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ORIGINAL ARTICLE

3D Exploration of the San Lucano Valley: Virtual Geo-routes for Everyone Who Would Like to Understand the Landscape of the Dolomites

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Abstract This paper proposes a methodology to integrate 49 geomorphosites, identified and described in San Lucano Valley (Belluno, Italy), in the technological platform developed by the 2-year long Openalp 3D project (www.openalp3d.it). The valley that has been inscribed since 2009 on the UNESCO World Heritage list, as part of the Dolomites good, is well known as a tourist attraction for its wonderful natural environment, where many sports are often practised: ice climbing, rock climbing, mountaineering, hiking, biking, fishing, etc. However, it is not equally known for its geo-elements even if these are some of the key elements needed to understand the geologic and geomorphologic evolution of the Dolomites. In the virtual 3D scenario, the user can explore, at the same time, the geomorphosites and all their related explanations (geological and geomorphological sketches, pictures, how to reach them, attached documents.pdf, etc.) and tables, on different types of maps and on the same setting together with natural, historic-cultural heritage elements and tourist accommodations and facilities information. In order to be a planning tool for sustainable tourism development and for territory promotion, Openalp 3D creates a network on the territory for an extremely accurate analysis of landform, integrating geomorphosites, geological sites and paths in the multidisciplinary and multiscale database. This powerful support to science at all levels might help everybody to understand the importance of the conservation and enhancement of geomorphosites.

Keywords Geomorphosites · Multisciplinarity · Multiscale · 3D visualization · Dissemination · Dolomites

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Introduction

In recent years, the development of information technology has led to a rapid development of tools for managing spatial data banks; after a phase of specialization in functionality, the ease of use has become a priority.

Many tools used to communicate to non-specialists have been developed, although specific research for geo-interpretation and on the impact of geotourism products is not widespread and should be encouraged (Martin 2014).

Geoheritage is mostly recognised by geoscientists, but is still poorly understood by the public and political authorities (Martin 2014).

The concept of 'geo-interpretation' has been defined as "the art or science of determining and then communicating the meaning or significance of a geological or geomorphological phenomenon, event or location" (Hose 2012). A model for environmental and cultural tourism should achieve the following targets: educate people on geological science and on the importance of their geoheritage and environmental preservation and safeguard sustainable socio-economic and cultural development (de Grosbois and Eder 2008).

To better understand the geological, morphological and environmental importance of an area, it is essential to choose the right tools for communicating this kind of scientific information (Ghiraldi et al. 2010; Suma and de Cosmo 2011; Cayla et al. 2012; Martin et al. 2014).

Fundamentals include the functions that enable the updating of information and maps (Aldighieri et al. 2011; Ghiraldi et al. 2014), and the tool must be able to collect and rigorously classify scientific data about geological heritage within a database but it must also provide a simple display, integrated with geo-referenced, static and dynamic maps, allowing the user to understand and interpret the evolution of the landscape. It must also be a tool with a simple user interface, allowing the dissemination of information, previously processed by specialists using the GIS, to different types of users (specialists, students, tourists, etc.).

In this paper, we propose an extension of the tool developed in the Openalp 3D project and describe an example of its use for contributing to the public understanding of science (Martin et al. 2010), which is usually difficult to achieve.

The Openalp 3D project, directed by GAL (Local Action Group)–Regional Rural Development Plan 2007–2013, is included in the Veneto-Local Development Plan ('V.E.T.T.E.'), measure 313 'Incentives for tourist activities', Action 4 'Information'. In this project, the authors, as scientific coordinators of the project, have chosen to adopt a platform of shared type: this option makes it possible to create a 'community network' in which each user can promote the development of sustainable tourism utilizing his/her own experience and emotions to enrich its content concerning nature, history, culture, traditions and tourism in a proactive way.

Presentation of the Openalp 3D Scenario

The hybrid platform Openalp 3D consists of two portions: the 3D scenario (DTM, digital terrain model) including the database structure, which can be freely downloaded on a PC from www.openalp3d.it or www.3drte.it, and the database contents that reside on an external server. Both the software for 3D navigation and the 3D scenario containing vector elements (lines, points and polygons), raster maps (maps, digital orthorectified images, etc.), as well as links to online maps (e.g. Google maps, National Cartographic Portal, etc.) must be downloaded and installed.

The architecture of the system ensures content dynamics through an upgrade process. The external server does not only provide HTML pages containing information and documents but also acts as a collector for new items from those who are authorized to enter data, upload to the server vector elements and create html pages containing related information, images and files to download (gpx, kml, pdf, etc.). Every time a user opens the scene

