3D data, but they do not impact the overall mapping of the area, as is discussed below.

Table 1 – Location accuracy per Ground Control Point in X, Y and Z.

Check Point	ErrorX (m)	Error Y (m)	Error Z (m)	Projection Error (pixel)
beco03	-0.0218	-0.0110	0.0729	1.02
beco05	-0.1511	-0.1224	-0.0617	0.40
beco10	-0.0597	0.0347	0.2638	0.45
beco23	-0.0026	0.0791	0.0287	0.39
beco24	-0.0076	0.0844	0.1193	0.53
beco26	0.0286	0.1193	-0.0298	0.52
beco28	0.0671	0.0423	-0.0542	0.28
beco29	-0.0872	-0.0194	-0.1591	0.54
amarelo03	-0.0451	-0.1036	0.0280	0.41
amarelo05	-0.1162	-0.3011	0.2447	0.80
amarelo13	0.0567	0.0098	-0.1135	0.97
amarelo14	0.1900	0.0138	0.1076	0.74
amarelo16	-0.0011	0.1119	0.0940	0.60
Mean (m)	-0.0107	-0.0045	0.039	
RMSE (m)	0.082	0.107	0.125	

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4.2 Digital Surface Model

The DSM of the Chã das Caldeiras with 25 cm resolution shows unprecedented topographic detail and allows for excellent visualization and quantification of the terrain morphometry. The iterative improvement of the point cloud by a detailed visual analysis of the DSM shaded relief model followed by adding almost 700 manual tie points in the model and reprocessing, allowed to reach a very high-quality result (Fig. 6). The final model is the result of a resampling of the first model obtained with 10 cm resolution.

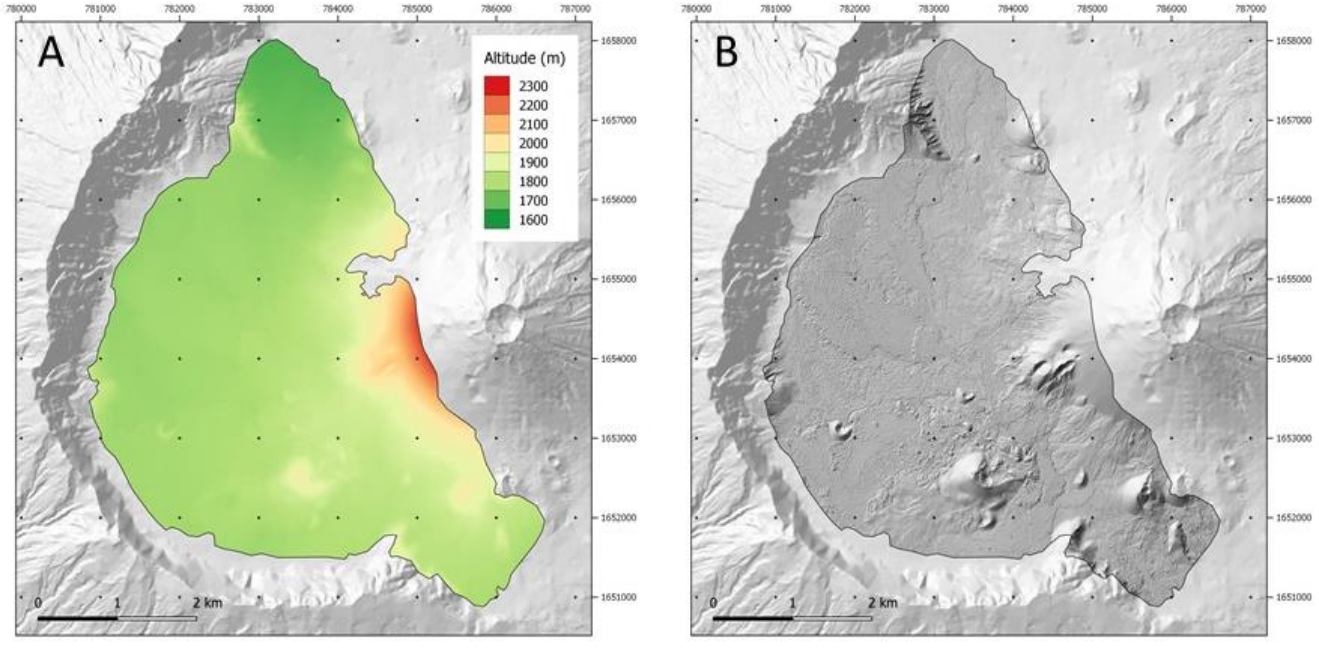

Figure 6 – Digital surface model of the Chã das Caldeiras (A) and DSM shaded relief model (B). The surveyed area is overlaying the DEMFI (2010) 5 m DEM.

In order to guarantee the quality of its use, the DSM was divided in three quality zones (Fig. 7). The zonation is available in the dataset as a shapefile that can be used to mask the DSM depending on user needs. The high resolution (10 cm) shaded relief model derived from the DSM, as well as the 50 cm equidistance contours interpolated from the DSM were used for the systematic visual analysis and for manual delineation of the areas with errors in the DSM.

