MAPPING VERTICAL CLIFFS
– EXPERIENCES FROM THE DOLOMITES MOUNTAINS –

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Abstract
The article reports the challenging work of 3D surveying and accurately modeling the "Tre Cime di Lavaredo", often considered the icon of the Dolomites. They fully represent, with their shapes and colors, the concept itself of the UNESCO's site. The 3D recording is based on a fusion of oblique airborne and terrestrial laser scanning, in order to survey all the relief complex, focusing especially on the vertical cliffs. Aerial and terrestrial high-resolution images are also employed for texture mapping purposes. Results of the produced high-resolution photo-realistic 3D model are presented and discussed.

Figure 1: The "Tre Cime di Lavaredo" (Three Peaks / Drei Zinnen), an icon of the Dolomites (NE Italy).

Introduction
The Dolomite mountains (NE Italy) have been declared a UNESCO World Heritage Site in 2009. It features some of the most beautiful mountain landscapes anywhere, with vertical walls, sheer cliffs and a high density of narrow, deep and long valleys. This is particularly true for the "Tre Cime di Lavaredo" (Three Peaks or Drei Zinnen), often considered as one of the "trademark" symbol of the Dolomites as they fully represent with their shapes and colors the icons of the UNESCO's site. The vertical dimension of these and similar mountain complexes are usually unmapped and poorly resolved in a cartographic "nadir-dominated" world. The goal of the project called "Peaks-3D" is the highly detailed 3D surveying of the "Tre Cime di Lavaredo" (and other similar rock complexes), especially their vertical cliffs, nearly 600 meter high, for digital documentation and conservation, geological and geomorphological analysis, tourism and communication purposes, 3D mapping of the ascent roots, etc. The digital recording of the current situation and the monitoring of ongoing processes are fundamental prerequisites for analyses and establishment of sustainable measures of protection.
The 3D surveying of the "Tre Cime di Lavaredo" is based on a fusion of oblique airborne and terrestrial laser scanning. Aerial (nadir and oblique) and terrestrial high-resolution images are also employed for texture mapping purposes. 3D surveying and modeling works, based on the integration of aerial and terrestrial

LiDAR data are presented in Ruiz et al., (2004) and Boehm & Haala (2005) respectively for steep terrain modeling and 3D city modeling. Landslide monitoring is presented in Sturzenegger et al., (2007), Szekely et al. (2009) and Squarzoni et al. (2009). Gruen & Murai (2002) reported the image-based 3D surveying and modeling of Mount Everest for cartographic and mapping applications.
In the next sections the 3D recording campaign with the achieved results of the realized high-resolution photo-realistic 3D model are presented and discussed.

3D recording campaign

The 3D surveying was firstly attempted with a traditional aerial photogrammetry approach, combined with some terrestrial laser scanning (TLS) acquisition to overcome some occlusions of the aerial views. After the first photogrammetric results, we realized that the available images were not ideal for the automated DSM generation and so an oblique LiDAR flight was performed and integrated with the TLS data. Terrestrial images were also acquired, both in the visible and IR domain, for photo-realistic visualization of the final 3D model and further thermal analyses of the geological structures.

Photogrammetric surveying

Photogrammetry is able to derive metric and accurate 3D results at various scale of applications and aerial photogrammetry is the primary source for mapping and cartography. For the 3D recording and modeling of the "Tre Cime di Lavaredo", a dedicated photogrammetric block was flown on September 2004 by CGR Parma (Italy) using a Wild RC30 camera with a 153 mm lens and 60% forward overlap (Figure 2a).