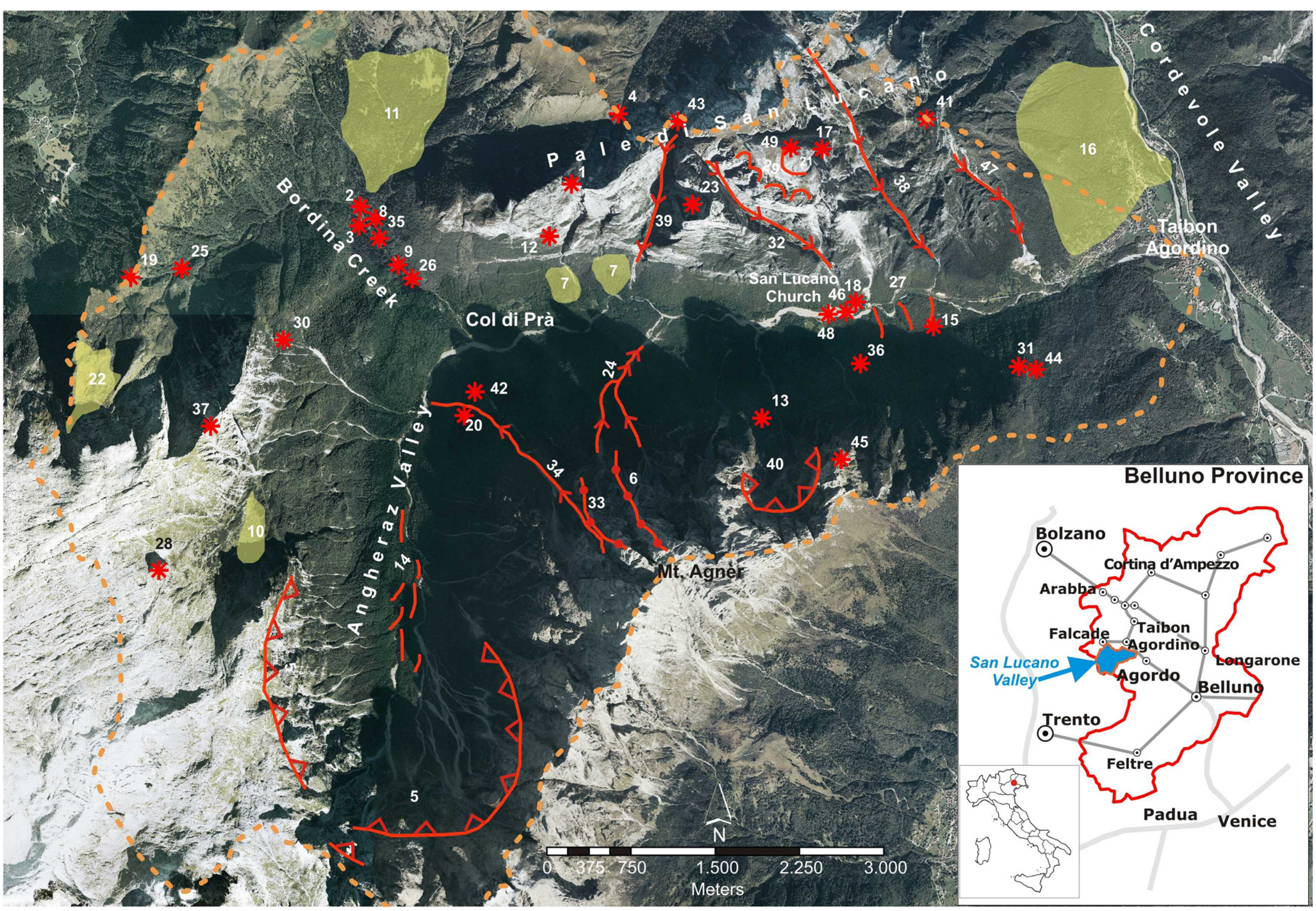


Fig. 1 San Lucano Valley and localization of its geomorphosites. See Table 1 for the description of the 49 geomorphosites. *Asterisk* geomorphosite with limited area, *red line* geomorphosite with linear extension, *yellow area* geomorphosite with extended area, *orange dashed line* boundary of San Lucano Valley

with an Internet connection, it automatically downloads these updates. A further application for 2D display of the same information contained in Openalp 3D has also been developed and named Openalpmaps (www.openalpmaps.it). This application is easy to use on all mobile devices equipped with GPS.

The 3D scenario is made up of a raster component (the cartographic background) and a vectorial component (the recorded and geo-referred elements).

The '3D cartographic background' consists of raster maps processed according to the DTM (5 × 5 m cell): 2006–2007 Veneto Region orthophotos; Regional Technical Map (CTR), scale 1:10,000; aspect map and the hillshade map with the hydrographic network.

The descriptive vectorial elements, concerning the natural, artistic and historic-cultural qualities, are organized in a 'content tree' in the main menu located near the map. The main menu is populated as the project is developed. The database is organized into categories and subcategories, as follows:

> Nature: viewpoints, 'Enrosadira' (Alpenglow), biotopes, geosites, waterfalls, monumental trees, glacial-snowfields, springs, flora, etc. (e.g. 'point' elements); protected areas (regional parks, provincial parks, etc.), sites of community interest, UNESCO areas (e.g. 'Polygon' elements)
> Art, history, culture, traditions: museums, churches, historic buildings, historic areas of interest, sundials, artistic monuments, rocks with engraved cross-signs, fountains, 'calchere' (lime kilns), 'ial' (areas once used to produce wood charcoal), abandoned mining sites (only those accessible), archaeological sites, Venetian sawmills, mills, sites linked to the First World War, micro-toponymes, legends, texts from literature, figurative works, pictorial representations, coats of arms, etc.
> Routes: Dolomite Highways n.1 and n. 2, www.camminodelledolomiti.it, www.ciclabiledolomiti.com, www.viadeipapi.org, many routes concerning artistic, cultural and/or natural peculiarities
> Tourist accommodation and facilities: shepherd's huts, sheds, shelters, camps, hotels, 'Bed & Breakfasts' accommodation, farms, rock climbing sites, skiing areas, bike trails, etc.

Navigation Tool in Openalp 3D

The recommended minimum configuration for its use is 4 GB of RAM, Core i3 Processor, Windows 7, 3D graphics card with 512 MB of dedicated RAM. The initial window presents the map in the whole extension. A compass in the upper right and a series of buttons allow navigation with a 3D interface similar to Google maps. A series of buttons in the top left open the drop-down menu for browsing content. Below, the coordinates and elevation of the mouse and the center of the screen (UTM or Lat-Long) and azimuth are shown. This option allows the user to

Table 1 Short description of the 49 geomorphosites of the Valley of San Lucano and of their characteristics