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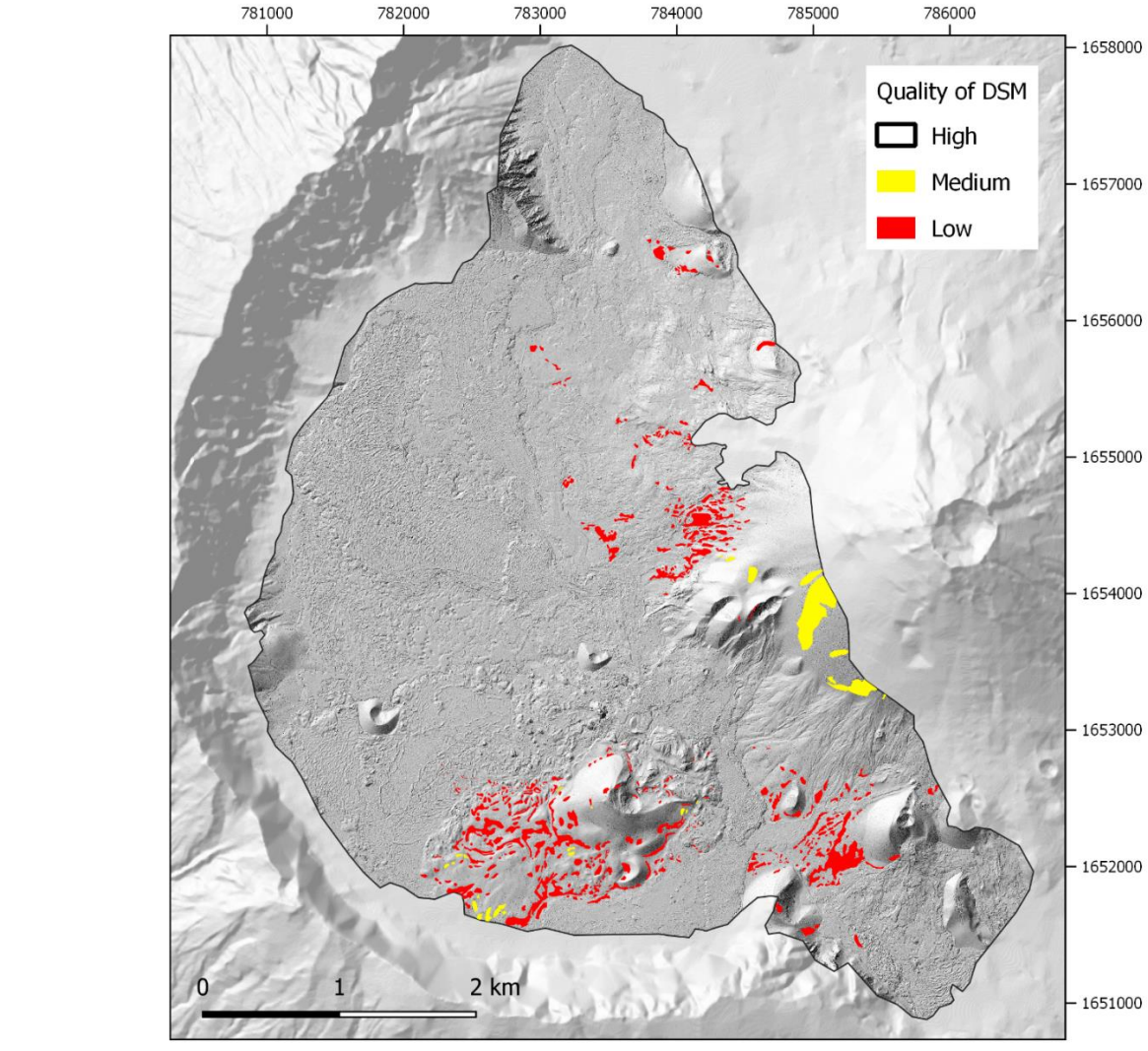

Figure 7 – Quality of the digital surface model in the Chã das Caldeiras. Shaded relief outside the surveyed area derived from the DEMFI (2010) 5 m DEM.

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The high-quality zones cover 96.8% of the entire survey and coincide with areas of rough surfaces with numerous automatic and manual tie points, where the morphology is very accurate, and the point cloud model has high resolution. Figure 8 shows some selected examples of the types of surface present in the survey area, which allow to visually assess the quality of the model:

370 - The ‘a'ā lava flow fields are characterized by high rugosity and numerous features which are easily matched between aerial photographs, including blocks, frequent sharp slope changes and pressure ridges (Figs. 8-A and 8-B).