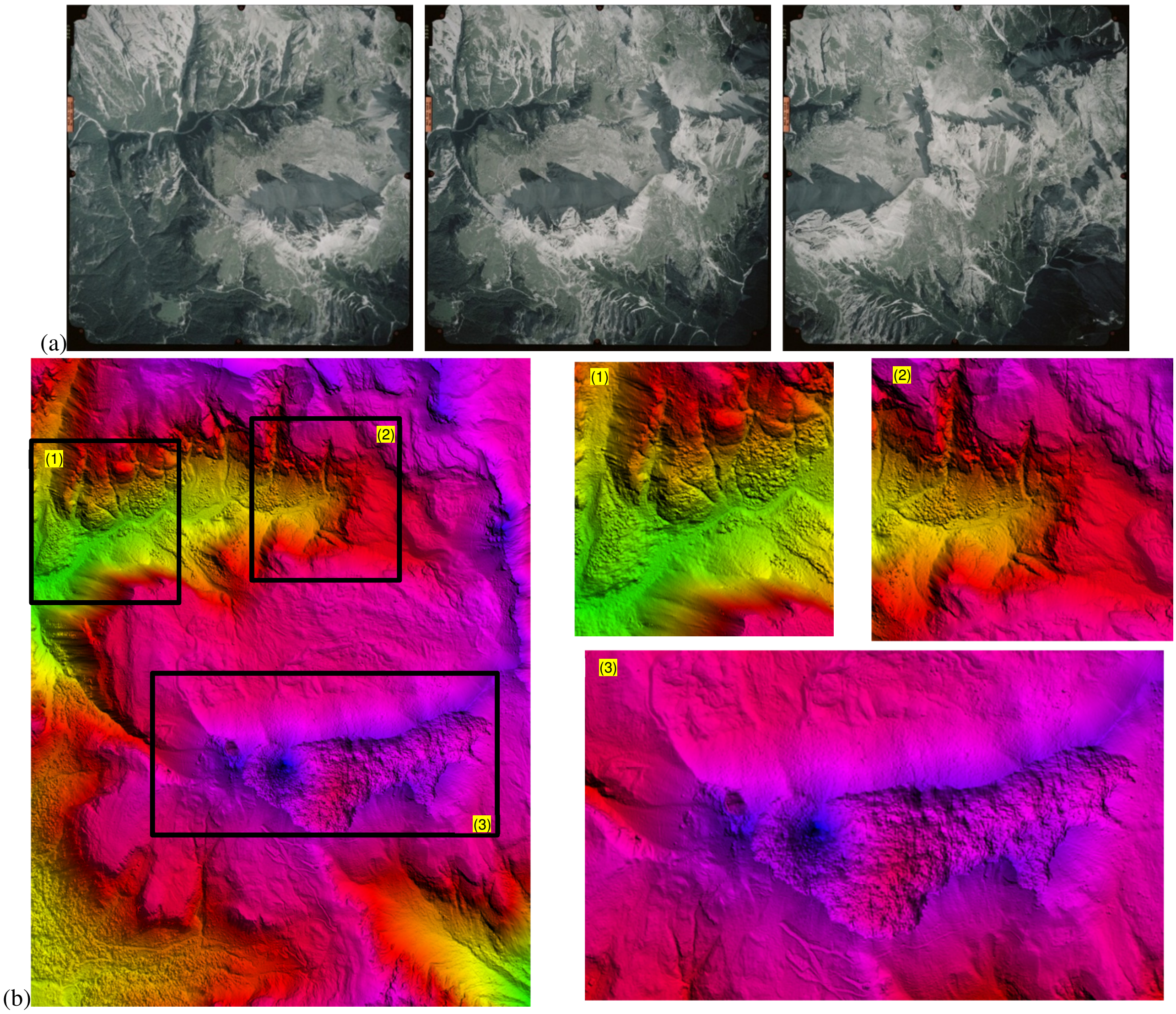
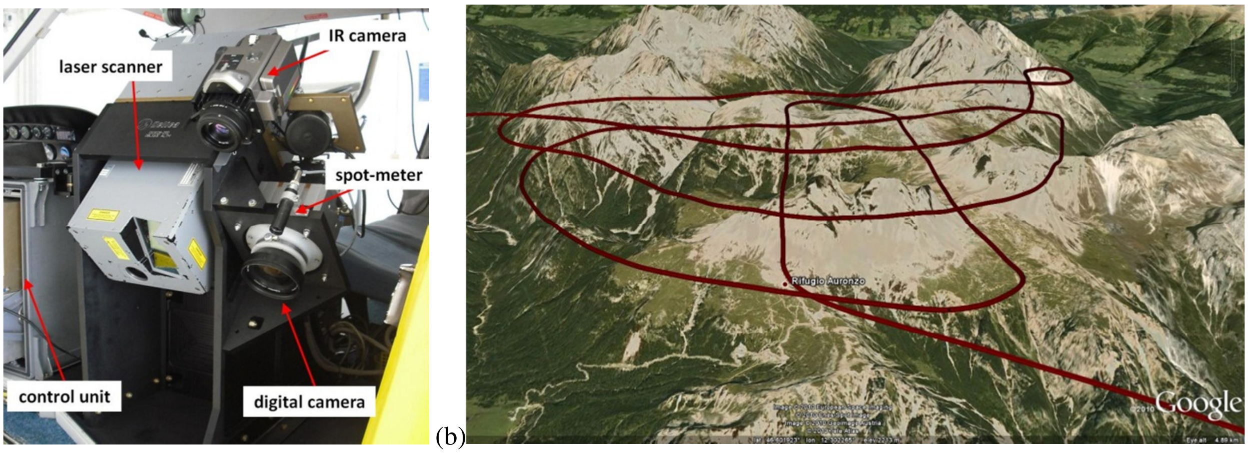