	Geomorphosite	Type	Short description
1	Pizèt	EM, EE, SHV, SCV, CRV	Pizèt is a huge pyramidal rocky outcrop (volume around 10,000 cubic metres). A big fracture divides these unstable masses from the peak. The crown scarp from which the 1908 landslide detached is still observable (geomorphosite no. 7)
2	Pónt breccias–Black Marble cave	SHV, CRV, SEV	In the Pónt area, above the Morbiach Limestone, there is the Moena Formation, made up of limestone block breccias inserted in a bituminous matrix. The so-called Black Marble, extracted from both open-air and underground quarries, was usually cut in big square blocks that can still be seen near waterfalls
3	Pónt waterfall	EV, EE, SCV	The waterfall is located where the Rio di Gardés meets the Bordina Creek near Pónt. It has a drop of about 30 m, and it falls from the grey rocks of Morbiach limestone
4	Forcella di Gardès	EE, PE, EM	The pass (1998 m.a.s.l.) between the Gardès Valley and the Torcol Valley (Cencenighe) represents an exceptional example of facies heteropy between the reef slope rocks of Pale di San Lucano and the basin volcaniclastic rocks in the Monte Prademur area
5	Angheràz Valley Cirque headwall	EM, EE, PE, SCV	The headwall of Angheràz Valley is a wonderful example of glacial trough
6	Agnèr north edge and wall	NR, EV, SCV	It is the symbol of the valley. The north wall, more than 1600 m high, is made of Ladinian dolomite and it is the highest wall in the Dolomites
7	Pra and Lagunàz landslide	SHV, CRV	On the night of 3 December 1908, a landslide detached from the fourth Pala di San Lucano and buried Pra and Lagunàz villages, causing 28 casualties and 10 wounded, and 200 people lost their home
8	Pónt deposit	NR, EM, PE	A lake glacial deposit, with clay sediments and small pebbles, emerges near Pónt

Table 1 (continued)

	Geomorphosite	Type	Short description
			barns and along the street that goes up to Pónt de la Pita
9	Cascata dell'inferno (Hell Waterfall)	EE, PE, SCV	The waterfall is 38 m high. It falls from the Agordo Formation rock bank and, in its lower part, it carves the Voltago Conglomerates red sandstone
10	Pian di Mièl	EM, EE, SCV	The karst glacier hollow (1866 m.a.s.l.), on the left side of the Angheràz Valley, is delimited by a reverse slope that is probably due to tectonic control. In the area, there are some karst cavities. In one of these cavities, at 1960 m.a.s.l., there is a spring
11	Sill di Malgonera	NR, EE	There is a big intrusion of volcanic rocks inside the basin rock of the Livinallongo Formation. Several magmatic differentiations phenomena can be noticed in that area
12	Van del Pez	NR, EE	Interesting site for synsedimentary faults, "sutured" by Contrin Formation. In this way, Anisian age can be confidently determined for dislocations
13	Livinal dell'Acqua–La Sfèsa	EE	Springs alignment between Membro di San Lucano (Werfen Formation) and the above Dolomia of Serla Inferiore: Grotta Sorgente (Rising Cave–Veneto Cave Register = VBL 3521) or "Busi della Sorgente" or, as local people say, "La Sfèsa". Water temperature goes from 5 to 6.2 °C and the flow rate from 22 to 300 l/s
14	Stadial Moraines Valle di Angheràz	EM, EE, PE	Gschnitz stadium moraine bars: from a height of 1080–1090 m.a.s.l. (Casera di Angheràz Bassa) to 1300 m.a.s.l.
15	Le Peschiere–lake	PE, EE, EM, SEV, SCV	Small intra-moraine lake hollow, inside a moraine bar (Bühl stage moraines) at Masarèi de le Tòrte locality
16	Péden post glacial landslide	PE	At the foot of the first Pala di San Lucano, there is a great landslide, positioned where the San Lucano Valley meets the Cordevole River valley. It was originated by glacier pressure processes when Dolomites glaciers withdraw. The landslide formed a hill made of huge rocks isolated by rock pinnacles, the "Piloi". On its top, the ruins of Pèden Fort, built at the end of 1800 for defence purposes are still visible
17	Campanile della Besàuzega	EE, SCV	Rock peak (2191 m.a.s.l.), 30 m above the top terrace of the second Pala di San Lucano and joined to it with a thin ridge. At the bottom of the peak, there is the inner platform progradation of Pale di San Lucano
18	Fossil vein f. di Agordo	EE, PV	This fossil vein (850 m.a.s.l.) is on the top of the debris cone, east of San Lucano church. Lateral transition between the Agordo Formation sandstones, Anisian limestones and calcarenites. Fossils plants (Cycadatae, etc.) were found in the arenaceous rocks
19	Forcella Cesurette	PE, SHV, MV, SCV, PRV, SEV	Cesurette is an important pass (1801 m.a.s.l.) between San Lucano Valley and Garés Valley. Mesolithic flintstone indicates that 7000–8000 years ago, the area was not covered by ice and was a connection point among the different areas of the group of Pale di San Martino. Copper and iron ores have been found
20	Interglacial conglomerate–Valón de le Scàndole	NR, PE	Vadose origin conglomerate blocks deposit with dolomitic-limestone pebbles. The deposit emerges on the Valón de le Scàndole at a height of 1050 m.a.s.l.
21	Amphitheatre second Pala di San Lucano	EE, PE, EV, SCV	Massive glacial cirque on the top of the second Pala di San Lucano: it is evident that the glacier has mouldered the stairs side in the typical bowl shape. In this area the inner part rocks of the top terrace of Pale di San Lucano are well kept and revealed.
22	Campo Boaro	EE, EV, MV, SCV	This wonderful grassland hollow (2000–

Table 1 (continued)

