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SCIENCE

Geostructure of Coroglio tuff cliff, Naples (Italy) derived from terrestrial laser scanner data

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We present a long-range terrestrial laser scanner application for the geostructural mapping of Coroglio cliff, a tuff rock face exposed along the coastal zone of Campi Flegrei, Napoli. The procedure includes several phases (geomorphological analysis, structural field survey, laser scanner data acquisition and data processing, 3-D model development and analysis, geostructural classification of discontinuity orientation data and 2-D vertical cartographic production). Field data were processed with specific software dedicated to geostructural and geometric analysis. Spatial data were managed with a geographical information system and have been used for the construction of 2-D and 3-D geometric models of the rock cliff surface and geostructural interpretation. The main product of this study is a vertical geostructural map of the Coroglio cliff at 1:500 scale that illustrates the spatial distribution and orientation of the major families of structural discontinuities detected along the exposed surface of the cliff. The cartographic product includes base information useful to identify the main rock failure mechanisms along the cliff and represents a first step for the zonation of areas susceptible to block failures and the planning of monitoring activities.

Keywords: vertical geostructural map; terrestrial laser scanner; GIS processing; tuff cliff; landslide monitoring; Campi Flegrei caldera; Naples

1. Introduction

Coastal cliffs are characterized by rapid geomorphological evolution due to intense weathering and failure processes, which cause abrupt changes in the shape of the slope and in the seafloor morphology at the toe of the cliffs. Failures along coastal cliffs are a major geologic hazard (Violante, 2009), because they are characterized by very rapid collapse of areas often including infrastructure, urban settlement and production facilities that greatly increase exposure and the

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corresponding level of risk. As rocky slopes are areas prone to rapid geomorphologic change, landsliding of coastal cliffs is also a relevant issue for coastal zone management and land-use planning (Fell et al., 2008).

The morphologic evolution of rocky coasts is typically characterized by a series of landslide phenomena including rock fall, rock topple and rock slide (Carter, 1988; Cruden & Varnes, 1996).

Rock discontinuities play a fundamental role in this context as they exert a significant control on the shape, volume and failure susceptibility of detached rock blocks (Bieniawski, 1993).

Among surveying techniques, terrestrial laser scanning (TLS) can be successfully applied to obtain extremely accurate digital elevation models (DEM) of rock slopes and cliffs, monitor landslide phenomena and understand rock failure mechanisms. In recent years, TLS has been used also to characterize the spatial orientation of discontinuities within rocks (Abellán et al., 2014; Lim, Rosser, Allison, & Petley, 2010; Olsen, Johnstone, Driscoll, Ashford, & Kuester, 2009; Young, Guza, O'Reilly, Flick, & Gutierrez, 2011). Moreover, a number of methods for automatic extraction of discontinuity orientation, based on triangle irregular networks (TIN), have been developed (e.g. Abellán et al., 2014; Slob & Hack 2004; Slob, van Knapen, Hack, Turner, & Kemeny, 2005).

Both the structural analysis of a rock slope and an understanding of potential rock failure mechanisms are necessary steps toward the definition of landslide susceptibility and hazard assessment of a cliffed coastal area. In particular, there are three main groups of methods that are commonly adopted to analyze the stability of rock slopes and construct failure susceptibility maps (Baillifard, Jaboyedoff, & Sartori, 2003; Di Crescenzo & Santo, 2007): (a) heuristic methods based on the practice of assigning a statistical weight to the various instability factors (Leroi, 1996); (b) statistical methods that compare landslide inventories with the distribution of the physical factors causing rock failure (Chung, Fabbri, & Van Westen, 1995); and (c) physically based methods that evaluate stability using physical laws (Terlien, Van Asch, & Van Westen, 1995).

All the procedures adopted to define the landslide susceptibility zoning of a rocky slope need to be complemented by the acquisition of various geological datasets derived from field mapping. Commonly, these data can be conveniently reported as a series of geothematic maps illustrating lithological, geomorphological and structural features that characterize the study area. The production of a geostructural map is only a first step to define the rock failure susceptibility along a cliff, but it is indeed a key issue for the identification of the mechanisms responsible for rock failures and their zoning along the slope.

This research presents the results of a long-range TLS survey conducted on the coastal tuff cliff of Coroglio, Naples (Italy), and illustrates a vertical geostructural map (Main Map, 1:500 scale) that was obtained by integrating the processing of TLS data with the structural mapping of selected outcrops in the study area. This activity is an integral part of the research project MONICA (Innovative Monitoring of Coastal and Marine Environment) and is also preparatory to the installation of a sensor network (extensometers, clinometers and optical fiber devices) for the real-time monitoring of selected areas along the Coroglio cliff (Minardo et al., 2014; Somma et al., 2014).

2. Study area

Campi Flegrei (Figure 1), along with Pozzuoli Bay, is an active volcanic district characterized by intense explosive activity and ground deformation during the late Quaternary (Del Gaudio, Aquino, Ricciardi, Ricco, & Scandone, 2010; Sacchi et al., 2014). With a population of more than 300,000 inhabitants and a range of infrastructure, Campi Flegrei is one of the highest volcanic risk areas in the world (De Natale et al., 2006). At the same time, its coastal zone is prone to a series of natural and anthropogenic hazards, including earthquakes, tsunamis, ground