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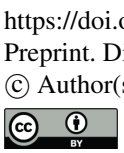

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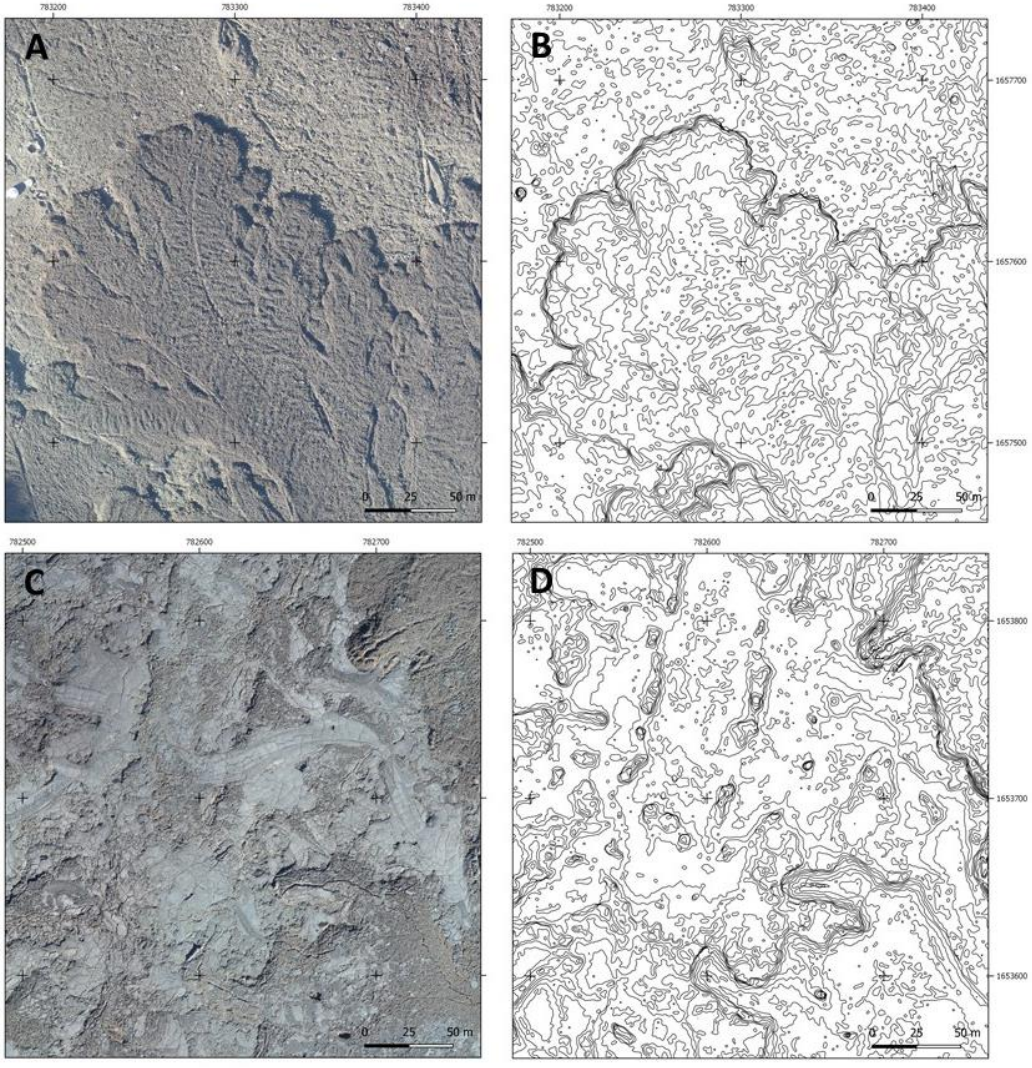
- Pāhoehoe lava flows show a much smoother and homogeneous surface, but they have frequent fractures and lineaments. They occupy generally small sectors of the orthomosaic and are bound by very rough a'ā lavas, facilitating point matching (Figs. 8-C and 8-D).

375 - Small volcanic cones with rough surfaces (e.g. boulders, footpaths, lava outcrops) show very high-quality results (Figs. 9-A and 9-B).

- Infrastructure, such as non-paved roads and houses show numerous matches and provide very accurate results. Cultivated areas occupy small sectors of the surveyed area, but the small holes dug to cultivate vines, as well as other small trees, are also very well represented in the DSM (Figs. 9-C and 9-D).



380 **Figure 8 – Examples of surfaces in the Chã das Caldeiras with high-quality results for the digital surface model, with orthomosaic for visualization (10 cm resolution) and contour lines derived from the digital surface model (50 cm equidistance). Note the good quality of the elevation contours. A and B. 'a'ā lava flows, C and D. Pāhoehoe lava field.**