Geomorphosite	Type	Short description
		2200 m.a.s.l.) borders the Pale di San Martino Plateau. It is very rich in minerals (calcite, goethite, etc.), and it is the geological threshold between the Triassic lavas (Campo Boaro peak and Sasso Negro) and the reef edge
23 Inclined plane	EE, SCV	This fault-inclined plane characterizes the third Pala di San Lucano. It is a direct fault with minor displacement
24 Crepe Rosse	EE, EM	Big rockfall stack on the right side of the Van de Mez, at the bottom of Monte Agnèr. The red rocks belong to the Werfen Formation and in particular to the Membro di Cencenighe which has the maximum thickness here. The nearby Van de Mez and Vanet del Piz offers a “Block Stream” phenomenon
25 Val Reiane waterfall	EE	The water precipitates carving the dark basin rocks of the Livinallongo Formation
26 Bordina fault	EE	It is a small direct fault with minor displacement along the Bordina Creek
27 Le Peschiere–Masarèi de le Tòrte	EM, EE, PE	A great debris deposit, with huge rocks, covers most of the valley bottom. It was originated by a Bühl stage deposit of 19,000 years ago. The moraine bars are positioned in such way to demonstrate that the rocks were located on unmelted glacier strip
28 Tromba del Mièl	NR, EE, SCV	Isolated characteristic peak, 2466 m high, which emerges from the Pale di San Martino plateau. It was left undamaged by the erosion of the glacier strip that was descending toward the Angheràz Valley. It divides the Vallòn di Mièl in two parts and its shape resembles a reverse trumpet
29 Peak cirques–Pale San Lucano	EM, EE, PE, SCV	These peak cirques and the second Pala amphitheatre are the most characteristic elements of the upper part of Pale di San Lucano. According to some authors, they are of the Gschnitz stage. The most notable peak cirque, located on the first Pala, at the foot of the Bivacco Bedin, is easier to reach. Maybe these cirques were originated by the underlying volcanic megabreccias, as they are more subject to erosion
30 San Lucano cave	SHV, CRV	The San Lucano cave has a development of 15 m and a gradient of 5 m. Inside there is an altar. According to a religious belief, a pious woman, the “Beata Vaza” (or Vazza) lived here in hermitage. Inside the cave (1765 m.a.s.l.), there is a little karst spring
31 Sass da le Cròss	SHV, CRV	Big dolomia (10 × 5 × 4 m) fallen from the Sass Pian slope. On the northern face of this rock, there are more than 200 engravings, mostly different size crosses. Engraving age is not known; perhaps these crosses were engraved for some cult
32 Boràl di San Lucano (San Lugàn)	EE, SCV	A deep fracture divides the second from the third Pala di San Lucano. It is oriented N 45 W. On its bed, there are huge rocks. The Agordo Formation emerges with a limestone rich in Brachiopods beneath one of this rock
33 Torre Armena	EE, SCV	Magnificent tower rock (2652 m.a.s.l.) separated from the Agnèr Mount by the Vanét del Piz gully. The Piz Pìcol, made of ladinian dolomia, in 1929 was named Torre Armena as a tribute to the alpinist Ohannes Gurekian
34 Valón de le Scàndole	EE	This deep fracture is oriented NW from the Torre Armena. It ends with Spizzón mountain pass (2623 m.a.s.l.) and, in the lower part, it carves the Membro di Cencenighe Werfen formation red rocks and the upper Anisian age formations
35 Epigenetic river bed Bordina	NR, EM, PE	Small fossil creek carved in the Agordo Formation calcarenites. It is located

Table 1 (continued)

Geomorphosite	Type	Short description
		near Pónt in correspondence with a fault line, and it was the old riverbed of Bordina Stream
36 La Ghiacciaia–(Giazèra de 'l Cavàl)	NR, EE	Small cave in the south-west edge of the lawn called Pra de 'l Cavàl. In past ages, it was used as a small natural refrigerating room as cold air pass through it. The stacked debris creates an inverted air circulation funnel
37 El Cor	NR, EE, EM, SCV	This characteristic natural heart-shaped rock window is located on the crest that goes from Coston de la Vena to Cima dei Balcòni (2034 m.a.s.l.)
38 Boral de la Besàuzega	EE	It divides the first Pala di San Lucano from the second one and it is oriented N 30 W
39 Boral di Lagunàz	EE, SCV	It divides the third Pala di San Lucano from the fourth one and it is oriented N-S. At its bottom, a thick Agordo Formation outcrop emerges. It is rich of fossils and shows big gastropods
40 La Scudèla	EE, PE	Glacier cirque located in the upper part of the Livinal dell'Acqua. It collects water descending in deep cracks and canyons from Pizzetti d'Agnèr and other near peaks (Spiz d'Agnèr, Spiz de la Lastìa, etc.). A permanent snowfield feeds the near spring called Livinal dell'Acqua (La Sfèsa)
41 Corno del Bus	EE, SCV	Rock spur (2069 m.a.s.l.) that dominates the deep Gaf canyon, just above its mountain pass. It has a typical pyramidal shape with ledges usually hidden by the vegetation
42 Covol Mont	EM	The small cave in interglacial conglomerates proves that the valley was once filled with debris. It is located at 1050 m.a.s.l., on the left side of the Valón de le Scàndole. In this area, a fault connects the Agnèr Group ladinian dolomia with the red Membro di Cencenighe Werfen Formation rocks
43 Arco del Bersanèl	EM	This typical rock arch on top of the Boràl di Lagunàz was created by mechanical processes and karst dissolution
44 Cól de l'Usèrta	SHV	It is located along the path to Sass da le Cròss and it is made of big collapsed blocks that form a sort of two-room cavern in which the bandit Desiderio Manfroi, named Usèrta, took refuge at the end of the XVIII century
45 Pòles	NR, EM, SCV	This tower peak (1892 m.a.s.l.) is shaped like a thumb and is divided by the North edge of Spiz de la Lastìa by a deep fracture
46 San Lucano springs	EM	At the foot of the small church of San Lucano, there are many springs. Most of their water is collected for drinking purposes, with a temperature ranging from about 3 to 6–7 °C
47 Roa del Forn	PE	A steep canyon, located on the south side of the first Pala di San Lucano, can be seen from the valley bottom. Its terminal stack debris has been exploited in the mine that is still visible near Forno di Val (Taibon)
48 Knickpoint	NR, EM, EE, SHV	San Lucano church is located over a knickpoint where a buried dam causes a thick gravel upstream deposition. From this point, the slope steadily increases until the stream meets the Cordevole River (a jump of 140 m in 3 km)
49 Dolomitisation outcrop	NR, EM, EE, PE, SHV	Relict structures are also well preserved in most of the Dolomites, indicating that they are a dolomitised limestone. Limestone passes both laterally and vertically into the dolomite, showing numerous dolomitisation fronts, in which the calcite passes into pure dolomite within a few decimeters