Figure 2: The photogrammetric images over the "Tre Cime di Lavaredo" area (a): the large baseline between the consecutive images caused problems for the 3D reconstruction of the great discontinuities and the vertical cliffs. The produced DSM at 1 m resolution and some closer views are shown in color-code mode (b).

The flying height above sea level was approximately 5,400 m and produced an average image scale of 1:20,000 (scale variation from 1:15,000 close to the peaks to 1:23,500 in the surrounding valleys). The analog images covering the area of interest (Figure 2a) were digitized at 14 micron pixel size, leading to an average GSD of 28 cm (GSD variation from 21 cm to 33 cm). Some GCPs were acquired on site with a Topcon GNSS and used for the triangulation of the aerial images within ERDAS LPS. The successive DSM was produced using the advanced image matching algorithm of SAT-PP (4Dixplorer AG) with a grid size of 1 m. As shown in Figure 2b, due to the huge parallaxes and insufficient texture in many portions of the mountains, the automated DSM generation failed in those areas while the surrounding valleys are pretty well matched and reconstructed. These results suggested to survey the area with an aerial LiDAR approach.

Airborne laser scanning (ALS)
The aerial LiDAR survey was performed by Helica (http://www.helica.eu) using an Eurocopter AS350 B2 and the instrumental set-up shown in Figure 3a. The patented Helica installation (Table 1) consists of an Optech ALTM 3100 EA LiDAR system coupled with a Rollei digital camera and a NEC infrared digital camera. The ALTM 3100 EA is an ideal solution for engineering and corridor applications while maintaining the flexibility to collect higher altitude data. It provides simultaneous measurement of first and last return for each emitted pulse with an elevation accuracy of 5 cm at 500 m distance. The oblique mounting of the laser scanner, although requires a more delicate flight planning, allows the detailed surveying of complex sites where a traditional nadir acquisition would not be sufficient. The flight was planned to survey the vertical cliffs at different altitudes with four strips along the peaks and two strips in the orthogonal direction (Figure 3b).

(a)


(b)

Figure 3: The Helica instrumental set-up for the oblique LiDAR surveying and image acquisition (a). The flight-path for the 3D surveying of the "Tre Cime di Lavaredo" area with the oblique LiDAR system of Helica (b).