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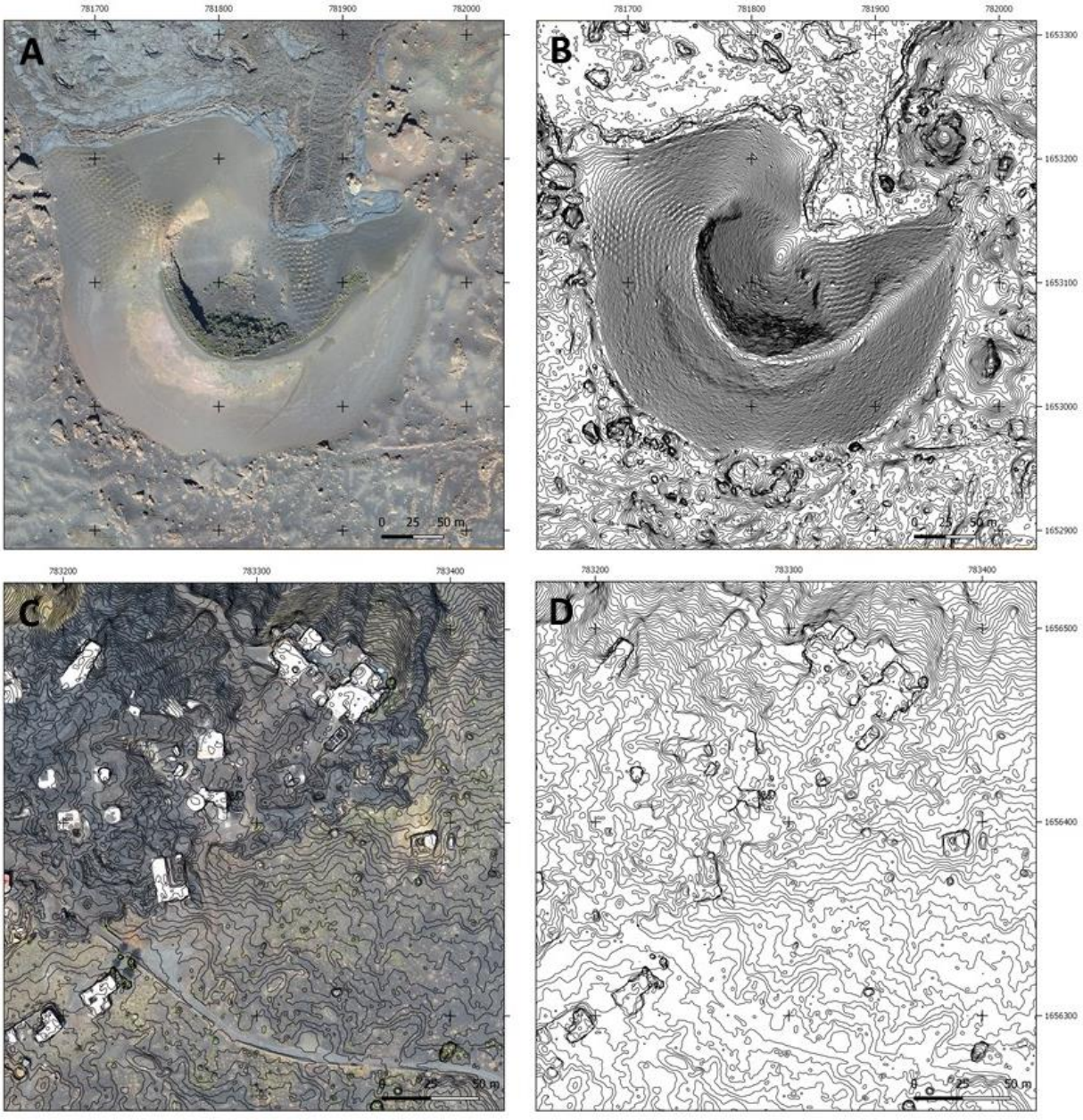

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Figure 9 – Examples of surfaces in the Chã das Caldeiras with high-quality results for the digital surface model, with orthomosaic for visualization (10 cm resolution) and contour lines derived from the digital surface model (50 cm equidistance). Note the good quality of the elevation contours. A and B. Volcanic cone with cultivated areas inside the crater, C and D. Lava field with buildings and a road.