NR naturalistic rarity, *EM* evolution model, *EE* educational example, *PE* paleoenvironmental evidence, *EV* ecologic value, *SHV* scientific-historic value, *MV* mineralogical value, *PV* paleontological value, *SCV* scenic value, *PRV* prehistoric value, *CRV* cultural religious value, *SEV* social economic value

Fig. 2 Virtual visualization of the glacial cirques on the First and Second Pala di San Lucano. *Flag* geomorphosite with limited area, *yellow line* geomorphosite with linear extension, *closed purple line* geomorphosite with extended area, *blue line* snowshoes trail, *lens* San Lucano Church, *blue house* Bivacco Bedin

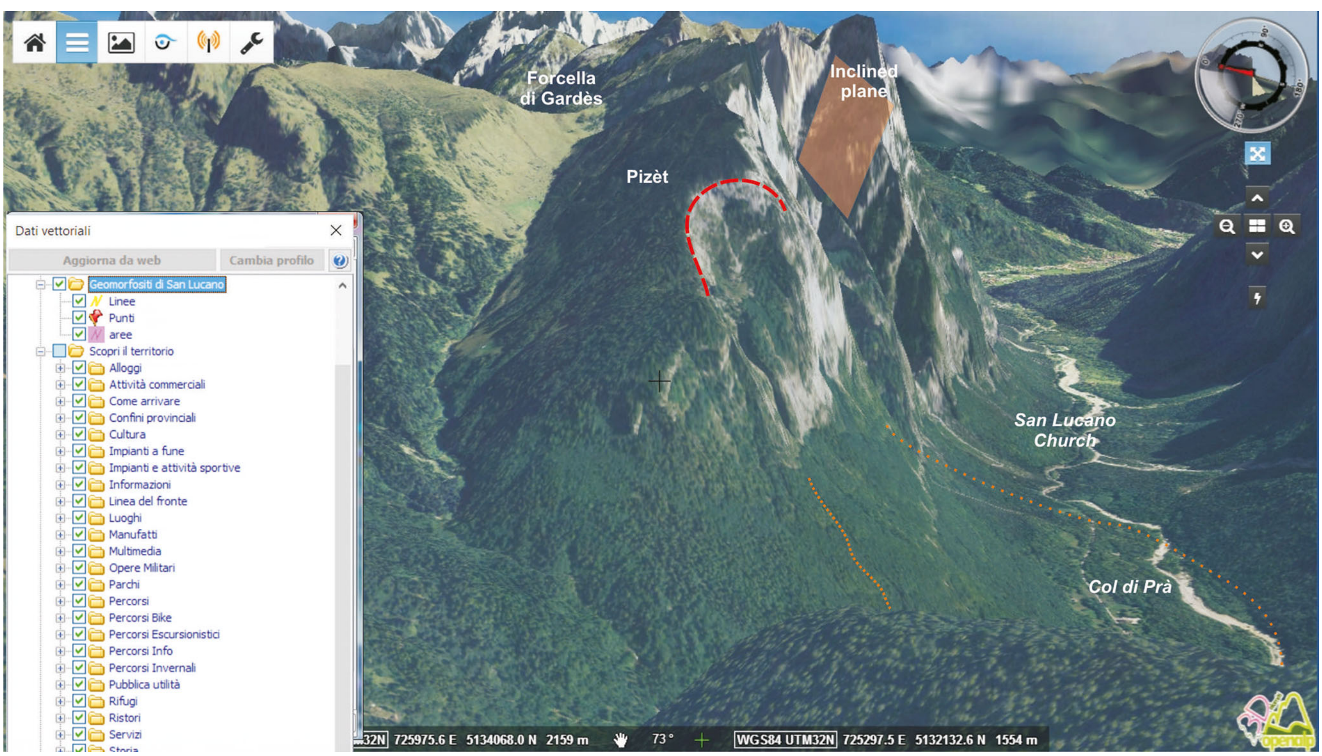


Fig. 3 Virtual visualization of Forcella di Gardes (geomorphosite no. 4), of Pizèt (geomorphosite no. 1), of the niche from which the landslide was originated and the rockfall on Prà and Lagunaz (geomorphosite no. 7) and of the "Inclined plane" (geomorphosite no. 23). Virtual visualization of Forcella Gardes (geomorphosite no. 4), of Pizèt (geomorphosite no. 1), of the niche (*red dashed line*) from which the landslide was originated and the rockfall (*orange dotted line*) on Prà and Lagunaz (geomorphosite no. 7) and of the "inclined plane" (geomorphosite no. 23) (*brown polygon*)

