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Use of terrestrial laser scanning for engineering geological applications on volcanic rock slopes – an example from Madeira island (Portugal)

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Abstract. This study focuses on the adoption of a modern, widely-used Terrestrial Laser Scanner (TLS) application to investigate volcanic rock slopes in Ribeira de João Gomes valley (Funchal, Madeira island). The TLS data acquisition in May and December 2008 provided information for a characterization of the volcanic environment, detailed structural analysis and detection of potentially unstable rock masses on a slope. Using this information, it was possible to determine specific parameters for numerical rockfall simulations such as average block size, shape or potential sources. By including additional data, such as surface roughness, the results from numerical rockfall simulations allowed us to classify different hazardous areas based on run-out distances, frequency of impacts and related kinetic energy. Afterwards, a monitoring of hazardous areas can be performed in order to establish a rockfall inventory.

1 Introduction

Engineering geological applications, e.g. rock mass characterization or slope stability analysis in volcanic rock slopes, face many challenges. A volcanic rock slope typically shows a wide range of rock and soil types in a random pattern with often poor lateral continuity (Del Potro and Hürliman, 2008), together with a high variability of mechanical properties both laterally and vertically (Apuani et al., 2005). Due to the different material properties and different weathering resistances, steep slopes with overhangs are common, causing frequent landslides, like rockfalls and rockslides. In case of a significant hazard to people, infrastructure or buildings, engineering geologists usually have to investigate the potentially dangerous areas to perform slope stability analysis or hazard risk assessments (Bell, 1999). Often confronted with difficult and dangerous accessibility to the exposed rock face, traditional data acquisition is insufficient. Consequently, assumptions have to be made e.g. on material properties or distribution of rock and soils from very basic geometrical and geotechnical models. Compared to these previous methods, TLS represents a substantial improvement in accuracy, reliability and such factors as time and safety. In general, terrestrial remote sensing can retrieve more comprehensive information on rock slopes and data of inaccessible outcrops. Currently several types of laser scanners are in use (Beraldin, 2004; Kersten et al., 2006). For geotechnical applications, especially for morphological studies and long range applications, laser scanners using the time-of-flight technology are the most suitable. It is possible to determine the distance and position of objects at up to several hundred meters distance. The resulting point-cloud data can be used to process high resolution 3-D surface models. Today, detailed TLS surveys are used in many different geological environments, for different purposes like detection, measurement and monitoring of deformations or displacements (Slob and Hack, 2004; Jones, 2006; Oppikofer et al., 2009; Abellán et al., 2009), back-analysis of rockfalls (Abellán et al., 2006), structural analysis (Slob et al., 2005), rockfall hazard assessment (Rosser et al., 2005) or lithology identification (Pesci et al., 2008). Although most of them have been performed in a non-volcanic environment, a survey of a high-relief volcanic environment will share some of the same characteristics

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and problems, e.g. appearance of occlusions, restricted accessibility and vegetation. First studies have shown that TLS can also be successfully used in volcanic environments to characterize the volcanic rock masses (Liu et al., 2007; Pesci et al., 2008) or to precisely measure the morphometry and volumes of volcanic features (Pesci et al., 2007). Other studies describe the monitoring of unstable slopes and active mass movements in volcanic environments to determine morphologic changes (Jones, 2006). However, few researchers have focused on engineering geological issues by analyzing rock slopes on islands of volcanic origin. These islands are subjected to dynamic change in morphology due to frequent mass movements. Unique for volcanic islands are the amount, spatial density and different types of mass movements that occur. This paper presents the adaption of TLS applications for engineering geological investigations on an exemplarily volcanic rock slope on the island of Madeira (Fig. 1). This paper will show how TLS data can be used to characterize volcanic rock masses using a high-resolution digital elevation model (HRDEM), including semi-automatic discontinuity analysis and kinematic failure prediction. The output can be used as input for numerical rockfall simulations to identify hazardous areas. Further applications include the analysis of multi-temporal TLS data for magnitude-frequency analysis and monitoring of rockfall activity, as well as providing a method with which to document the in-situ situation. Thus, several expeditions for data acquisition were made in May and December 2008 to Funchal (Madeira).

1.1 Location

Madeira island is located on a 140 Myr old oceanic crust and rises from more than 4000 m water depth up to 1862 m a.s.l. The geology of Madeira is divided into three main units: a basal unit (late Miocene to Pliocene), consisting primarily of volcanic breccias and pyroclastic deposits with minor lava flows; a middle unit (Pliocene to Pleistocene) composed primarily of alkalic basalts lava flows and an upper unit (Pleistocene), consisting of scoria cones and intracanyon lava flows. The middle unit covers most of the island and is made up of lava sequences thicker than 500 m and are locally cut by dike swarms. The last eruption occurred during the Holocene, approximately 6450 years BP in the S. Vicente valley (Schmincke, 1998).

The entire island of Madeira is characterized by high mountain ridges and deep valleys within steep slopes, cutting into the ancient lavaflows and tuff layers. Therefore, the occurrence of rockfalls and rockslides is a frequent and serious problem, causing severe damage to the infrastructure and a number of annual fatalities (Rodrigues and Ayala-Carcedo, 2003). In this research, slopes of one of the three main valleys in Funchal city, the Ribeira de João Gomes valley (Fig. 1), have been mapped and investigated regarding the rockfall hazard potential. The analyzed slope is built-up