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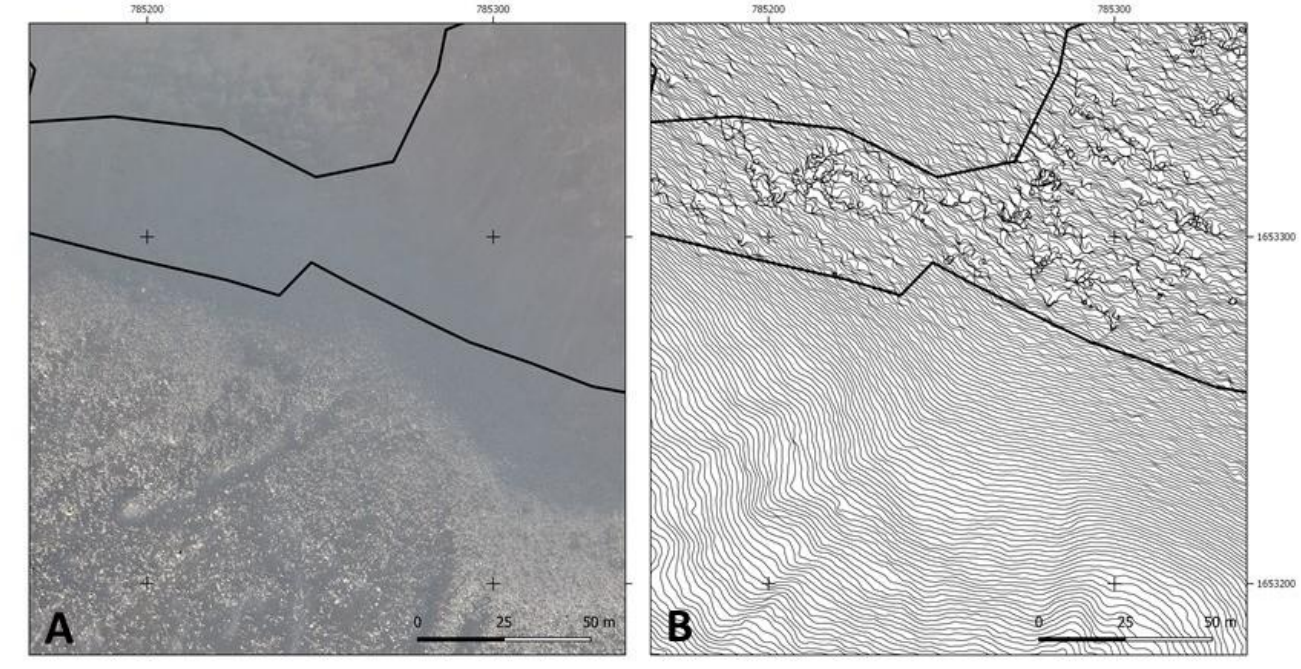

Figure 10 – Steep slope covered with ash in the Chã das Caldeiras with medium-quality results for the digital surface model. A. orthomosaic (10 cm resolution), and B. contour lines derived from the digital surface model (50 cm equidistance). The black line shows the boundary of the medium-quality area. The contours are very irregular in detail, but the overall slope at a coarse resolution is maintained. The area where the deposits are coarser provide a good DSM.

The medium-quality zones are sectors dominated by ash and lapilli, where sporadic 3D errors occur and occupy 0.6% of the survey. These areas, which in general can be used for visualization purposes and even for quantification, but with special care. Most errors in these zones are very small (dm scale) and can be smoothed by resampling, for example to 1-2 m resolution (Fig. 10).

The low-quality zones correspond to patches where the point cloud was poorly resolved, having numerous artefacts in the DSM (Fig. 11). These areas cannot be used for quantification purposes and their visualization shows errors, which sometimes are significant. The low-quality zones only occupy 2.6% of the survey area. These cases occur in very smooth surfaces of ash and lapilli or in sectors where a small number of overlapping aerial photos exists. They are located mainly in the base of some slopes, concave areas and also in the top of Monte Beco, due to the lack of photo overlapping.

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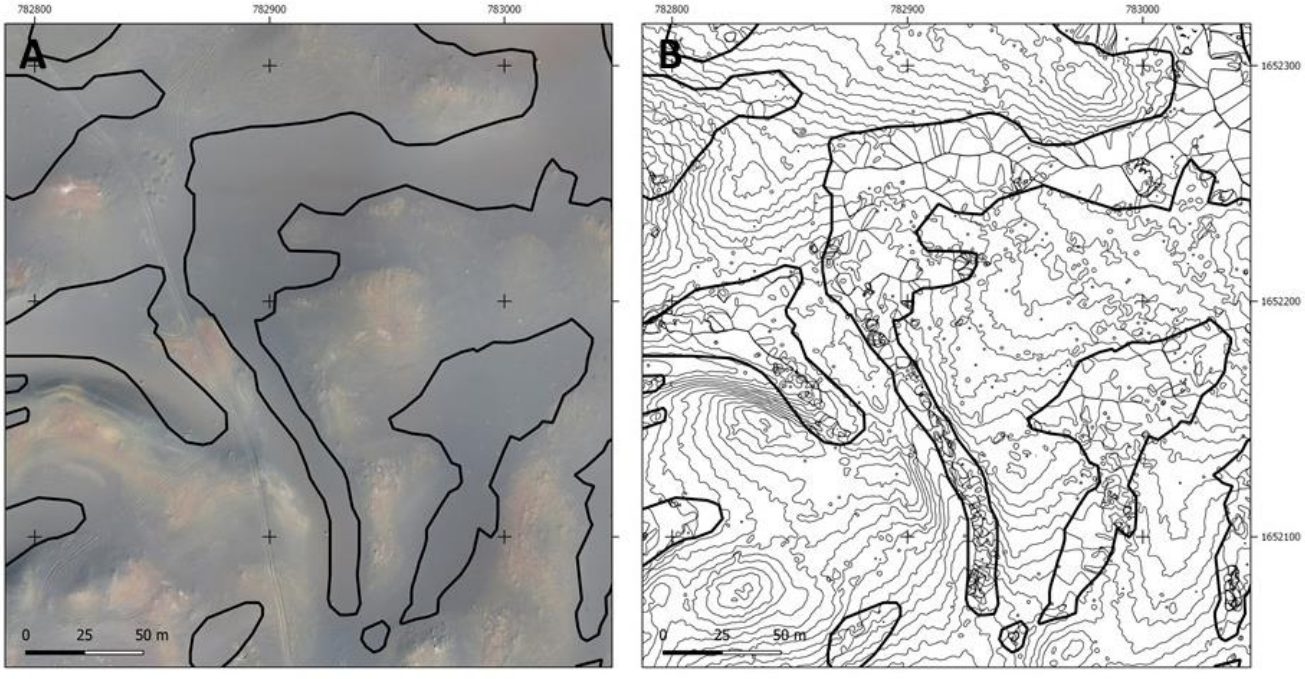