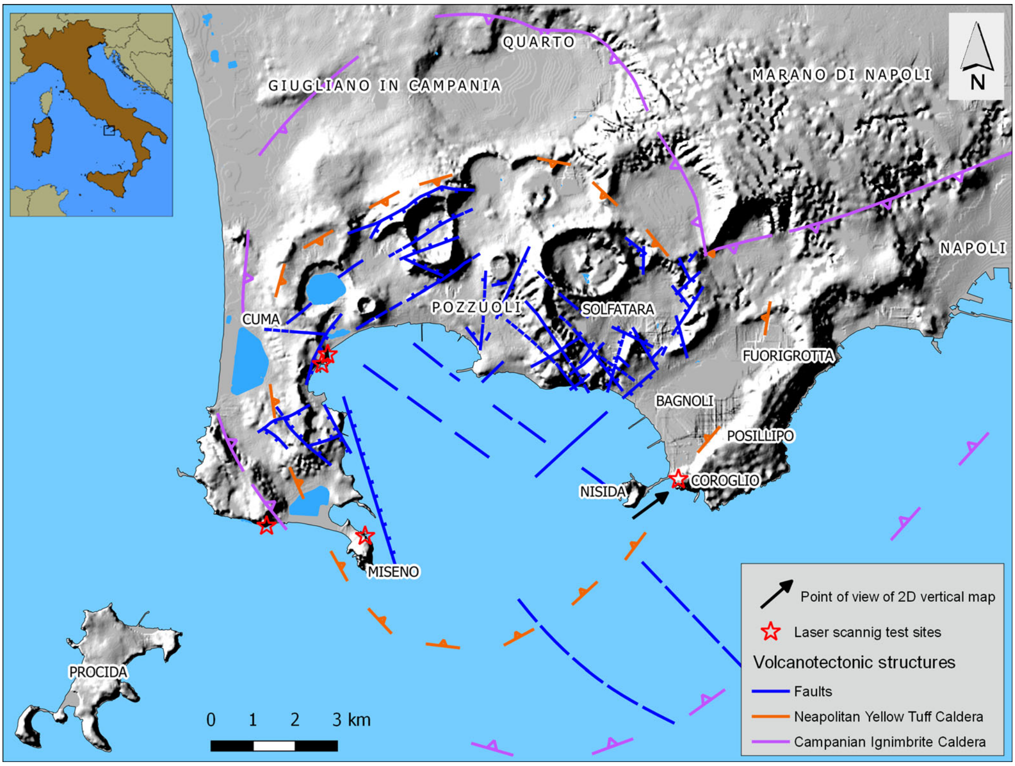

Figure 1. Study area with location of Coroglio cliff. The hillshade derives from 5 m pixel DTM of the Carta Tecnica della Provincia di Napoli (CTPN) topographic map at 1:5.000 scale (http://sit.provincia.napoli.it/cartografia_ctp98.html).

deformation, landslides, floods, storm surges and coastal erosion (Beneduce, D'Elia, & Guida, 1988; Lirer, Petrosino, & Alberico, 2001).

The coastal zone of Pozzuoli Bay is represented by both rocky cliff and sandy beach segments. Cliffed areas mostly consist of welded pyroclastites, tuffs and ignimbrites. The superposition of different rock types, characterized by variable cohesion and cementation grade, as well as the occurrence of a series of well-developed structural discontinuities and the differential erosion of bedrock are all factors that favor instability processes (Evangelista, Scotto Di Santolo, Zimbardo, Ercoli, & Nocilla, 2010). The coherent but highly erodible volcaniclastic rocks are also prone to weathering in a marine coastal environment and are subject to accelerated erosion that can be often perceived on centennial and even decennial time scale.

Based on an inventory of the coastal tuff cliffs of the Campi Flegrei (Somma et al., 2014), the eastern side of Pozzuoli Bay, Coroglio, was selected as a test site for the application of a TLS survey to begin a monitoring program of the area, on a long-term basis.

The Coroglio cliff is located along a coastal segment of Naples metropolitan area, on the southwestern side of Posillipo hill (Figure 1), a volcano-tectonic ridge formed during the large caldera collapse that accompanied the eruption of the Neapolitan Yellow Tuff (NYT), which occurred ∼15.3 ka BP (Deino, Orsi, de Vita, & Piochi, 2004). The structure constitutes the eastern boundary of the Bagnoli–Fuorigrotta depression (Figure 1) and represents a segment of the structural border of the NYT caldera (Orsi, de Vita, & Di Vito, 1996) that has been partly modified by erosive and dismantling processes (Calderoni & Russo, 1998).

Prior to the NYT eruption the area was mostly emerged, and it was characterized by the occurrence of older vents, namely the Trentaremi tuff cone (~22.3 ka BP, Cole, Perrotta, & Scarpati, 1994) whose products, partly dismantled by the erosion, are overlain by the NYT deposits. The youngest volcanic activity in the area is represented by the eruption of Nisida tuff cone, dated 3.9 ka BP (Scarpati, Perrotta, Lepore, & Calvert, 2013) (Figure 1).

The Coroglio cliff (Figure 2) is 140 m high and 250 m wide, exposed to the SW and displays an average orientation of 158°N. The upper part of the cliff has slope angles varying from 35° to 45° and is represented by ~ 30 m of stiff to loose Holocene and recent pyroclastic deposits, made up of thin-layered sandy ash and pumice, lapilli and scoria fragments, interbedded with palaeosols. At the top of the slope, soils and colluvial deposits formed by very loose reworked volcaniclastic deposits occur.

The median sector of the cliff displays nearly vertical slopes and is formed by a succession of two tuff units, separated by an angular unconformity (Figure 3). The upper part of the succession is formed by a yellowish lithified ignimbritic deposit, belonging to the upper member of the NYT formation, represented by alternating coarse-grained matrix-supported breccia, thin-laminated lapilli beds and waved welded fine ash deposits. The rock face associated with the NYT displays a relatively homogeneous texture and locally sub-planar surfaces likely controlled by structural discontinuities.

The lower part of the succession, mainly exposed on the western side of the cliff, is represented by the deposits of Trentaremi formation that consist of slightly welded to welded, whitish to yellow, pumiceous coarse-grained fragments embedded in a sandy ash matrix and lapilli beds (Lirer, 2011). The rock face associated with the Trentaremi unit is markedly controlled by the bedding of pyroclastic deposits and is characterized by diffused dm-scale vesicles and vacuoles due to differential erosion. The base of the cliff is covered by slope talus breccia and gravelly beach deposits that mainly occur along the shoreline (Figure 3).

The volcaniclastic succession cropping out at the Coroglio cliff is characterized by a complex system of structural discontinuities and fractures, mostly steep and planar with highly variable density, with well-developed NE–SW and NW–SE directions and subordinate N–S and E–W trends. This suggests the occurrence of both fracture patterns genetically associated with the

Figure 2. Coroglio cliff viewed from Nisida Island.