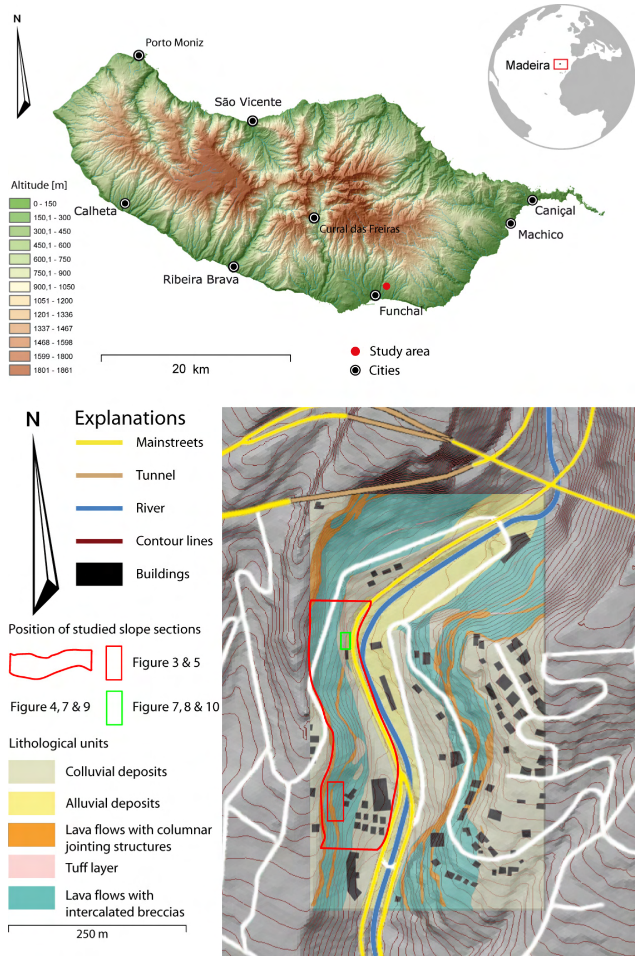

Fig. 1. Location of the volcanic island Madeira (Portugal) in the Atlantic Ocean and the extent of the study area in Funchal.

of thick basaltic lava flows with columnar jointing structures and intercalated breccias and tuff layers (Fig. 2). Many of the columns already lack basal support and show a wide joint opening (Fig. 2d). In the study area, the João Gomes river cut a v-shaped valley into a series of different volcanic rocks, exposing up to 120 m high slopes. Below these basaltic cliffs, more shallow dipping areas are located with terraces formerly used for agriculture. Colluvial and alluvial deposits cover the bottom and the footwall of the valley. Within this unit, precipitation-triggered small landslides are common. High-traffic roads at the valley bottom and their connecting roads winding up to valley shoulders are exposed to rockfalls from the steep slopes and overhangs of the highly fractured basaltic cliffs. The entire area is densely covered by vegetation, with the exception of nearly vertical cliffs (Fig. 2).

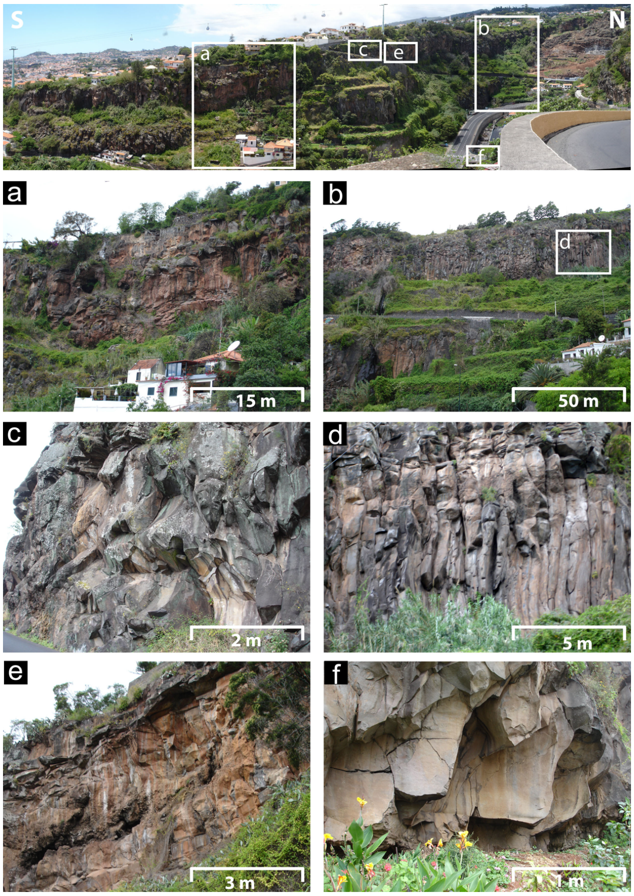

Fig. 2. Panorama of east exposed slopes in the study area (top). Steep slopes over houses **(a)** and streets **(b)** consist of thick basaltic lavaflows **(c)** with columnar jointing structures, lacking basal support **(d)**. Within the slopes: notches, overhangs **(e)** and open cracks are common **(f)**.

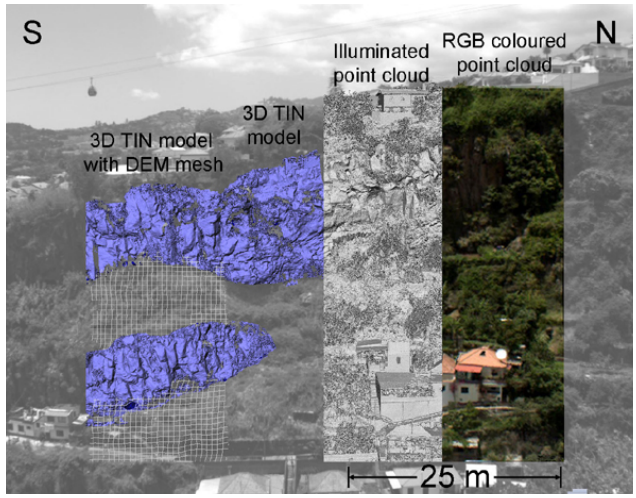

Fig. 3. Coloured and differently illuminated point clouds ease data processing and interpreting of specific geological features. Following up with a triangle mesh (TIN) on rock faces in combination with a DEM, it has built-up the basic requirements for engineering geological applications.