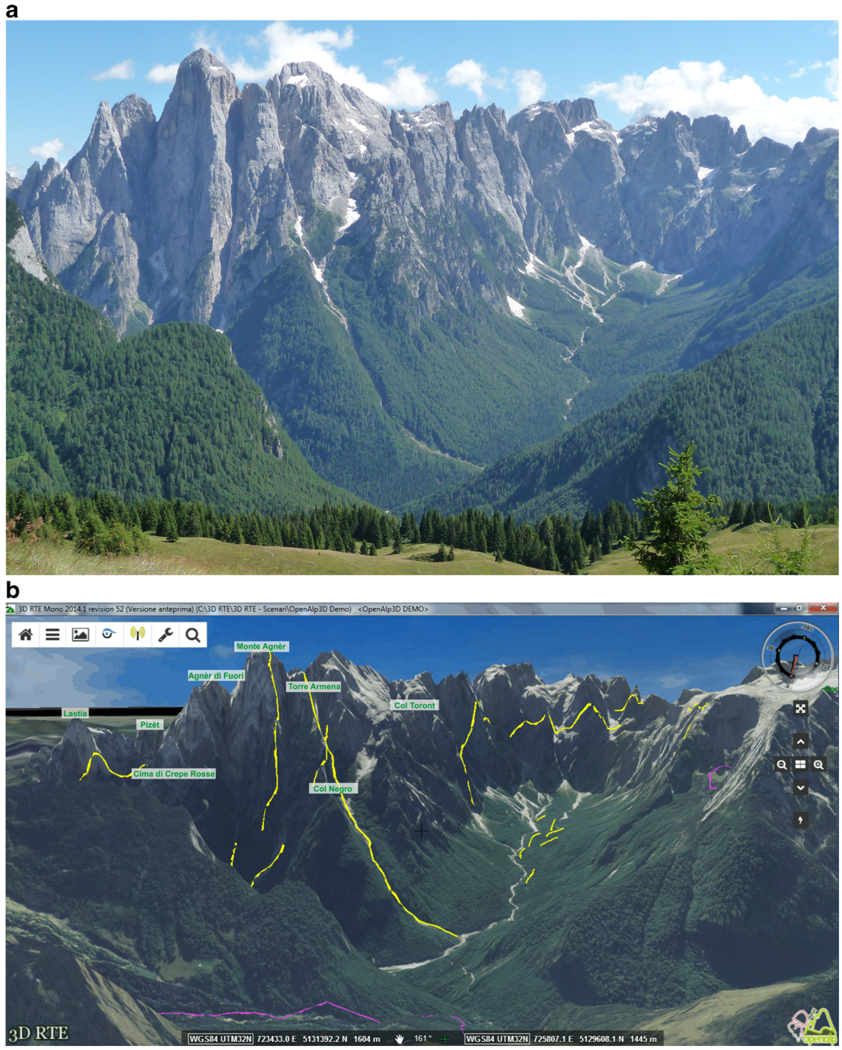


Fig. 4 Comparison between a real image (**a**) and a virtual image (**b**). The virtual image is extremely similar to a real photograph, but it allows easier reading of the landscape evolution. The *yellow lines* represent the geomorphosites with linear extension

navigate the graphical map, virtually forgetting the interface. For 3D navigation, the user can also use a combination of mouse buttons, which allows them to move, tilt, zoom and fly at a constant height.

The functions of the buttons on the top left are the following:

- Home: Displays the maximum extent of the map
- Scene data: Opens the manager tool, in which the layers are organized by themes, categories and subcategories. The user can select the layer of interest or search for a specific item belonging to the selected layer. At the top, the menu includes the key: "update from web", to allow the user to update the database in real time for each access
- Raster images: Opens a menu with the list of uploaded images in the scene, and then in the user's PC, or indicates related to online images. The user can set different degrees of transparency and change the display order to create a background map of the combination. The button "add images" is used to download new images from the server created by the project or from high-resolution images. To facilitate the download, a grid is provided, and the user can download the desired portion
- Track view: Tools to work on PC, including drawing lines, points and polygons, computing the elevation profile of a route, saving an item to track Google maps (kmz, gpx) and Garmin GPS, and to create custom maps to be exported to Google maps
- Tools: Prints a PDF of cartography showing the elements of interest, changes the scene, manages folders
- Search: Menu to search the contents of the 3D scenario and search for addresses on Google maps

Using the tools described, the user can navigate in a 3D scenario, select the item of interest, consult and download the descriptions and associated images, pdf files, gpx files onto his own devices (I-Pad, mobile phones and GPS) and create maps themselves. The user can also access the GIS database and display the existing vector items.

These interactive components are the most important, allowing the user to draw vector elements (lines, areas and

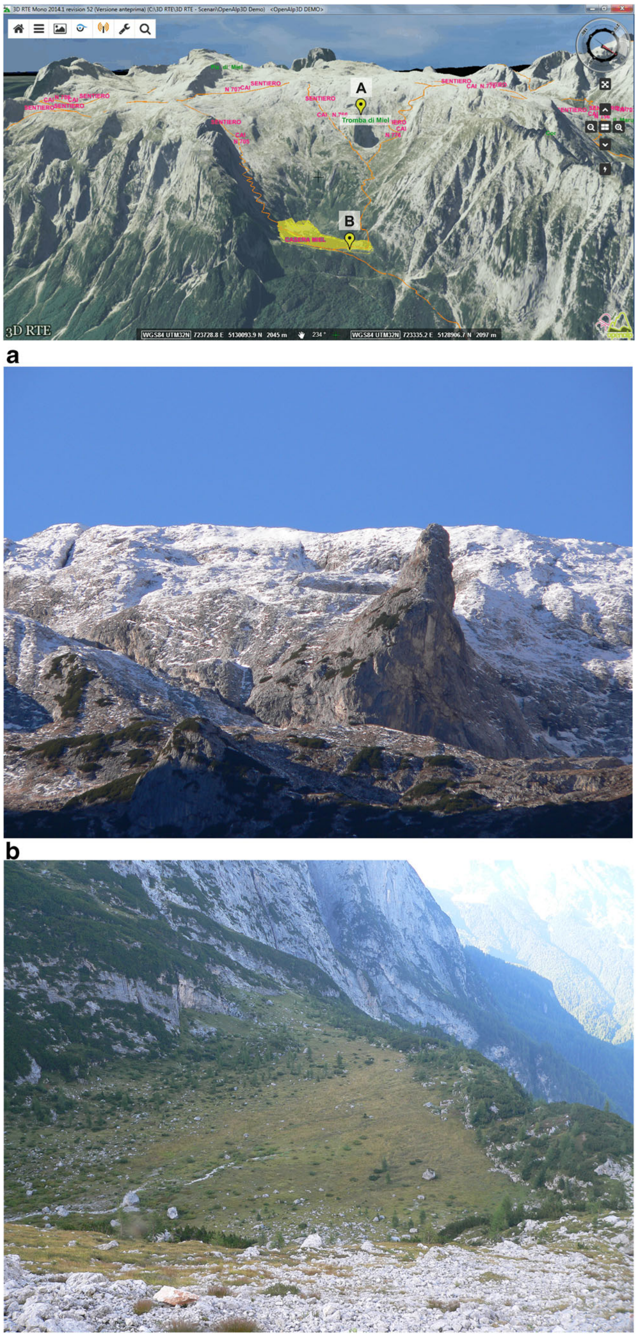


Fig. 5 Virtual visualisation of the western side of the valley of Angheraz. You can see the Tromba di Miel (**a**) and its karst glacier hollow (**b**) and their corresponding pictures

points), with which a series of operations can be carried out (distance and area calculations, profiles, etc.).