ALS		**Digital camera**		**IR camera**	
Type	Optech ALTM 3100 EA	*Type*	Rollei 6008 DB45 with Phase One H25	*Type*	NEC TVS-200 EX
Wavelength	1064 nm	*Sensor*	CCD, 5440 x 4080 px	*Sensor*	Uncooled FPA, 320 x 240 px
Class	IV	*Pixel size*	9 micron	*Wavelength*	8-14 micron
Operative dist.	80-3500 m	*Radiom. resol.*	16 bit	*Radiom. resol.*	14 bit
Elevation acc.	5-20 cm (1σ)	*Objective*	Super Angulon 50mm f/2.8	*Objective*	14 mm

Table 1: The components of the Helica patented installation, composed of an oblique LiDAR sensor, a digital and IR cameras.

	TLS 2009	**TLS 2010**	**ALS 2010**
stations	36	17	-
points	82 Mil	128 Mil	43 Mil
aver. resolution	5 cm	5 cm	>10 pt/m^2

Table 2: The acquired range data in the different campaigns and modalities.

Terrestrial laser scanning (TLS)

To overcome some recording gaps of the airborne LiDAR surveying, primarily due to occlusions and hidden rock features, two field campaigns were performed in the summers of 2009 and 2010. An Optech ILRIS 3D was used to acquire ca 210 millions points. The scanner has a range interval of 3-1700 m with a range accuracy of 7 mm at 100 m. The laser is class is 1 and the wavelength is 1535 nm. The range-based 3D surveying was performed from different positions trying to achieve an average geometric sampling step of 5 cm on the cliffs (Table 2).

3D data integration, modeling and interpretation

Data editing and registration

The aerial and terrestrial range data needed to be co-registered and merged into a unique and seamless 3D point cloud. Therefore the software solution to perform these operations should be able to deal with:

- multi-resolution data;
- 3D geometries (not only 2.5D);
- large amounts of geo-referenced data;
- texturing.

The range data editing and integration was performed using the JRC Reconstructor software (http://www.reconstructor.it/), a powerful solution to process 3D data from multiple sources. An ICP approach performed the registration of the multi-resolution data (Figure 4) which were afterwards converted into polygonal meshes for further analyses and geological studies.