Figure 11 – Irregular surfaces with linear depressions covered with ash in the Chã das Caldeiras with poor-quality results for the digital surface model. A. orthomosaic for visualization (10 cm resolution), and B. contour lines derived from the digital surface model (50 cm equidistance). The black line shows the boundary of the low-quality area. The contours are very irregular and show numerous errors. The border with the good quality areas is sharp with good topography where the ground surface is coarser.

4.3 Orthophoto mosaic

The digital orthophoto mosaic that shows a resolution of 25 cm (Fig. 12), but the high accuracy of the survey allowed to make a mosaic with a resolution of 10 cm. This product may be delivered upon request. The mosaic shows an overall high graphic quality, with few problems relating to shadow effects close to the Bordeira wall in the south of the Chã das Caldeiras, and with varying illumination conditions in the lava flows of the northwest part of the survey, where stripping occurs. The sectors with medium quality in the DSM do not affect the overall quality of the ortho mosaic, but the interpolation may result in geometrical inaccuracies in the orthophoto mosaic in the areas of low quality in the DSM.

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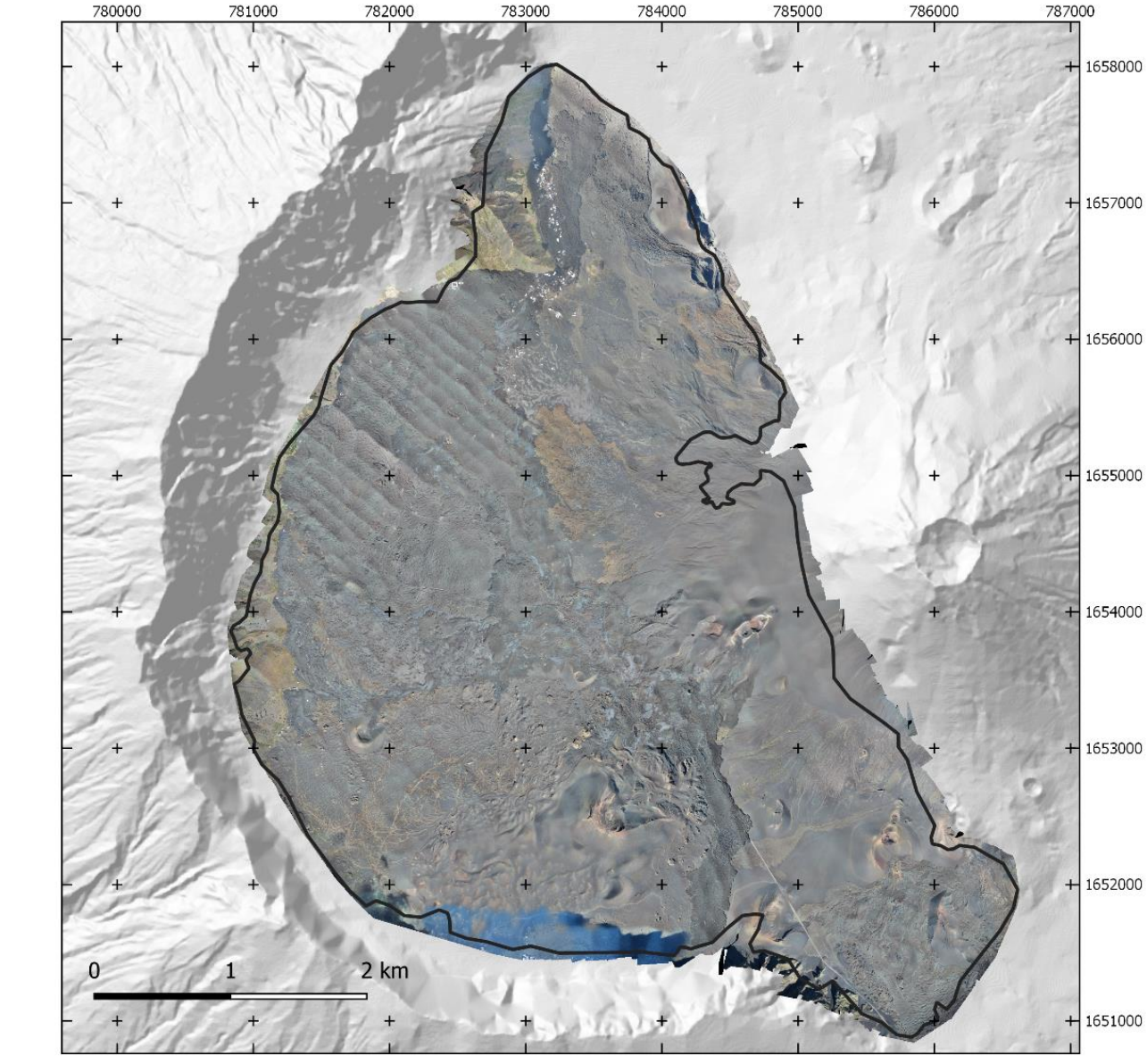