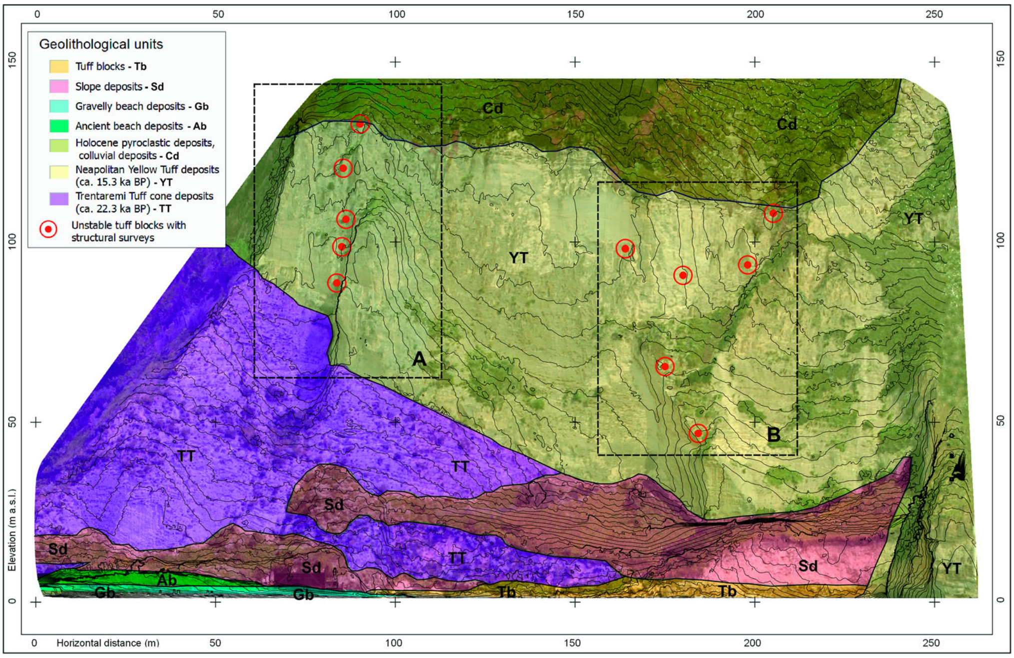

Figure 3. Geological map of Coroglio cliff with location of selected unstable tuff blocks, where geostructural surveys have been performed (A = northern sector; B = southern sector). The age of tuff units is expressed in thousands of years Before Present (ka BP). Contour line interval is 0.25 m.

structural evolution of the NYT caldera rim and a control of regional extensional structures (Acocella, 2010; Calcaterra, Gianni, Ietto, & Pappone, 1988; Vitale & Isaia, 2014).

In the easternmost sector of the Coroglio cliff, close to our study site, Froldi (2000) identified the following families of discontinuities, on the basis of the statistical analysis of 46 structural measurements (dip/dip direction): (1) K1 (83/081°) oblique to the cliff; (2) K2 (90/260°) oblique to the cliff; (3) K3 (83/307°) sub-orthogonal to the cliff; (4) K4 (81/167°) oblique to the cliff and (5) K5 (88/011°) subparallel to the cliff. According to Froldi (2000), the uniaxial compressive strength of the NYT cropping out at Coroglio is characterized by an average value of σ_c 5.39 MPa, with a mean bulk density ρ of 1.46 Mg/m^3. Therefore, the rock can be regarded as weak to moderately weak, according to the British Standards Institution (1981) classification.

Due to the general instability conditions of the Coroglio cliff in recent decades, particularly after a major rock fall that occurred in 1990, the northern sector of the upper part of the tuff cliff has been subject to reinforcement works with steel bars anchored and bolted to the rock and a wire mesh and steel cable network applied to the tuff wall.

3. Data and methods

In this study, we integrate the results of a long-range TLS survey conducted on the coastal cliff of Coroglio, Naples, with the structural mapping of two selected sectors of the study area in order to construct a vertical structural map of the tuff cliff.

The geostructural analysis was based on the method for automatic extraction of discontinuity orientation by TLS data proposed by Fanti, Gigli, Lombardi, Tapete, and Canuti (2013) that includes the construction of a 3-D model of the slope. The detection of significant discontinuity families was assisted by statistical analysis of orientation data extracted from the 3-D model of the slope and calibration of structural data measured at a number of stations for two significant transects along the rock face of the cliff (Figure 3). All georeferenced data were managed with a geographical information system (GIS).

In order to obtain a detailed 3-D model of the coastal cliff, we used the TLS time of flight method, which allows good accuracy and a great range (Abellàn et al., 2014). After data processing of the point cloud, we created an interpolated 3-D surface (triangular mesh type) and calculated the orientation (dip/dip direction) of each facet. The facets were classified into discontinuity families made on the basis of their spatial orientation and then a 2-D vertical geostructural map was produced.

3.1. *TLS data acquisition*

A long-range laser scanner, the Riegl VZ1000, was utilized for data acquisition. The scanner was equipped with a 14-megapixel external reflex digital camera, the Nikon D90.

Given the exposure conditions of the rock cliff and the possible locations for laser scanning stations, two fixed stations (Figure a on the Main Map), located along the isthmus between Coroglio and Nisida (Figure 1), have been utilized during the TLS survey in order to minimize occlusions and ensure complete coverage of the rock cliff surface.

The topographic framework of the TLS survey was produced using a Leica TS12 3″ R1000 total station. The network in the study area consisted of 2 scan stations, 5 leveling benchmarks and 11 high reflectivity targets already installed on the slope. Target positions were defined using the total station survey. Benchmarks and station positions were defined with a rapid static GNSS survey by referring to the permanent network SmartNet ItalPoS (http://it.smartnet-eu.com/), linked to the RDN network (http://www.igmi.org/rdn/), with the GNSS Leica Viva GS08plus and converted to the UTM coordinate system (datum WGS84) using Verto3 software.

The TLS survey was also anchored to the altimetry benchmark CS192 Coroglio and CS194 Nisida (Del Gaudio et al., 2005) of the 'Campi Flegrei' topographic leveling network, managed by the INGV – Osservatorio Vesuviano (Del Gaudio et al., 2010).

The scanning was acquired under fair weather conditions without fog or rain and, as the scans were made during late spring, the cliff surface was dry. The Riegl VZ1000 operates with a range of up to 1400 m for 90% of reflectivity of the target. The yellowish tuff of Coroglio cliff has an estimated average reflectivity of about 40%, so the optimal maximum range is about 600 m. In order to obtain an accuracy of 0.05 m, we set a maximum distance of $\sim$ 400 m and a minimum distance of $\sim$ 100 m (Figure a on the Main Map) from the scanning stations to the rock cliff. Four total scans of the entire cliff surface were acquired in a single scene from the two scanning stations, utilizing the view angle of the instruments ($360^\circ \times 100^\circ$).