2 Terrestrial laser scanning (TLS)

2.1 Technique

Regarding their measuring technology, TLS systems can be separated into triangulation scanners, time-of-flight scanners and phased-based scanners (Rosser et al., 2005). Most suitable for morphological and geological studies are time-of-flight scanners for reflectorless and contactless acquisition of point clouds of any topography due to their ability to operate from great distances (Sturzenegger and Stead, 2009). The scanner used in this study is an Optech ILRIS-3D scanner which has an operating range of up to 800 m, depending on the reflectivity of the target. This scanner has a view field of 40×40 degrees and emits an infrared pulse of laser with a wavelength of 1500 nm via two mirrors, in a direction defined by the azimuthal and zenithal angles (Staiger, 2005). From the travel time of back-scattered pulses and orientation of the emitted laser beam, the 3-D coordinates of each point can be computed in a local reference system (Teza et al., 2007). With a recording frequency of 2500 points per second, measurement speed is very high. The recorded 3-D data is usually quite large and, depending on the task, each scan consists of several million data points, forming a so called point cloud. In addition to the spatial information (X, Y, Z) of the point cloud, each point has a returned laser pulse intensity (with values ranging from 0 and 255), which is valuable additional information in order to identify vegetation or rock types. It is common to use a co-axial mount with an installed or integrated high-resolution digital camera to collect true-colour images as additional quantitative information for the TLS scan (Fig. 3). By colouring point cloud data with RGB values from the digital camera, a supplementary source for data processing and interpretation is available (White and Jones, 2008). The Optech ILRIS-3D scanner has an integrated 6-megapixel digital camera providing the advantages of high-accuracy registration of images on TLS point clouds. If there is bad lighting, then suboptimal images may be replaced by taking images independently and registering them manually to the scan data (Buckley et al., 2008).

2.2 Data acquisition

To perform a TLS survey, careful planning is essential. Geological engineering field studies are conducted at a number of scales and distances, so it is necessary to plan ahead for required accuracy and precision mapping, scan resolution and the set-up of the scanner (Buckley et al., 2008; Sturzenegger and Stead, 2009). Due to both physical and technical constraints and the occurrence of occlusions (shadow zones) the choice of the scan positions is of high importance. To get a 3-D surface model, generally an orthogonal setup of the scanner to the outcrop is advantageous, including the change of positions to avoid horizontal and vertical occlusions. Additionally, it is advisable to scan from higher elevation for better data quality and signal intensity. If scans are performed at an elevation equal at or below the bottom of the slope, then it is difficult to avoid occlusions at top faces. Typical methods to solve this problem are scanning from natural or artificially higher positions (Doneus and Neubauer, 2005) or completing TLS data with airborne LiDAR data (Oppikofer et al., 2009). Due to the extended operating range of the TLS scanner, data acquisition has been performed from the opposite side of the valley to obtain data points with a minimum of occlusions in the highest faces. Although it often makes sense to scan the entire area with the best acquirable resolution, the enormous amount of data requires a very powerful computing environment and will slow down data processing substantially. To speed up the process, different scanning windows with different resolutions may be used, depending on the scale of the geological features and the requirements for the chosen geological engineering applications (Fig. 4). In the area of interest, several scans were performed at distances between 150 m and 400 m with point densities (resolution) between 5.3 cm and 7.2 cm to derive a complete point cloud. To quantify discontinuity orientation and to monitor surface deformation, additional close-range scans at a distance of 30 m to 50 m have been performed with a setup resolution between 5 mm and 10 mm. Unfortunately, such small point spacing leads to an oversampling with the effect that fine details become blurred, since the beam width of the laser is wider than the point spacing due to the beam divergence (Lichti and Jamtsho, 2006). From these investigations, a TLS dataset comprising approximately 300 million points was complied. Thus, for modelling purposes, a subsequent resampling of these raw scans to a resolution wider than 20 mm was necessary to achieve good results. However, these scans have been performed at the highest resolution for archival storage, as they document the recent situation and might be used for further application in the future.

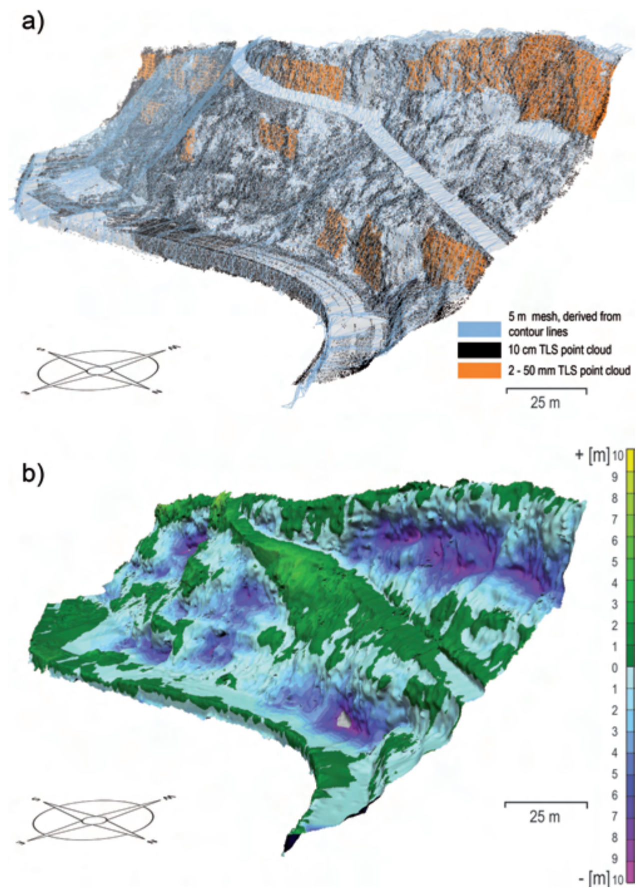

Fig. 4. A 5-m resolution DEM (blue mesh) derived from contour lines of the study area lacks geometrical detail, such as overhangs or notches. Positioning a 10-cm resolution point cloud (black) into the data sets improves the vertical geometry in particular. Simultaneously, the DEM can be used to close gaps or to cover less interesting area between different point clouds. For structural analysis, the same procedure has been used with high resolution point clouds (orange) **(a)**. The fusion of the different data sets results in a high quality model which differs up to 10 m in comparison to the 5-m resolution DEM **(b)**.