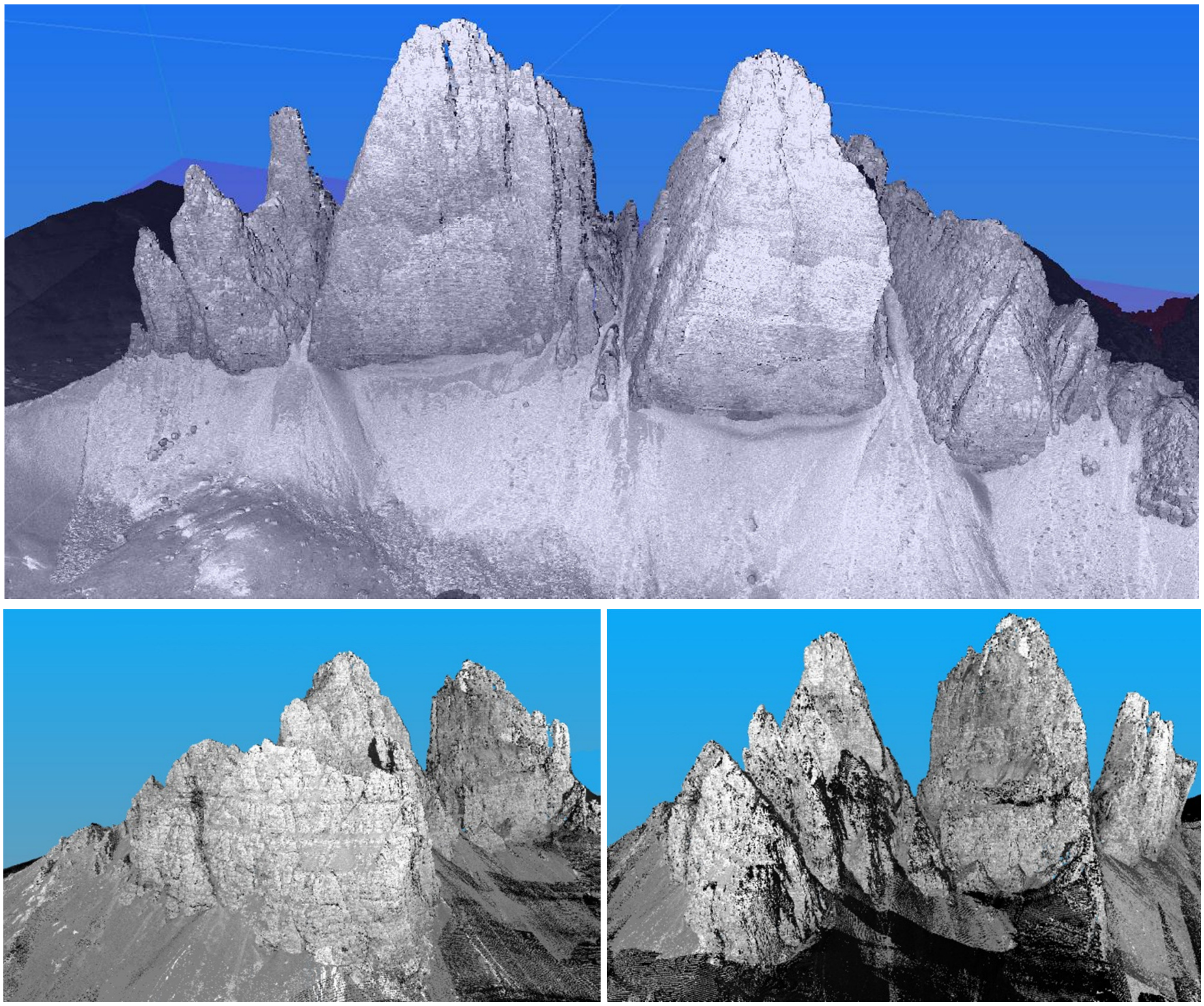


Figure 4: The aerial and terrestrial LiDAR data of the "Tre Cime di Lavaredo", aligned and visualized with JRC Reconstructor. Views respectively from north, south-west and south-east.

Photo-realistic visualization

JRC Reconstructor allows also the texturing of range data, with a classical DLT approach between the 3D data and a visible or IR image. Some results are shown in Figure 5.