A detailed series of photographs were also acquired with the calibrated camera mounted on the scanner during the laser scanning operations. The main output of the TLS data acquisition is a raw 3-D point cloud with a point density of 5 cm^2 and RGB images of the cliff.

3.2. *TLS data processing*

Raw TLS point data were processed in order to obtain a clean series of point data, registered in a specific coordinate system for further analysis (Abellàn et al., 2014). Data pre-processing was performed by using Riegel RisScan Pro and followed various steps including filtering, registration and decimation.

After the selection of the area of interest in the scanned scene, the filtering step consisted of noise reduction filtering and the removal of non-ground points (vegetation, metallic nets, other artifacts, etc.) through automatic filtering for trees and manual editing for others.

The registration step was aimed at merging the four scans into a unique dataset and locating the dataset in a reference coordinate system (Abellàn et al., 2014). The alignment of the four scans was obtained using the iterative closest point algorithm of Riegel RisScan Pro. This processing allowed for a significant reduction of occlusion cases.

The georeferencing of the point cloud dataset in the UTM reference coordinate system (datum WGS84) was carried out using a target-based registration, through the recognition of previously georeferenced and calibrated targets within the point cloud.

The decimation step consisted in the reduction of the number of points to produce a point cloud with a uniform sampling of 5 cm over the entire area. This was also important in order to reduce overlaps of points deriving from different scans.

The point cloud dataset is complemented by true color information, a result of matching the point cloud with the RGB images of the cliff acquired by the calibrated camera. Finally, all the points related to vegetation were removed from the point clusters associated with the rock surface. A 3-D model (triangular mesh) of the rocky sectors of the cliff, referred to as Rocky Terrain Model (RTM), was generated by processing the point cloud using Meshlab. The 3-D model is valid for the areas of the rock outcrop, and its resolution was set to 20 cm in order to reduce the computational weight. Each triangular element of the mesh has been associated with the orientation of each facet and the ellipsoidal elevation of their central point in meters above sea level.

3.3. *Structural field survey*

On the basis of a morphological analysis conducted on the outcrop, including inspections performed by climber geologists, as well as on the 3-D model of the rock surface, two sectors with evidence of generalized instability (Figure 3) have been recognized along the Coroglio cliff. Over these sectors, a series of prismatic tuff blocks >1 m^3 bounded by open fractures have been identified. Structural measurements, including dip and dip direction were collected at 11 selected stations using traditional structural fieldwork methods (ISRM, 1978). A field survey was required for kinematic characterization of the selected unstable blocks and the design of the later monitoring phase of our study.

The structural survey was conducted by rappelling along the two unstable sectors of the cliff. Cross measuring (two measuring tapes of 3 m length approximately perpendicular) was carried on each potentially unstable tuff block along the descending paths (Figure 3). Structural measurements were reported on stereographic plots, using the lower hemisphere projection (Figure 4). Contour plots were then utilized to derive the orientation of major potential failure surfaces and, consequently, estimate the possible mechanisms and kinematics of slope failures (Di Crescenzo & Santo, 2007).

3.4. *Classification of geostructural data*

The orientation of rock discontinuities can be obtained from TLS data by several methods, including automatic detection of structural discontinuities from the TIN (Abellán et al., 2014; Gigli & Casagli, 2011; Lato, Diederichs, Hutchinson, & Harrap, 2009; Slob & Hack 2004; Slob et al., 2005; Sturzenegger & Stead, 2009). These methods allow significant reduction of the error associated with measurement of discontinuity orientation (Feng, Sjögren, Stephansson, & Jing, 2001; Kemeny, Turner, & Norton, 2006). Fanti et al. (2013) obtained the semi-automatic extraction of the main discontinuity sets of a rock mass by traditional stereo plot analysis of a mesh representing the rock face of the outcrop.

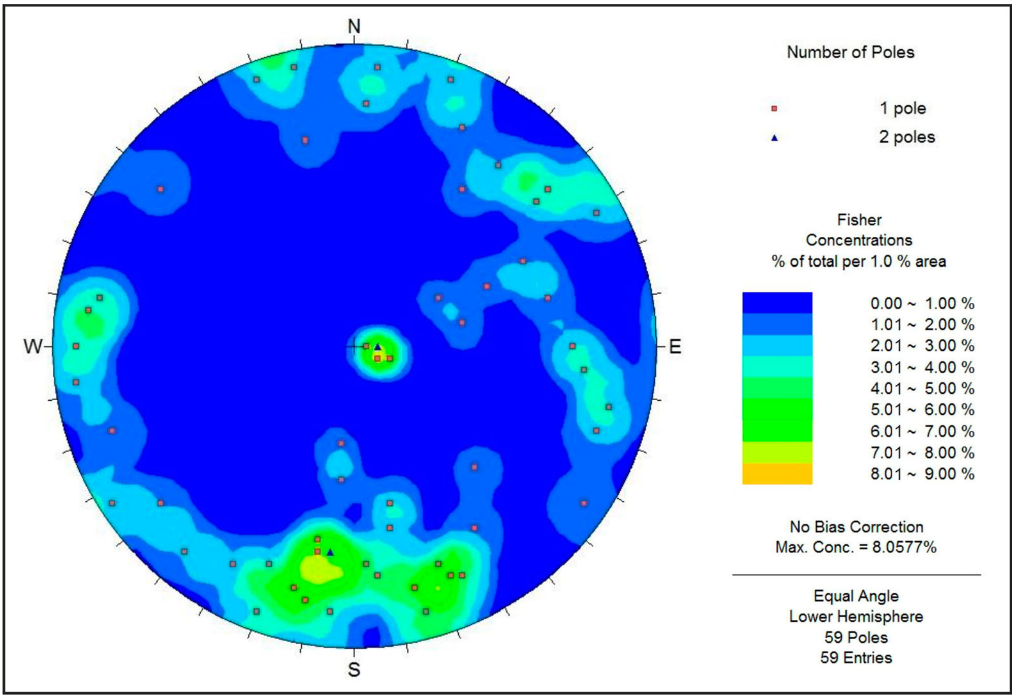

Figure 4. Pole density contour of data derived by structural field survey.