2.3 Data processing

TLS datasets of the study area were computed, using the software PolyWorks (InnovMetric, 2010). First, the single scans are registered in a relative coordinate system continued by transforming (alignment) following scans into the same system. Alignment starts manually by identifying common points in the point clouds. Following this rough matching, an automated iterative procedure with a point-to-surface Iterative Closest Point (ICP) algorithm was carried out in order to minimize the co-registration errors (Besl and McKay, 1992; Teza et al., 2007). Commonly, overlaps of approximately 10–20% between the different scans are necessary to ensure good matching. In a typical workflow, one scan is held fixed and subsequent scans are matched in turn, fixing each as it is solved. This leads to large data amounts slowing down data processing considerably. Therefore, from the previously registered scan, only the overlapping area is clipped to a new file and used for registration of the following scan scene. Even though these additional processing steps extend a typical workflow, the benefit is that the registration process speeds up effectively. Finally, a global alignment is carried out to adjust all scan positions relatively, allowing the point clouds to be merged in the same coordinate system. Afterwards, an intelligent point data reduction has to be done to remove left-overs, such as vegetation and other non-geological points. For this purpose, a square sampling grid is used to subdivide the point cloud data, to create the ground surface and to select data points that are beyond a user-specified distance from the ground surface. After a visual check, vegetation such as trees and bushes, buildings and infrastructures, can easily be removed. In case of a RGB coloured point clouds, data points of vegetation close to steep slopes and ground can be selected for removal using green values larger than 50. Otherwise a manual removal can be performed by subdividing the point cloud data into several strips. On the side view of each strip, vegetation and other non-ground objects appear clearly and can be easily selected for removal. Special care must be taken to ensure that the elimination does not lead to an over-simplified model. For most applications, this processing level is more than sufficient to carry out all measurements, interpretation and modelling tasks. Moreover, the acquired TLS data often do not cover the entire study area without gaps, due to removal or occlusions. To close these gaps and to ease orientation, the TLS data has been inserted into an ordinary DEM derived from 5-m contour line data from precise topographic maps (Instituto Geográfico do Exército: Funchal, Ilha da Madeira. [map], 1:5000, Lisboa, I.G.E., 2004) via a global registration. By merging both datasets, a HRDEM without data gaps can be created (Fig. 4). As it is normally neither effective nor necessary to use the complete TLS dataset at once, a hierarchical use of different TLS datasets (separated by resolution and area) has been performed depending on the application. With the option to select only areas of interest from the whole data set for further processing and investigation, the amount of data can be kept manageable and efficient. This allows us to create a DEM of large areas with lower resolution or to perform structural analysis on small areas with high resolution. Data preparation finally ends with a virtual outcrop model by texturing the resulting DEM with georeferenced images and orthophotos, providing a 3-D photorealistic model for investigation, visualization and education. Techniques for texturing are presented in Buckley et al. (2008) and White and Jones (2008).

3 Engineering geological applications

3.1 Characterization

The first aim in engineering geological investigations with TLS is the characterization of the volcanic environment with digital and field-based mapping. TLS data provide the ability to measure and visualize topographic relief down to centimetre resolution for digital inspection. This may include the determination of the spatial distribution of low erosion-resistant units such as tuffs, weak-welded pyroclastics and intercalated breccias and their weathering state. Due to different erosion-resistance of the rocks, overhangs and notches form, leading e.g. to a lack of basal support and to a potential rockfall source.

Using ESRIs ArcGIS applications, different levels of information can be added to the outcrop data for an intelligent and interactive data interpretation. Figure 5 is an example of a scanned outcrop of a lavaflow translated from raw TLS data into a 2-D grid. Interfering objects (e.g. vegetation) can be marked in the RGB image and considered in subsequent slope gradient and intensity analysis as non-relevant. The slope gradient analysis has been performed twice, first at a cell size of 1 cm and followed by one of 5 cm. Using the coarser analysis as a transparent overlay with a stretched colouring (inverted to the finer one), neighbouring diversely dipping cells resulted into discoloured areas. Thus, a manual pre-allocation of autoclastic breccias is possible due to its more irregular surface with respect to basalt surfaces. A particular attention has been paid to rough top faces of basalt columns, which are difficult to distinguish from breccias. To avoid misinterpretation, visual cross-checks using the information from different sources and data derivations like hillshades or RGB data might be used. Different weathering conditions within the rock slope can be distinguished by discolouring of the host rock, which can in turn be detected by higher intensity values. Analysis of related intensity values of pre-assigned and clarified areas support the semi-automated classification of the outcrop model. Although vegetation can usually be identified by low intensity values, sometimes small plants or leaves of plants may mix up with background intensities of rock mass, depending on the model and image resolution. This results in misleading or obscure vegetation patterns as shown in Fig. 5. Therefore using a cross-sourced information (e.g. RGB images or slope analysis) can be applied to avoid these problems. The last step is the manual assignment of unit boundaries by tracing 2-D or 3-D lines directly onto a virtual outcrop model. Depending on the joint patterns, traced lines subdivide the lava flow into different structural units, as presented in Fig. 5. After reapplication to different outcrops, a correlation of the different units over a wide area makes it possible to set up a consistent and comprehensible geological model to identify potential rockfall sources. At these locations, structural analysis for discontinuity characterization may follow.