Exploring the 3D Scenario

The localisation of each site, together with the more common descriptions, classifications and pictures, enables the user to understand the geomorphosites in detail. It is easier to appreciate them when they are displayed in a 3D scenario, either when laid over orthophotos or geological, geomorphological or other thematic maps. In this way, it becomes easier to identify relevant morphological sites and to understand not easily identifiable elements. In this way, different types of users will be able to appreciate thoroughly the scientific, educational and scenic characters of the geomorphosites. These elements are a key to understanding the distinctive geological, geomorphological features of the valley and their evolution, using all the possibilities offered by the 3D tool and to gain an overall picture of the territory. As a study area, we selected the San Lucano Valley (Taibon Agordino municipality, Belluno, Italy) due to its abundance and variety of geological and geomorphological sites (Fig. 1) as witnesses to a 200-million geological history and show how these elements are still preserved (Testa et al. 2013).

San Lucano Valley: a Test Site for Understanding Geomorphology and Geology

This valley is already well known for its natural attractions by hikers and tourists and is characterised by a large variety of geological and geomorphological sites that are the keys for understanding the geological history of Dolomites from the Triassic to the present (Testa et al. 2013). In particular, they show such a high degree of extrinsic geomorphodiversity (Panizza 2009) as well as the landscape structures and scenic values that they are inscribed on the UNESCO listing of World Heritage status (Gianolla et al. 2008).

The San Lucano Valley is deeply carved into the carbonate platform of the Pale di San Martino–Civetta, the largest of Ladinian cliffs of the Dolomites. Carbonate reef and Middle Triassic intrusive, extrusive and volcanoclastic rocks are directly connected to the genesis of the landscape. Lithology and tectonics are the factors that determine the geomorphodiversity of this valley. The presence of plant fossils in Anisian sediments also gives a particular interest for palaeogeography. A glacial landscape characterises the valley with the massive glacial cirque of Anghèraz Valley, suspended circques (Pian del Miel, Seconda Pala), *roches moutonnées* and moraines different glacial stages [e.g. Buhl stage at Le Torte, Gschnitz Stadium in Anghèraz Valley and Daun stage near the Tromba di Miel (at 2000 m.a.s.l.)].

Gravity is the most important morphogenetic action since the disappearance of the glaciers, and here gravity-related forms has produced an important example of intrinsic geomorphodiversity at a regional scale for the complexity of their categories, causes, age, lithology, motion, extension, etc. (Soldati et al. 2004): debris flows (Anghèraz Valley and Van de Mez), deep gravitational slope deformation (Castiglioni 1939; Zampieri 1987) below the Pale dei Balcoi, landslide deposits in the Reiane Valley volcanics, etc. The well-known rockfall of Pra Lagunaz, which detached in 1908 from the Cime di Van del Pez (where unstable masses are still observable) (Doglioni and Bosellini 1987; Doglioni 1987, 1992, 2007; Castellarin et al. 1996; Zattin et al. 2008; Stefani et al. 2007) combined with the Pizet, forms a site that is strongly connected with the local community history (quarry activities, landslides).

The combination of its geological, geomorphological, structural and stratigraphical features with its naturalistic values (Giordano 2011; Testa et al. 2013) generates, in this area, rich in geomorphodiversity, a unique 'natural book', in a unique environment. This valley has 49 geomorphosites (Bertini 2011; Testa et al. 2013), creating the "characteristic shape of the landscape with particular and significant geomorphological attributes that qualify as part of the cultural heritage of a territory" (Panizza and Piacente 2003).

3D Visualization as Tool for Geotourism and Geoeducation

The San Lucano Valley geomorphosites (Table 1) have been implemented in the technological platform Openalp 3D. This project aims to allow users to explore the 3D scenario, to analyse landscapes or inaccessible mountain areas (Martin 2014), to study geological and geomorphological evidences and to observe the sites of interest from different points of view, whilst reading related explanations, and learning how to reach them.

"Easy to reach" is the goal of the 3D tool: using it, the user can even have a helicopter view or can observe something from unreachable viewpoints—in other words, it allows a form of virtual 'geowatching' (Garofano 2014). Users will be able to appreciate thoroughly the scientific, educational and scenic characteristics of the geomorphosites. A good example is the dramatic glacier cirques on the Pale di San Lucano (geomorphosite nos. 21 and 29) that can be only seen