Figure 12 – Digital orthophoto mosaic with 25 cm resolution of the Chã das Caldeiras. Shaded relief outside the surveyed area derived from the DEMFI (2010) 5 m DEM.

4.4 3D models for visualization

A 3D texture mesh (.fbx) was produced for visualization purposes, allowing for the accurate visualization of the whole surveyed area (Fig. 13).

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Figure 13 – 3D visualization of the texture mesh of the Chã das Caldeiras.

4.5 New estimates of the 2014-15 lava flow field area

The lava flow field of the 2014-15 eruption was digitized manually using the orthomosaic and DSM. Unfortunately, our survey missed a small area of the lava flow with 0.007 km2 in the northwest sector of Chã das Caldeiras, close to Monte Amarelo and that sector had to be digitised using very high-resolution Google Earth imagery. The accuracy of the present survey allowed to calculate a new area for the 2014-15 lava flow field, which is 4.53 km2, a number smaller than the areas calculated by other authors using coarser resolution imagery, that varied from 4.8 to 4.97 km2 (5.8% to 8.9%). This discrepancy can be explained by the higher spatial resolution of our dataset that allows more accurate delineations, identifying in addition several kīpukas, i.e. small 'islands' (interior elevations surrounded by lava during the 2014-15 eruption) and also to a spatial variation effect (Chen, 1999) that results from the computation of the same areas in products with different spatial resolutions.

5. Data availability

The data is available at Zenodo: Vieira, Gonçalo, Mora, Carla, Pina, Pedro, Ramalho, Ricardo, & Fernandes, Rui. (2020). Digital surface model and orthomosaic of the Chã das Caldeiras lava fields (Fogo Island, Cape Verde, December 2016) (Version 1.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4035038.

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The dataset consists of the following files:

- cha_caldeiras_contours_50cm.zip: Compressed shapefile (shp) and auxiliary files. Contour lines of the Chã das Caldeiras in December 2016 with 50 cm equidistance, interpolated from the digital surface model. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N, elevation: ellipsoidal ITRF2014 (WGS84).
- cha_caldeiras_dsm_25cm.tif: Digital surface model of the Chã das Caldeiras in December 2016 with 25 cm resolution. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N, elevation: ellipsoidal ITRF2014 (WGS84).
- cha_caldeiras_error_assessment_areas.zip: Compressed shapefile (shp) and auxiliary files. Areas with errors in the point cloud obtained by visual analysis. 1. Low accuracy, 2. Moderate accuracy. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N.
- cha_caldeiras_ortho_25cm.tif: Orthomosaic RGB of the Chã das Caldeiras in December 2016 with 25 cm resolution. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N.
- cha_caldeiras_pix4d_report.pdf: Report of the processing of the aerial imagery in PIX4D.
- lava-2014-15.zip: Compressed shapefile (shp) and auxiliary files. Lava flows of the eruption of 2014-15 digitised from the original 10 cm resolution orthomosaic. CRS: ESPG 32626 - WGS 84 / UTM Zone 26N.

6. Conclusions

The 23.9 km^2 very high-resolution digital surface model and orthophoto mosaic of the Chã das Caldeiras lava fields developed from UAV surveys of December 2016, show unprecedented detail and accuracy (resolution = 25 cm and RMSE = 0.103 m). 96.8% of the survey area has provided a very high-quality DSM, which due to the scarce vegetation and built areas may be used as a DEM. The areas with moderate problems occupy 0.6% of the survey, with only 2.6% of the area showing poor-quality. The sectors with problems in the point cloud and DSM are those associated to very homogeneous ash and lapilli deposits. These areas can be easily masked out of the DSM by using the shapefiles made available in the dataset. The rough surface ‘a'ā lavas and the smooth pāhoehoe flows are very accurately determined, as well as the volcanic cones. The resulting DSM and orthomosaic constitute base datasets of unprecedent detail of high-value for geological research and for lava flow modelling with a high potential for applications in risk mitigation. These products allow delineating accurately the borders between different surfaces (lava types and other classes) and perceiving sub-meter surface features, which is less accurate or not achievable at all at meter scale, over an area of several square kilometres. These morphometrics features include pressure ridges, tumuli, flow channels, levées, dragged blocks and remains of human structures, among other smaller features.