3.2 Structural analysis

Dealing with large rock faces or slopes, a good understanding of present discontinuities is required, as they determine the mechanical behaviour of the rocks (Bieniawski, 1989). During a field survey, it is common practice to measure the geometry of discontinuities, such as orientation, roughness and location (ISRM, 1978) using standardized methods like scan-line surveys or cell mapping (Priest, 1993). However, the manual sampling and measuring is often discussed as erroneous. It has different disadvantages, as there is sampling bias due to restricted access to rock faces, or the

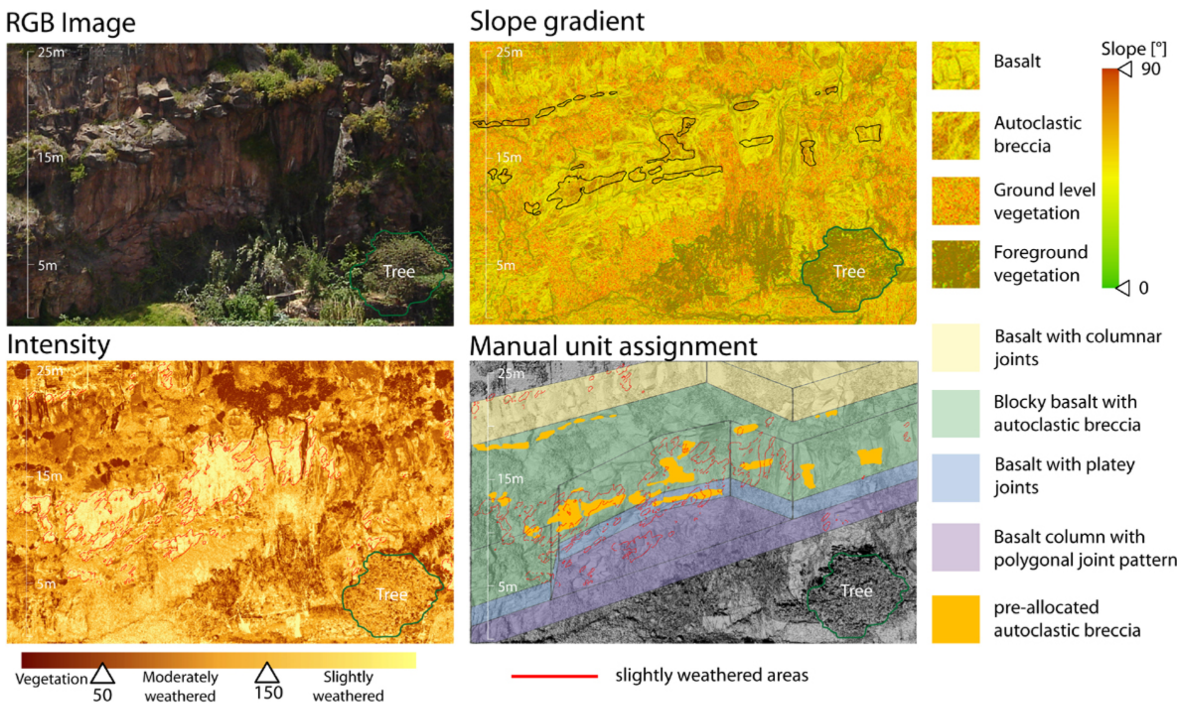

Fig. 5. Transformation of TLS outcrop data into 2-D relief data allows performing a slope gradient and intensity analysis for a pre-allocation of geological units and their weathering conditions in a GIS environment. Supported by the manual assignment of unit boundaries from a virtual outcrop model, evaluation and comparison of different sources allow the characterization of the outcrop.

experiences are time-consuming and labour-intensive (Slob et al., 2005). From the 3-D model, discontinuity characterization can be achieved by either manually fitting planes on individual surfaces and traces or by automatically using capable analytical software (e.g. Kemeny and Donovan, 2005; Slob et al., 2005; Jaboyedoff et al., 2007; Ferrero et al., 2009; Oppikofer et al., 2009; Sturzenegger and Stead, 2009). The only requirement is an accurate positioning of point cloud data either levelled in a relative coordinate system with respect to the North or by an absolute system using GPS, conventional surveying or a DEM.

A typical workflow to perform discontinuity characterization is subdivided into data processing and data analysis steps (Fig. 6). As part of the overall data processing, different raw data point clouds have been aligned and merged into the same coordinate system and subsequently cleaned of non-geological data. This can be done as described by the method above and is a prerequisite for further processing. By continuing with data reduction according to the scale of the scanned features, and subsequently completing a 3-D Delaunay Triangulation to mesh the entire point cloud, the strike and dip of each triangle can be measured. Grouping neighbouring triangles with similar orientation results in facets, whose orientation and density can be analyzed in a polar plot. Using clustering techniques (e.g. F-distribution), different rock mass discontinuity sets can be identified and mean orientations computed or plotted (Slob et al., 2005).

The software used (Split FX v1.0 by Split Engineering) detects facets on a triangulated mesh with the following criteria: edge length 0.15 m and a minimum of four neighbouring facets with a maximal 10° deviation of orientation to each other. With a visualization of cluster regions on the 3-D meshed surface and a subsequent colouring to distinguish different clusters, an initial identification of different discontinuity sets can be done. However, the use of semi-automated software may compute false orientation due to very small patches or discontinuities over several facets as shown in Fig. 7a. In addition, larger joints surfaces may have been undetected since their more irregular surface resulted in less uniform oriented faces, not fulfilling the used criteria. This conditioned a visual verification and manual editing to remove outliers or to add missing facets before calculating the average orientation of discontinuities.