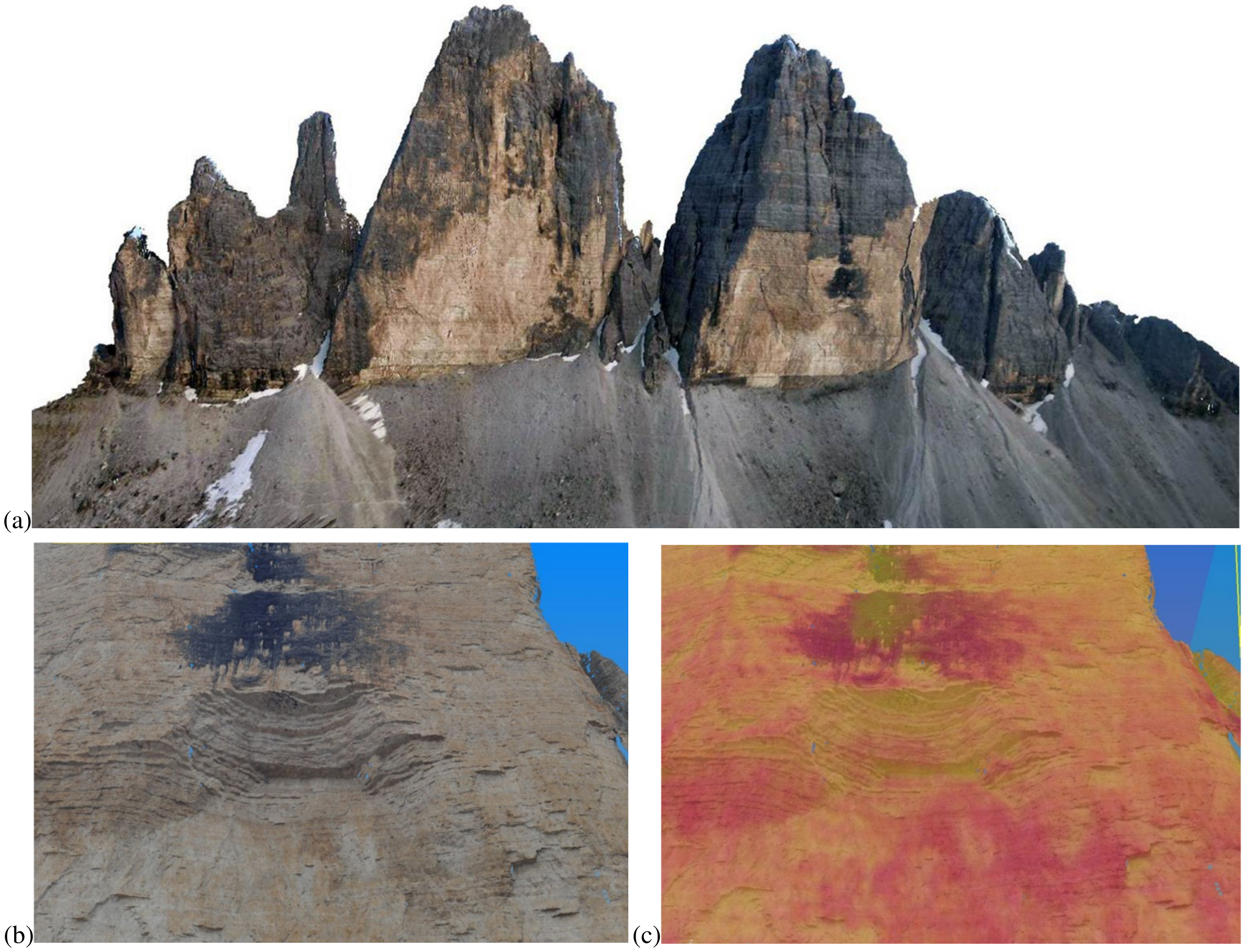


Figure 5: The final textured 3D model of the "Tre Cime di Lavaredo" viewed from north (a). A closer view of a particular overhanging area, correctly surveyed and modeled thanks to the sensor and data integration, here textured using visible (b) and IR (c) images.

Geomorphological and geological analyses

The "Tre Cime di Lavaredo" are entirely made up by compact Dolomia Principale or HauptDolomit (220-210 million years ago) and represent the most typical landscape in the Dolomites area, with forms of towers, steeples, crests and pinnacles. They are a typical example of landforms linked to morpho-selection, more specifically of morpho-tectostatics shape (Panizza, 2009) determined by the trends of important displacement and fracture lines and related belts of cataclastic rocks, which facilitate differential weathering and erosional processes. During the last decades there have been numerous rock falls and topples from over 2000 m high Dolomite peaks (Fazzini & Panizza, 2006). It is thought that these movements are the consequence of thaw of portion of frozen ground filling the crevices of Dolomite, related to the increase of summer temperatures, which has been recorded in the recent years. Progressive thaw-frost cycles have progressively caused a higher probability of rock block detachments with consequent falls and topples (Gruber et al., 2004). For all these reasons, the availability of accurate 3D geometric surveying over the entire relief complex of the "Tre Cime di Lavaredo" offers the opportunity to systematically study relationships between relief shapes (e.g. rock faces) and the network of planar discontinuity (e.g. faults, fracture, joint and bedding) that will be extracted from the unstructured 3D point clouds and mesh, by testing both commercial and in-house software. 3D data are also useful to detect and monitor active processing of rock-masses weakening and consequently falls and landslides. The latter is true, especially if the LiDAR data are linked to complementary datasets like multi-temporal thermal camera observations. Range data provides also information about intensity of the scanned scene that is, in principle, proportional to the surface's reflectance and depends on the physical and chemical properties of the surface. Experiments on reflectance series obtained from TLS data show intensity variations along a stratigraphic section and give an estimate of the rock content variations during the geological time and highlight cyclicities that can represent the clue of sedimentary cycles (Franceschi, 2008).