In our approach, we integrate the method of Fanti et al. (2013) and carried out GIS processing (with a spatial analysis tool) of the RTM model of the cliff and assigned attitude values (dip angle and dip direction) to each polygonal facet of the mesh.

The identification of the orientation clusters of mesh polygons was carried out through a concentration analysis of joint distribution frequency of dip and dip direction variables, performed on data of all the polygons (ca. 2.95 millions) forming the triangular mesh of the 3-D model. Statistical analysis shows a non-uniform, mainly bimodal, data distribution (Figure 5) and identifies three clusters of facet orientation in the 3-D mesh, namely C1 (dip direction 210–275°; dip 55–90°), C2 (dip direction 40–90°; dip 80–90°) and C3 (dip direction 300–355°; dip 70–90°).

The two main clusters C1 and C2 represent discontinuity sets mostly subparallel or slightly oblique to the average orientation of the cliff (85/248°). Cluster C3 includes nearly vertical structural sets that are sub-orthogonal to oblique to the cliff face. Due to its orientation, which implies limited morphologic expression on the rock face, this cluster displays relatively poor statistical relevance in the 3-D model mesh derived from TLS data. However, cluster C3, and its conjugate discontinuities, have been recognized by our structural fieldwork (Figure 4) and had been already detected by previous structural mapping of the area (Froldi, 2000).

In order to take into account all available datasets, we opted for an integration of the orientation of the mesh facets with the results of structural field mapping and data from the literature. We then used Esri ArcGIS, by means of repeated spatial queries on the 3-D model mesh of the cliff, to analyze the distribution of selected orientation intervals, derived by both structural measurements and mesh orientation data.

On the basis of the measured discontinuity sets controlling the detected block instability processes, clusters C1 and C2 were separated into three different structural sets, including their

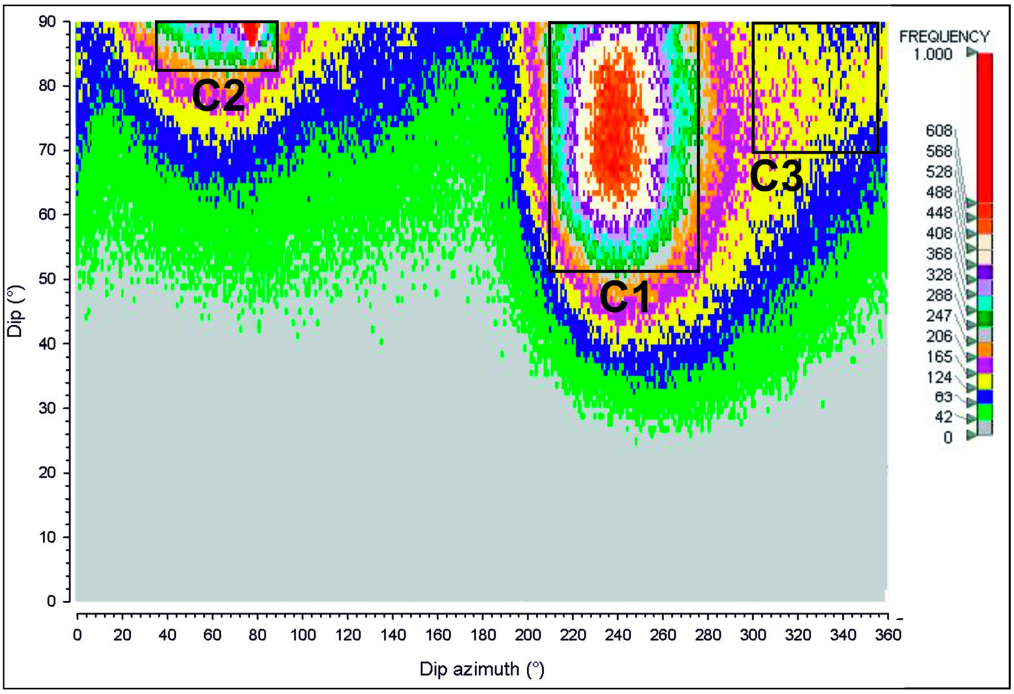

Figure 5. Data concentration plot of mesh orientation data with identified clusters.

conjugate intervals, characterized by almost contiguous ranges of orientation. Cluster C3 is associated with a minor structural set represented by nearly vertical discontinuities. Another group of discontinuities characterized by sub-orthogonal to oblique with respect to the cliff orientation is represented by sub-horizontal and slightly dipping sets (dip direction 50–195°; dip 20–65°). They were detected during the structural fieldwork but, due to their poor morphological expression, they remain substantially underrepresented in the results of the statistical analysis conducted on the triangular mesh of the 3-D model.

In this way we have identified the major orientation intervals of the structural discontinuity sets that represent a necessary dataset for the kinematic analysis of unstable blocks and the construction of a reliable geostructural map of the cliff based on the 3-D model.

Following the described heuristic approach, six main discontinuity sets have been extracted according to their attitude (dip and dip direction) ranges. Discontinuity families have been labeled from F1 to F6, according to decreasing statistical relevance (Table 1).

Table 1. Main joint sets identified on Coroglio cliff.

Set	Dip range	Dip direction range	Type
F1	>65	220–255; 35–65	Erosional and structural
F2	>65	180–220; 0–30	Structural
F3	>70	60–110; 255–280	Structural
F4	>70	110–180; 300–355	Structural
F5	20–65	50–195	Stratigraphic and/or structural
F6	<20	0–360	Stratigraphic

Set F1 is associated with parts of C1 and C2 clusters and field data. Set F2 is related to parts of cluster C1 and field data and partially matches with set K5 of Froldi (2000). Set F3 is associated with parts of C1 and C2 clusters and field data and partially matches with K1 and K2 sets described in Froldi (2000). Set F4 is related to cluster C3 and field data and partly matches with K3 and K4 sets (Froldi, 2000). Sets F5 and F6 largely correspond to discontinuity sets measured during the field structural survey.

The definition of discontinuity sets F1–F6 provided additional control on the structural characterization of the Coroglio cliff and allowed for the identification and mapping of the major families of discontinuities directly on the 3-D model of slope. The final product is a 3-D geostructural model of the cliff.