Joint spacing and distribution can be measured and analyzed directly from acquired TLS data at every position. For this study on Madeira island, only the areas of interest were processed and analyzed. This is necessary due to the enormous size of high-resolution scans, which can affect computing performance substantially, if they are loaded at the same time. Considering this point, potentially rockfall sources such as uncovered massive lavaflows have been scanned in high-resolution. Visual inspections of the basaltic cliffs on the slope clearly show systematic discontinuity sets. For stability and rockfall analysis, their local orientation, as

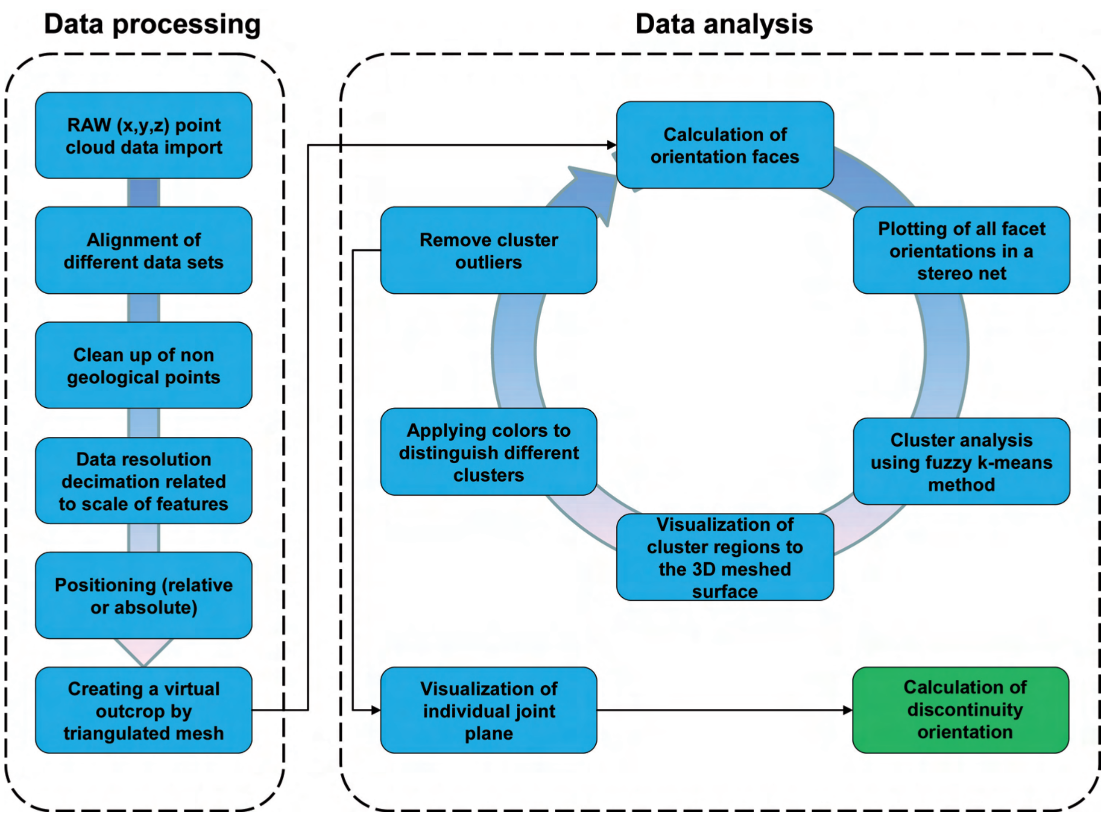

Fig. 6. Workflow describing the processing of TLS data for discontinuity analysis of rock slopes.

well as joint spacing is of high relevance. It is expected that due to cooling processes (DeGraff and Aydin, 1993), generally a sub-horizontal and two orthogonal sub-vertical joint faces should have developed in the lava flows (Moon et al., 2005). Figure 7b shows that it is possible to identify all of them from the point cloud data.

The plotted joint sets may be used for a kinematical failure prediction according to Hoek and Bray (1981). Furthermore, the data allows an evaluation of possible rockfall volumes depending on failure mechanism and spatial joint pattern. Due to the frequent occurrence of rockfalls, average block sizes are of particular interest. Using the stereographic projection technique, plane sliding can occur on column-bounding fracture plane CB 5 (Fig. 8). Limited by column-normal and column-bounding fractures, block sizes have been estimated with average volumes between 0.5 m^3 and 2 m^3. Corresponding to recognizable scars and blocks in the field, the estimated block sizes have been used for numerical or probabilistic simulation.

3.3 Numerical analysis

Numerical rockfall simulations are a common and important task in modern hazard assessments. They provide objective decision support for identification of endangered areas, providing run-out distances, impact frequency and energy. Since rockfall simulation is very sensitive to slope geometry, it is necessary to have highly detailed DEMs for 2-D or 3-D simulation (Rosser et al., 2005). Cross-sections can be derived manually or automatically from the TLS point cloud data, allowing a fast creation at frequent intervals. A major advantage compared to a typical DEM used in GIS is that overhanging parts of the slope and steep cliffs are represented much more realistically and with high details. Considering the option to select view-dependent profiles, orthogonal setups relative to the analysed slopes can be ensured, as shown in Fig. 9a. Rockfall simulations have been performed with Rockfall 6.1 software (Spang and Sönser, 1995), which has also been used in further studies for rockfall simulations (Mikos et al., 2006; Abbruzzese et al., 2009). It allows a physically exact simulation of the trajectory of a rockfall considering also the spin. Required input parameters like the shape, size and mass of a rock have been determined by the structural analysis from TLS and lab data. To consider geological uncertainty, a random parameter variation can