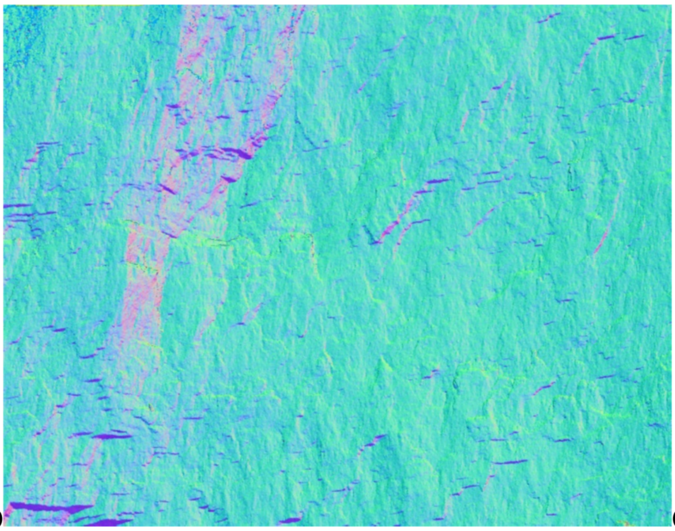
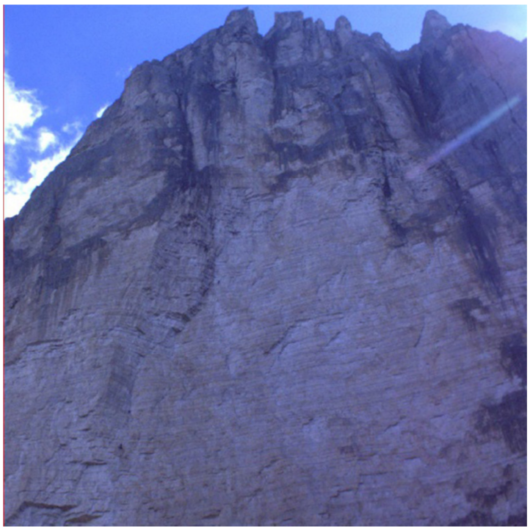
(a)  (b) 

Figure 6: Rendering of the surveyed central peak visualized according to the surface normal orientation.

Conclusions and future works

The article presented the preliminary results of the 3D surveying and modeling of the “Tre Cime di Lavaredo”, an icon of the Dolomites UNESCO’s site. The vertical cliff and complex geological structures required an integration of aerial and terrestrial 3D recording in order to accurately and fully survey all the site. In particular the oblique LiDAR acquisition system demonstrated its great potentialities for mapping vertical and steep mountains. A digital multi-resolution geometric model is now available for geological analyses (Figure 6), stratigraphic interpretation, physical replicas, 3D mapping and planning of the ascent routes (Figure 7), digital archiving, etc.