4. Cartographic production

Cartographic representation of geostructural data is usually made on vertical displays of a rock slope derived by a frontal topographic survey (Di Crescenzo & Santo, 2007). In order to develop a 2-D digital map designed for a vertical geostructural cartographic representation, it was necessary to apply further GIS processing to the acquired dataset. In fact, the RTM triangular mesh typically does not provide a full coverage of the cliff surface as it includes some 'gaps' (no data areas) that need to be 'filled' in order to develop a 2-D cartography. In the no data areas, the rock surface has been reconstructed by manual interpolation of the missing points from field measurements. Also in this case, a complete triangular mesh of the cliff (named CTM – Complete Terrain Model) has been interpolated using Meshlab.

The processing of the mesh (using Esri ArcGIS) resulted in the generation of a vertical TIN, where the '*x*' axis corresponds to the '*z*' axis (elevation), with reference to a vertical projection plane oriented 158°N, corresponding to the average direction of the cliff.

By using a GIS, the TIN model of the Coroglio cliff has been converted into a continuous spatial model, in the format of a DEM raster, characterized by contiguous pixels of equal size (20 cm). As an advantage, the spatial information of each point of the DEM is expressed in terms of Cartesian coordinates (*x*: length; *y*: height; *z*: elevation), where *z* corresponds to the distance of each cell from the selected vertical projection plane, in a direction orthogonal to the cliff. Moreover, the DEM interpolation allowed the creation of a level contour map at 1:500 scale in frontal view.

The photographs acquired with the calibrated high-resolution camera during the TLS survey were used to derive a frontal view (RGB) orthophoto of the Coroglio cliff at 1:500 scale. The mosaicking of individual photographs and subsequent ortho-rectification of the photo composition were completed using the DEM. Finally, the overlay of contour lines on the orthophoto obtained on the basis of the same DEM and reference system allowed for the production of an orthophoto map at 1:500 scale.

4.1. *The vertical geostructural map*

In order to produce a 2-D vertical geostructural map, the classified polygons of the 3-D geostructural model of the Coroglio cliff were projected on to the vertical topographic map and orthophoto. The spatial distribution on the cliff of the six discontinuity sets (Table 1) is shown on the Main Map. It is to be noted that these discontinuities are less represented in the lower left side of the cliff, where the poorly consolidated coarse-grained volcaniclastic rocks of the Trentaremi formation crop out.

The difference in the degree of coherence between the lithified tuffs exposed in the upper part of the cliff and the relatively soft volcaniclastics cropping out at the base of the cliff is also

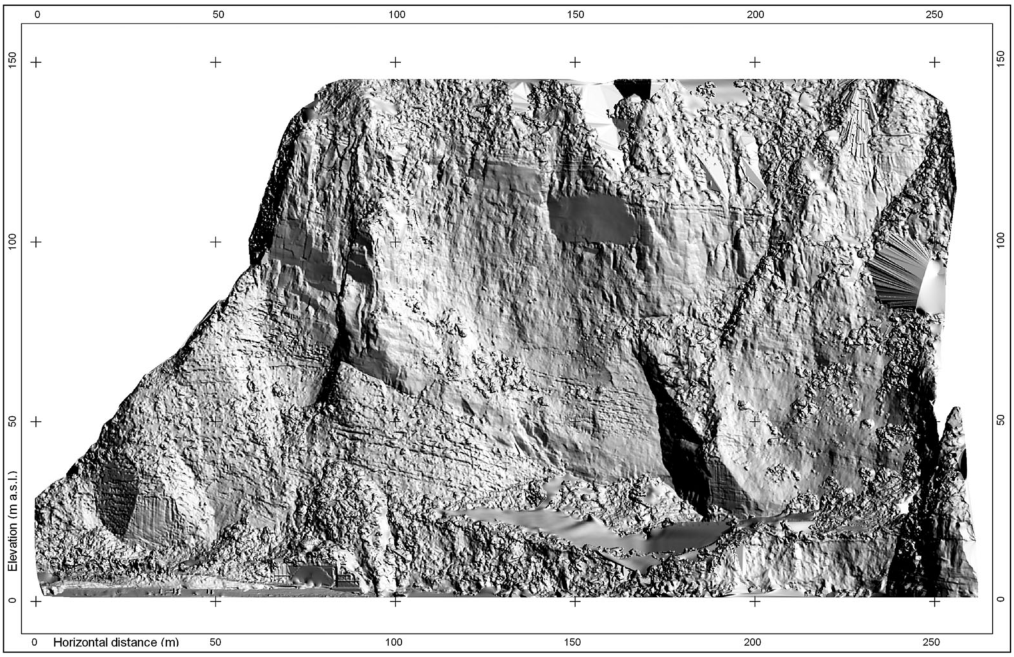

Figure 6. Shaded relief of the Coroglio cliff (DEM with 5 cm pixel; illumination from right side).

mirrored by a marked difference in the roughness of rock face topography, as expressed by the 3-D model (Figure 6).

Discontinuity sets F1, F2, F3 and F4 are vertical to sub-vertical (dip values from 65° to 90°), while F5 and F6 sets are inclined to sub-horizontal (dip values from 0° to 65°) (Table 1). Set F1 is subparallel to the cliff and shows a significant erosional control. It has been subdivided into three subsets (F1a, F1b and F1c) (Table 2) in order to better display local morphological variations.

Sets F2, F3 and F4 have a well-defined structural control but different aspect relationships with the cliff. Set F2 is subparallel to oblique to the cliff, set F3 set is oblique to sub-orthogonal to the cliff and the F4 is mainly sub-orthogonal to the cliff. These sets often identify tuff blocks isolated from the bedrock along the cliff. Sets F5 and F6 mainly display a stratigraphic control. They are often sub-orthogonal to the cliff and occasionally cut the isolated tuff blocks at their base.

Geostructural maps are the main thematic tool used in the analysis of failure susceptibility. It allows identification of areas with various classes of susceptibility toward different types of collapse on the basis of the analysis of failure mechanisms derived from the results of the geomechanical and geostructural surveys. In order to detect instability conditions and identify areas

Table 2. F1 subsets identified on Coroglio cliff.

F1 subset	Dip range	Dip direction range
F1a	>65	220–235; 30–50
F1b	>65	235–245; 50–60
F1c	>65	245–255; 55–65

susceptible to different types of collapse, a kinematic analysis needs to be performed by combining discontinuity dip and dip directions with actual slope orientation.