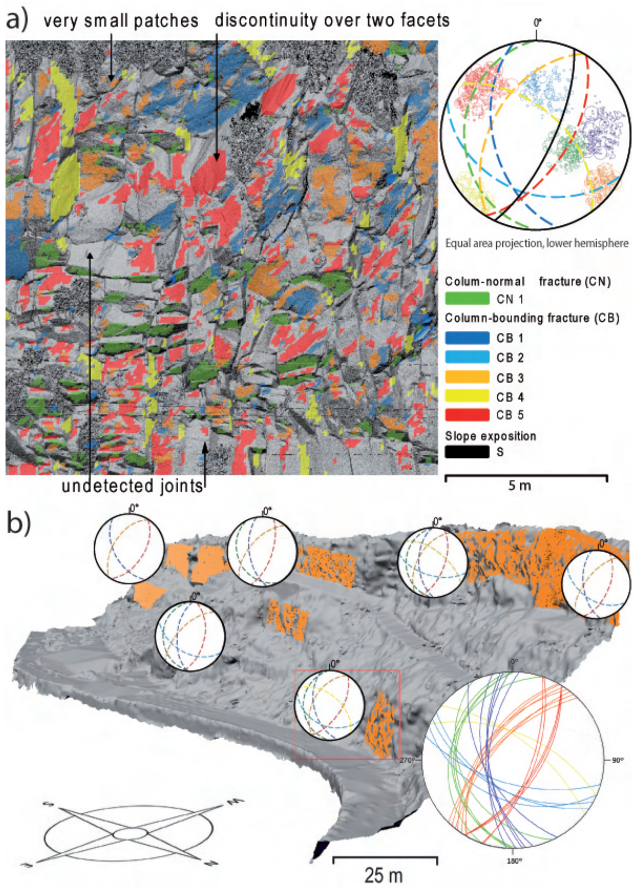

Fig. 7. Software aided semi-automated discontinuity analysis: small patches, discontinuities over several facets and undetected joints conditioned visual verification **(a)**. Displaying orientation data in lower hemisphere stereographic projections at each point of interest resulted in a discontinuity characterization of the overall slope **(b)**.

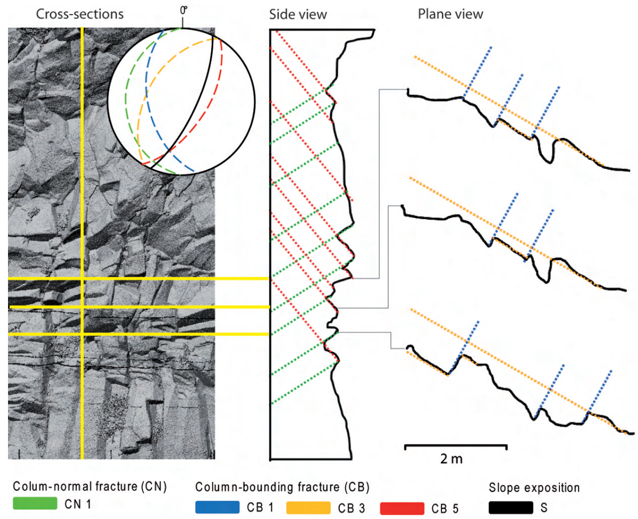

Fig. 8. To determine the size of possible planar sliding blocks at the outcrop shown, discontinuity sets have been plotted on cross-sections to measure their spacing.

be set for the simulations. Special care should be taken regarding the resolution of the simulation. Extremely detailed data may provide an unrealistically rough surface, which does not necessarily represent surface conditions in the field, thus producing errors.

The relevance of the surface accuracy becomes obvious when comparing the numerical simulations of the same profile, using a 5-m DEM and 0.3-m HRDEM, with the identical input parameters for simulation (Fig. 9b). Since the results differ critically in the magnitude of kinetic energy and spatial impact, hazard analysis in the study area will be improved by use of HRDEM data. Therefore, the results of the simulation for each profile have been classified by impact frequency and energy after the matrix diagram shown in Figure (Fig. 9c). It defines in case of a rockfall event, the probability of an impact on a given location within a defined energy class. The distribution of the kinetic energy classes based on the energy absorption capacity of improved wire cable constructions (100 kJ–300 kJ). Subsequently they are visualized in ESRIs ArcGIS as polyline data and draped over the DEM hillshade. To visualize the results a spatial interpolation has been performed to create 2-D grids with specific colours assigned to data ranges, allowing a spatial review of the entire simulation results (Fig. 9c). The benefits of this attempt are the availability of a spatial database for detailed countermeasure designs, addressing the administration for local or regional planning.

To this point, the hazardous zones shown are not a hazard map, since they do not consider the probability of rock failure. To create a hazard map, such as that proposed by Jaboyedoff et al. (2005), the probability of failure has to be estimated using the frequency of historical events or from monitoring periods (Rosser et al., 2005).

3.4 Monitoring

The previously presented analysis methods determine potentially unstable rock masses and their consequences, neglecting the frequency of different magnitudes of rockfalls in the study area. Without historical records, monitoring using TLS is one option to develop a local magnitude-frequency relationship function for hazard analysis. Its requirements are the detection of number and sizes of rockfall blocks or scars and their changes over time. Furthermore, displacements and deformation rates might be monitored. This can be done by comparing TLS data from different time epochs after an accurate matching of repeated measurements. Using different applications to calculate spatial displacements between two or more sequential scans, information about their spatial distribution, type of movement, total displacements and rates can be