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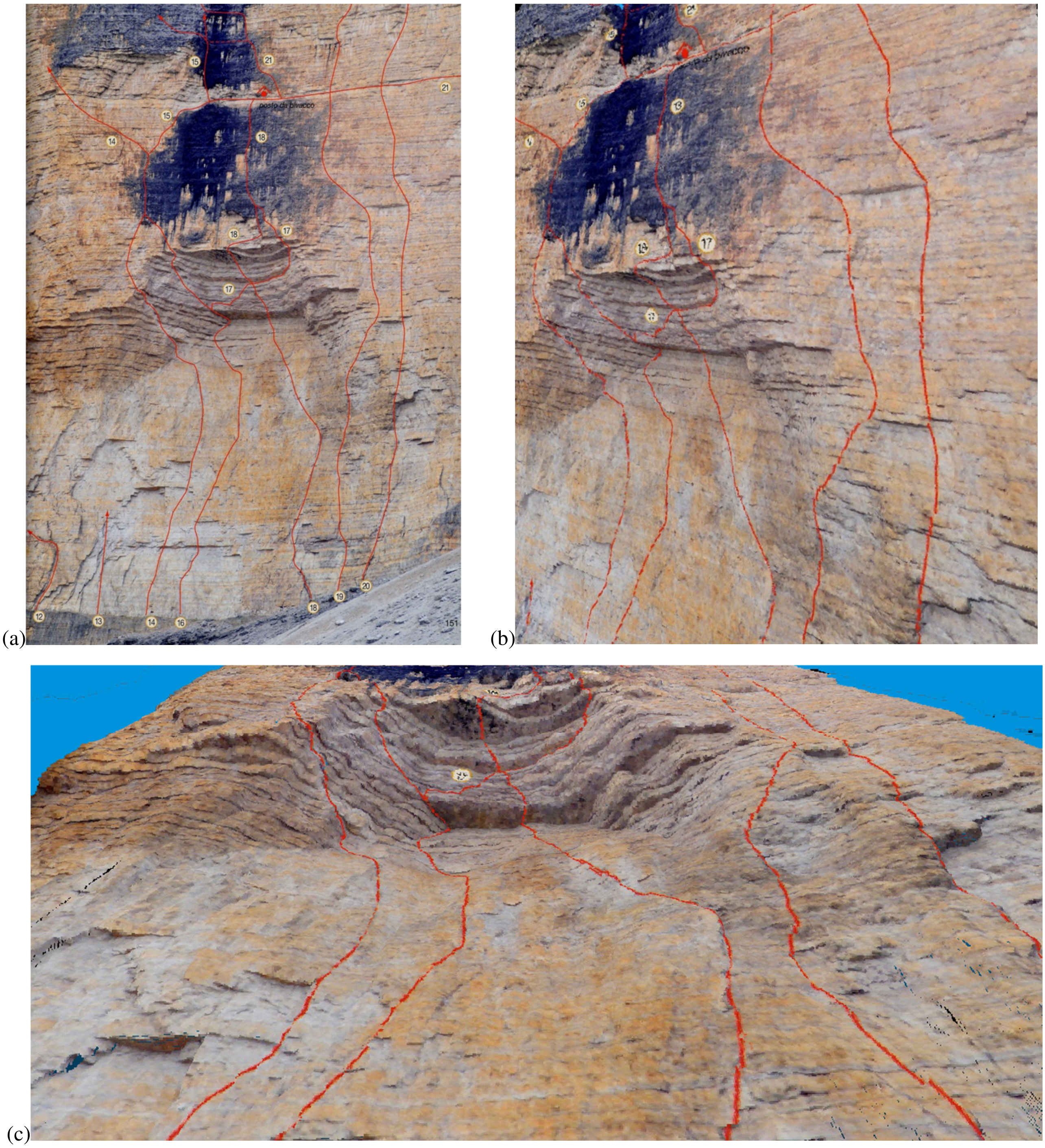

Figure 7: An image of the ascent routes (Svab & Renzi, 2009) (a) mapped onto the 3D model of the west peak (b, c).

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