Conclusion

This study illustrates a long-range TLS application for geostructural mapping of the tuff coastal cliff of Posillipo hill, Naples. In this context, the accurate and rapid detection of structural discontinuities of the rock plays an important role for the definition of the failure mechanism and rock failure susceptibility.

The procedure adopted in this study consisted of an integration of several steps, including geomorphological analysis, structural field survey, laser scanner data acquisition and processing, 3-D model development and analysis, geostructural classification of discontinuity orientation data and 2-D vertical cartography, managed within a GIS.

The processing of TLS data had the main objective of implementing a detailed 3-D digital model (triangle mesh), derived from a point cloud filtered and cleaned from vegetation, without interpolated surfaces. In the 3-D model, each triangular facet is characterized by its spatial orientation data (dip and dip direction) and elevation data at 1:500 scale.

With a heuristic approach that includes integration of a statistical analysis of mesh facets from a mesh model of the Coroglio cliff with structural field data from field surveys in selected sectors and data from the literature, we identified the orientation of six main discontinuity sets (F1–F6). A classification of the 3-D facets on the basis of their spatial orientation was made, according to the defined discontinuity sets, in this way producing a 3-D geostructural model of the tuff cliff.

The pattern of detected discontinuity sets has been utilized for the construction of the vertical geostructural map of the Coroglio cliff and it is relevant for kinematic analysis of unstable blocks along the cliff surface.

In order to construct the 2-D cartography, the spatial model and geostructural data were rotated to a vertical projection plane oriented 158°N, which is the average direction of the cliff. Following this approach, we have produced a geostructural map of the discontinuity sets that may control the potential failure mechanisms recognized on the cliff.

The main result of this research is a geostructural vertical map of the Coroglio tuff cliff at 1:500 scale (Main Map) reporting the spatial distribution and orientation of the six discontinuity sets detected along the slope.

The map can be used for identifying the main failure mechanisms along the cliff and represents a first step for the zonation of the rock failure susceptibility of the study area. The 3-D geostructural model of the cliff can be also used in a multi-temporal monitoring method by means of repeated TLS surveys and for reference to the installation of monitoring sensors.

Software

TLS data acquisition and processing was performed by using Riegel RisScan Pro. A 3-D model (triangular mesh) was generated by processing the cleaned point cloud using Meshlab. The statistical analysis of orientation data of mesh polygons was carried out with XLSTAT 2014.

RockScience Dips was used for analysis of the geostructural data and their stereographic projection. Verto3 was used to convert target, leveling benchmark and station position data to the UTM coordinate system (datum WGS84).

GIS processing of the 3-D model of the cliff was performed in order to assign attitude values to the triangular mesh by using Esri ArcGIS. ArcGIS was also used to generate the final 2-D map by converting the mesh to a vertical TIN and then a DEM. Interpolation of the DEM resulted in the production of a contour map and an orthophoto at 1:500 scale in frontal view.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Istituto Nazionale di Geofisica e Vulcanologia

Geostructural vertical map of the Coroglio cliff, Naples (Italy) by long-range Terrestrial Laser

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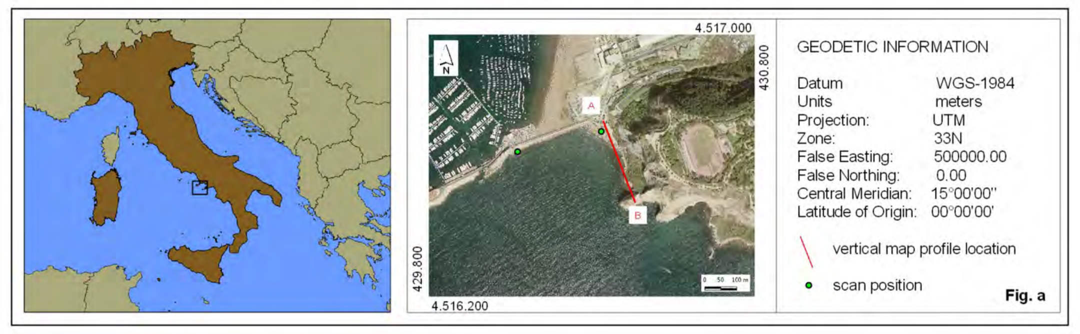

Fig. a

VERTICAL MAP EXTENSION (meters)

X min 430.400
Y min 4.516.550
Z min 0

X max 430.500
Y max 4.516.800
Z max 150

The maps show the results of a long-range Terrestrial Laser Scanner (TLS) application for rock slope geostructural mapping along the Coroglio tuff cliff, located in the coastal zone of the Posillipo hill, Naples, in the Campi Flegrei active volcanic area (southern Italy) (Fig. a).

The geological, geomorphological and geostructural field survey allowed the recognition of various geolithological units cropping out along the cliff (Fig. b) and the characterization of the main sets of fractures determining the possible failure mechanisms of unstable tuff blocks. The elaboration procedure includes several phases of work with the use of different specific softwares in Geographical Information Systems, such as: i) Laser Scanner (mod. RIEGL VZ1000®) data acquisition and data processing, ii) 3D model development and analysis, iii) discontinuity orientation classification, iv) 2D vertical cartography and orthophoto elaboration (Fig. c).

The main result is a geostructural vertical map of the cliff at 1:500 scale (central figure in the map) reporting the spatial distribution and the orientation of six discontinuity sets (F1 to F6) detected along the exposed surface of the slope. In order to allow a better view, the single joint set (with F1 set divided in 3 sub-sets) are showed in the lateral figures in the map at a 1:1000 scale .

The study is aimed at identifying the joint sets controlling the main failure mechanisms along the cliff. The map is the first step to define susceptibility zoning to block failures and is also preliminary to monitoring activities, including installation of a sensor network and multi-temporal TLS surveys.