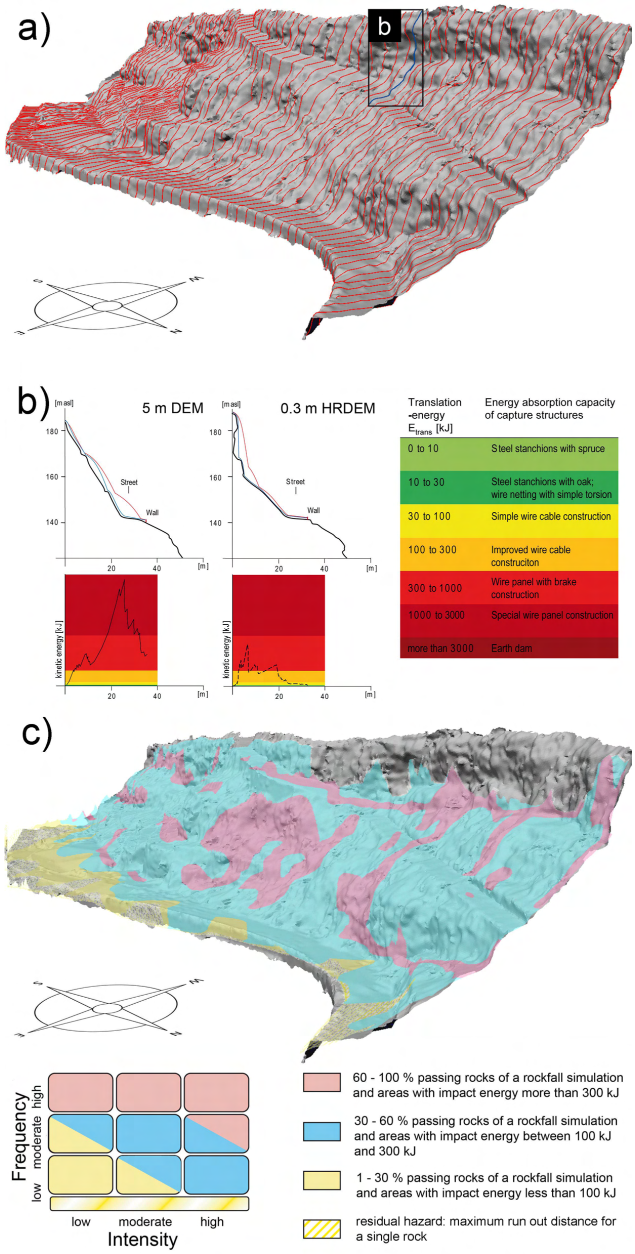

Fig. 9. Automatically created cross-sections (red lines) on a HRDEM are used to perform rockfall simulations along the slope at frequent intervals **(a)**. Comparison of numerical simulation of profiles at the same location, using DEM and HRDEM data with identical input parameters **(b)**. Classifying the simulation results, a zoning by impact frequency and energy, is possible **(c)**.

determined (Rosser et al., 2005; Oppikofer et al., 2009). In the research area, scans from May 2008 and December 2008 have been compared focusing on rock cuts next to streets and buildings. However, even using high-detailed point clouds with an ICP alignment on the reference data, millimetre displacements cannot be measured directly due to the TLS instrumental error (Abellán et al., 2009).

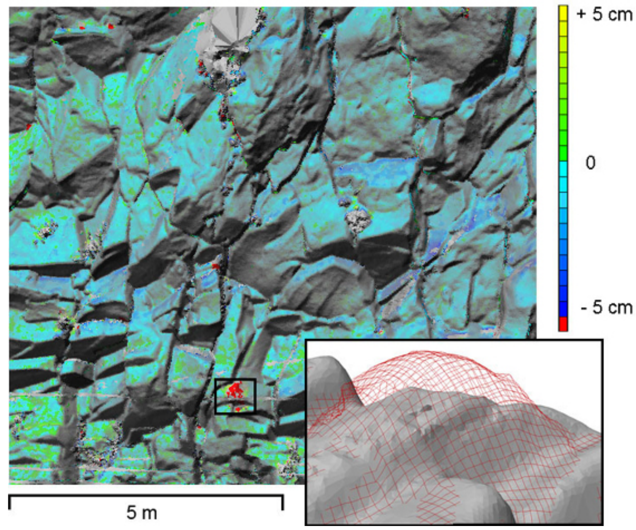

Fig. 10. Multi-temporal comparison of the TLS point clouds from May 2008 and December 2008. Changes beyond a basic scatter value are due to different scan positions and instrumental errors. Small scale rockfalls are visualized in red. The enlarged view of the marked area (box) shows a missing volume of 0.5 m^3 between the scan of May 2008 (red mesh) and December 2008.

For a magnitude-frequency analysis of rockfalls, instead of comparing the shortest distances between the two point clouds, DEMs were created from the different scans and subtracted from each other in ArcGIS. Displayed as differential area diagrams in e.g. ArcScene, changes are indicated as peaks or notches. This highlights moved or have missing blocks, which can be considered to be related to the mechanism of deformation. It should be noted, that again the use of cross-sourced information is useful to delimit changes from vegetation. Due to instrumental errors, alignment errors and modelling errors (Teza et al., 2007), a comparison error with basic scatter values up to 4.6 cm exist as Fig. 10 shows. The error has been calculated from a differential area diagram. It amounts to the double standard deviation of difference with respect to the error. Displacements beyond this error can be considered as real displacements values. Analysis shows that during a period of seven months, single small volume rockfalls (up to 0.5 m^3) occurred. This dataset can be used to set up a database for frequency-magnitude analysis for a defined area. To estimated rockfall frequency for longer periods, a rockfall inventory by continued documentation is necessary.

3.5 Documentation

An advantage of TLS application in engineering geology of volcanic slopes is that due to the time-efficiency of data acquisition, rapid documentation of recent in-situ activities for a given rock slope can be accumulated. Once acquired, the data provide a basis for many engineering geological investigations, which can be done independent of accessibility, especially if new questions arise. Furthermore, if new and improved analyzing techniques and tools are available for analysis, a repeated or enhanced analysis also becomes possible as well. For volcanic rock slopes, especially in the study area, obtained TLS data will serve as a long-term reference in detecting changes. In addition, a back-analysis of future rockfalls and rockslides becomes possible. Therefore, the concept of digital outcrop models and digital outcrops analysis are substantially improved, supported by the TLS technology now available.

4 Conclusions

TLS application developed for other geological settings can be adopted for volcanic rock slopes. It eases the characterization of the environment by reducing fieldwork data acquisition time and simultaneously providing additional data of inaccessible outcrops, which would have been very difficult to obtain. By intelligent use of software to automate data processing and analysis, many applications requiring geometric data of the rock slope can be done effectively and more precisely. The benefits for engineering geological application in the study area include:

- Detailed data of the vertical geometry.
- Fast assignment of spatial distribution of engineering geological units and their weathering states.
- Prompt and unbiased measurement of discontinuity sets and their orientation along large slopes.
- Rational quantification of rockfall hazard with spatial allocation.
- Detection of instable areas down to a centimetre scale.
- Safe and remote monitoring of dangerous, active mass movements.

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