Finally, we consider that these highly detailed products can play a relevant role in the assessment of volcanic hazards and related research and whose importance is surely excelled by becoming open access.

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Author contributions

GV, CM, PP and RR prepared the UAV survey planning and wrote the manuscript. GV and CM conducted the UAV surveys. PP and RR conducted the GNSS GCP collection. GV and CM conducted the modelling. RR digitised the lava flows. RF coordinated the GNSS activities. All authors contributed to discussion and review of the manuscript.

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CENTRO DE ESTUDOS GEOGRÁFICOS

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REPLY TO REVIEWER 4

Dear Dr Pablo F. Gonzalez,

Thank you very much for your very good comments and suggestions that complement very well the other reviews.

The manuscript and figures were significantly edited with the following, being the main changes:

- The title was modified in order to make clear the type of survey and the use of UAV.
- The abstract was improved to clarify the methods and the objectives, as well as the potential applications of the data set.
- The introduction is now shorter and more focussed on the significance of the dataset, supported by a clearer motivation and objectives. A very brief review of the applications of UAV-based surveys is presented. We have completely removed the previous section 2 on the applications of UAVs to volcanic areas, as suggested by several referees.
- The section 2 (Study area) is more concise now.
- A new section 3 on the volcanic activity of 2014-15 and previous digital elevation models was added. This section includes a more concise review of the last eruptive event and a more detailed review of the existing DEMs and their characteristics, as requested.
- The section 4 (Methods) was substantially improved with a more detailed description of the procedures and inclusion of tables with data and a new figure with the workflow. We have also improved the description of the procedures followed to generate the point cloud and the DSM. The figures were improved and several new ones with the inclusion of survey details, have been added. We have clarified the procedures used to evaluate the model accuracy, including the ones based on the visual inspection of the DSM to delineate its quality zones. A better description of the lava flow delineation procedure was also included, supported by an example in a figure.
- The section 5 (Results) presents more details on the evaluation of the quality of the data set, with a much more in depth analysis of the quality of the point cloud, as well as with quantitative measures of DSM quality.
- The figures throughout the manuscript were significantly improved and some were removed, following suggestions by referees. New figures allowing to improve the data set characterization and the evaluation of its accuracy have been added.

- The dataset made available in Zenodo now includes all the aerial photos, as well as the 10 cm DSM and orthomosaic, as required by some reviewers.

Following your comments, we have proceeded with the following modifications:

- Although the lava flow extension revision not being our main goal, we agree with your comments and we have expanded section 4.5 in order to clarify the delineation procedures and have included also a figure to illustrate it.
- We have checked and corrected the exponentiation.
- Kipukas are now defined in the abstract too.
- We have rephrased the Introduction and made the objectives clearer, following your suggestion. Thanks!
- We have added the reference to James et al (2020).
- A new figure 3 includes the landing sites now.
- We have improved the description of the data collection and made available the list of coordinates of the GCPs. Figure 5 now includes the location of the base stations. Unfortunately, we don't have the uncertainties of the GCPs.
- A new table (Table 1) was made with the flight details.
- We have clarified in the text what are the independent checkpoints (not used in the model, but used to evaluate the point cloud accuracy) and also how the survey was made using GNSS RTK mode. We did not find a correlation between the type of the terrain and the accuracy of the checkpoint. If the checkpoint is visible in the images with high quality, and since it is manually inserted by the operator in the model, then the accuracy will depend on the visibility in the image and on the operator precision in the software.
- We have tried several filters in CloudCompare during the processing of the model and while some solve issues with outliers in the point cloud in areas of poor quality, they reduce the quality of the point cloud in other areas. Hence, we decided to maintain the point cloud as produced from PIX4D, which guarantees a good quality in the lava flows (that show no gaps in the cloud), while we have decided to manually identify the poorly represented areas (with gaps and affecting the DSM) in figure 13 and develop a qualitative assessment of the DSM. This was a solution we found in order not to provide a DSM with gaps, but also not offer a product only covering the lava flows. It is a compromise solution. We have also added the accuracy assessment for the elevation in the DSM, by comparing it with the GCPs collected in the field, which is now accompanied by a more in-depth discussion.
- We have added the files with the check points and GCP coordinates, as well as the full survey data set and dense point cloud.
- We have rephrased the mention to the "unprecedented" characteristics of the survey.

We hope that with the significant changes we have made to the manuscript, following your comments, but also integrating the comments from other three reviewers and from the public discussion, the manuscript is now in good shape to be accepted for publication in ESSD.

Our sincere thanks for the time you have put into this review and for very useful comments.

Best wishes,

Gonçalo Vieira