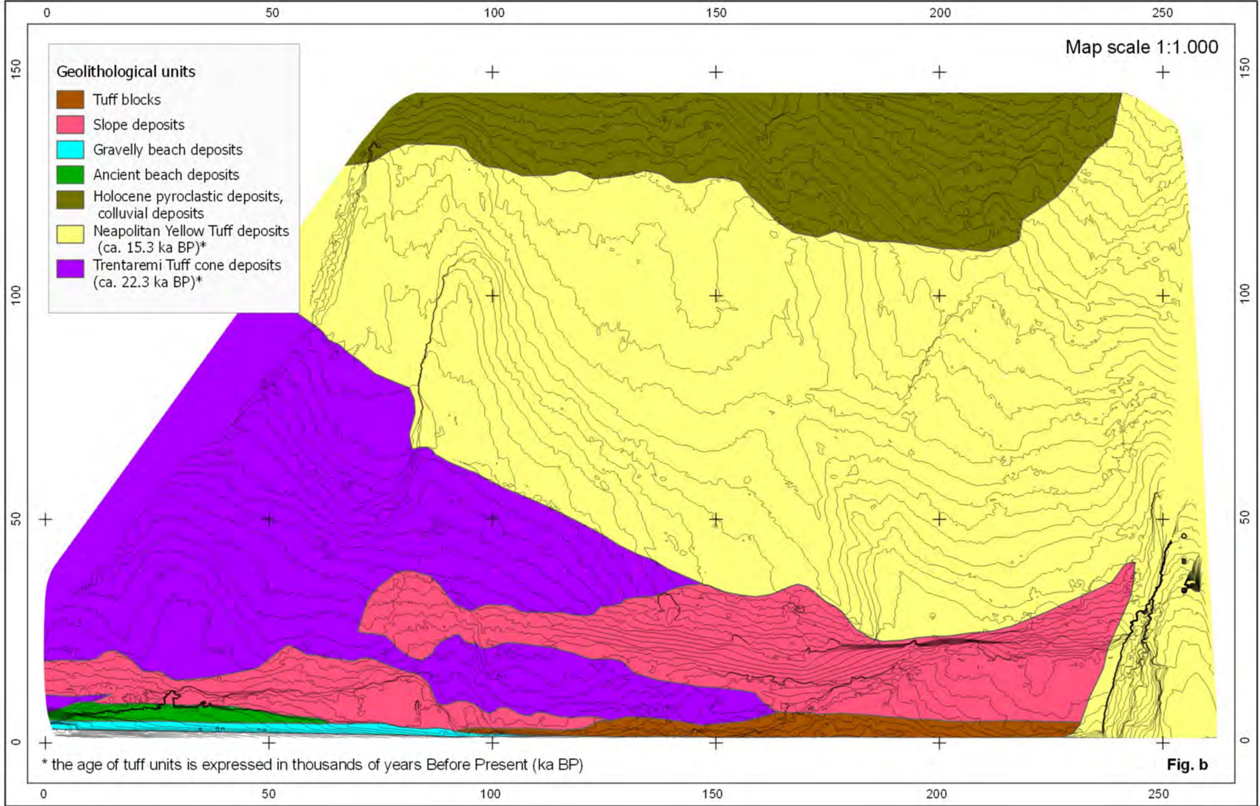

Fig. b

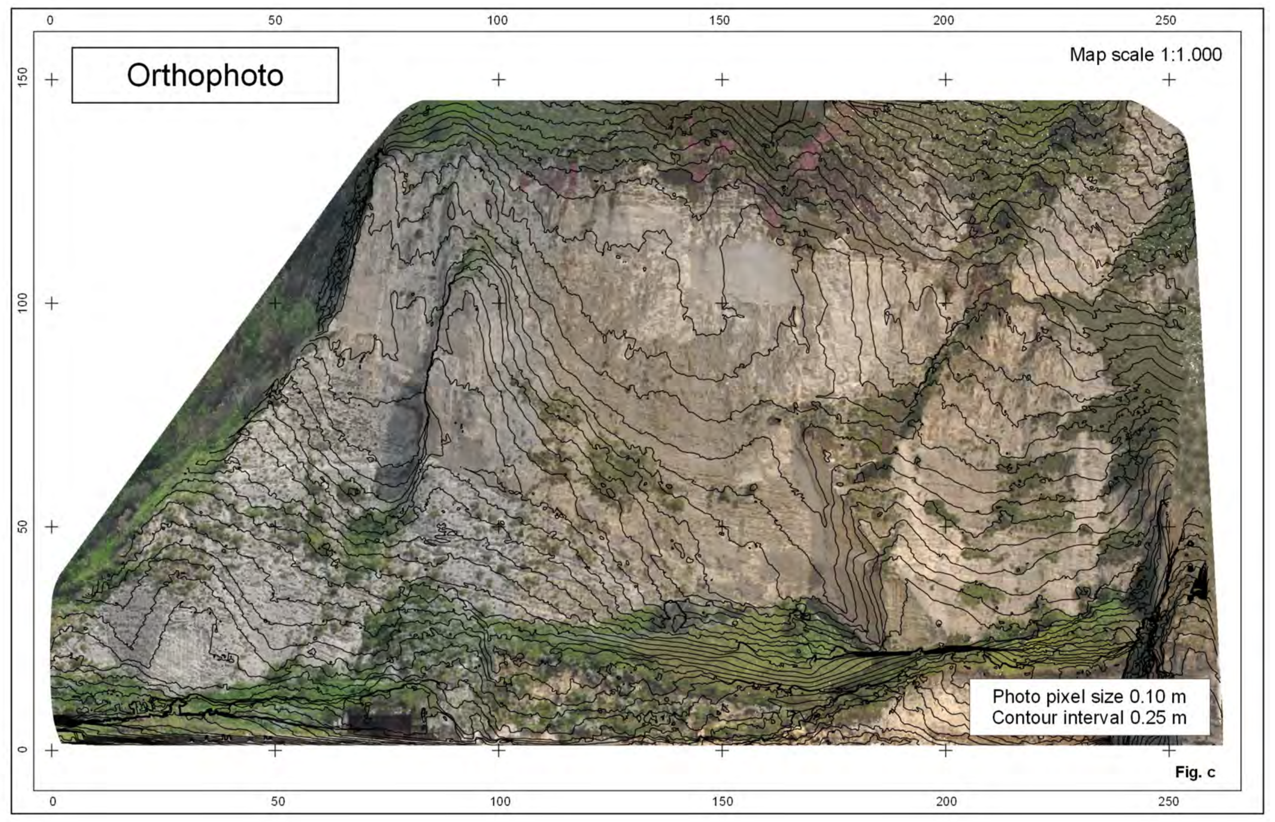

Fig. c