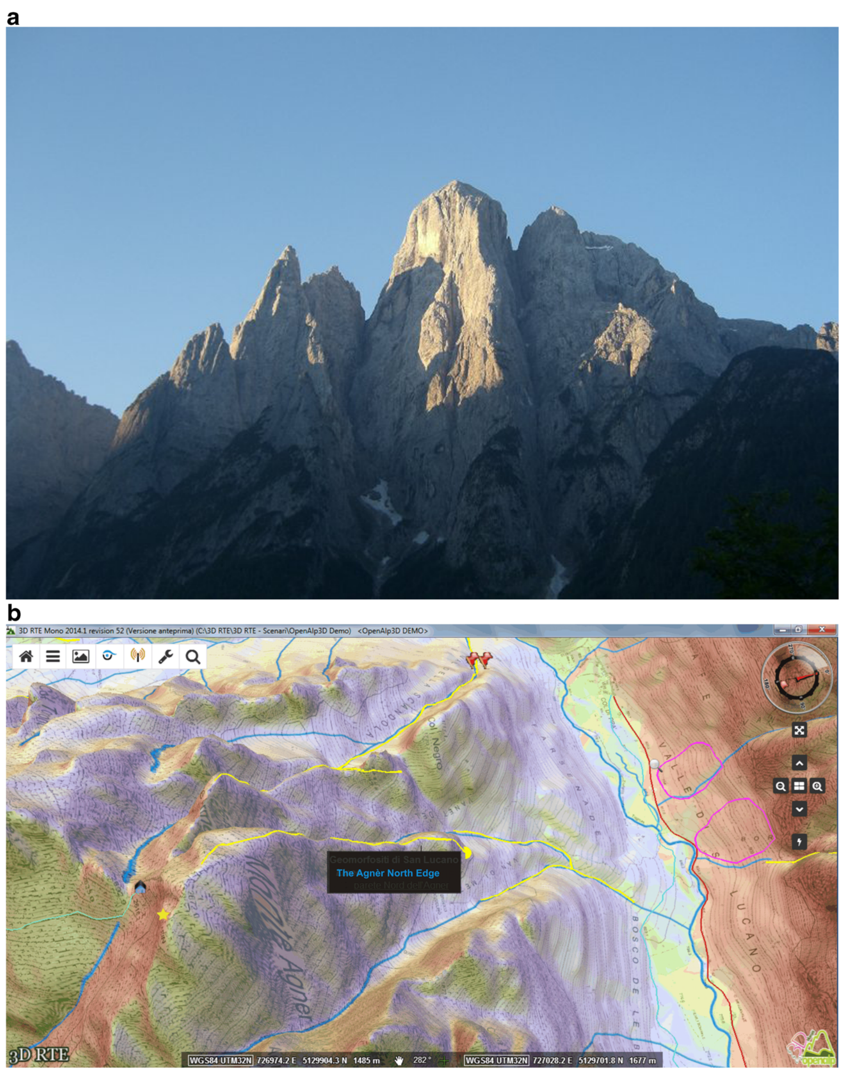


Fig. 6 The Agnèr North Edge (**a**) highlighted by the morning light. The same edge is evidenced by the aspect map (**b**). *Yellow line* geomorphosite with linear extension, *closed purple line* geomorphosite with extended area, *blue line* stream

from the opposite side of the Cordevole Valley, after climbing a 2300-m high mountain that is 3000-m distant (Fig. 2). The user needs only to register on the server, which allows him/her to consult this tool from any location for scientific curiosity or simply to plan a 'flying' trip over the Dolomites.

By exploring with orthophotographs this 3D scenario for a geomorphosite with a high educational value or important landscape elements, the user can appreciate different lithologies, their colours and all their morphological elements. For example, the complexity of the Forcella di Gardès (geomorphosite no. 4) with a great contrast between reef slope rocks and the basinal volcanoclastic rocks can be appreciated (Fig. 3).

The Andraz Valley large glacial cirque (geomorphosite no. 5) is an important educational example and has a great landscape value. In Openalp 3D, it can be seen either from the Malgonera viewpoint (Fig. 4) or by 'flying over' the Angheraz Valley from the stadial moraine at geomorphosite no. 14, to the headwall of the valley, thus revealing its evolution. Flying over the karstic glacial hollow (geomorphosite no. 10) and over the Tromba del Miel (the only residual fragment left after the glacial erosion at geomorphosite no. 28) gives an overall impression of landscaping evolution during the Last Glacial Maximum. This spectacular example of the potential of 3D visualization for geomorphosites which are difficult to access is shown by Fig. 5. This 3D image shows the difficulty access and allows the user to plan carefully how to reach the sites, or to 'fly over' them as shown by Fig. 5a, b, and observe them from different angles.

From the valley bottom and from the Forcella Cesurette (geomorphosite no. 19), the 3D scenario allows the user to appreciate the highest north ridge in the Dolomites: The Agnèr North wall (geomorphosite no. 6), important for its natural uniqueness, for its scientific-historic value and for the many alpinists that have been climbing its many routes since the 1920s (Fig. 6a). In the 3D view of Fig. 6b, the edge corresponds to a line, and in Table 2, logistical information is shown.

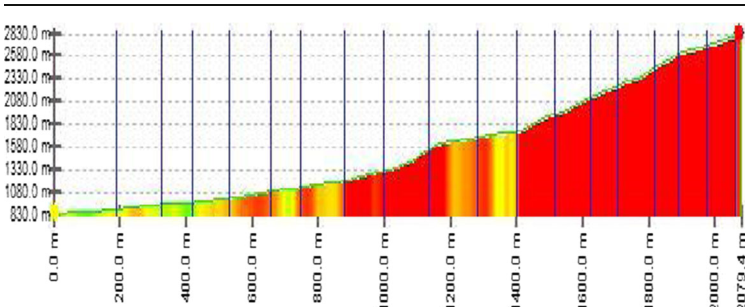
With the help of the drawing tools provided, it becomes easier to understand the key elements of the tectonic structure of the valley (Fig. 7). It is, therefore, possible to explore virtually the inner part of the Boral of Lagunaz, shaped by a sub-vertical transcurrent fault, oriented N-S (geomorphosite no. 39), and appreciate its width and height and fully understand all its features. It is also interesting to explore the 'Inclined plane' (geomorphosite no. 23) that is the most characteristic morphological element of the Third Pala di San Lucano, which comprises a NW-SW normal fault with minor displacement, sub-vertical in its upper part and with a decreasing slope. It is the most characteristic fault on the south face of Pale di San Lucano.

Discussion

State-of-the-art digital imaging and 3D modelling applied to research and dissemination have been recently analysed by Cayla (2014), Ghiraldi et al. (2014) and Cayla et al. (2014). The most important aspect of the system OPENALP-3Dolomiti is that it is a dynamic 3D tool (http://www.3drte.com/content/openalp-3d) which can explore large areas of the territory (2300 km^2) through a digital terrain model with a resolution 'fit for purpose' (e.g. a 5 × 5 m cell). This free-to-use 3D scenario allows the user to navigate through available

Table 2 Logistic data related to climbing the north ridge of Mount Agnèr starting from the valley (see Fig. 6b), provided by the "Track view" function

Accuracy	Extremes	Quote	Total drop
Soil sampling step = 1.00 m	Point 727115.9 5130954.3	Start = 835.77 m	Ascent = 1979.3 m (along 3005.4 m)
Control points = 20	Point 727406.8 5129091.3	End = 2820.61 m	Maximum slope uphill = 244.3 %
	Distance 2D = 2079.42 m	Minimum = 835.77 m	
	Distance 3D = 3036.67 m	Maximum = 2820.61 m	
		Delta quote = 1984.84 m	



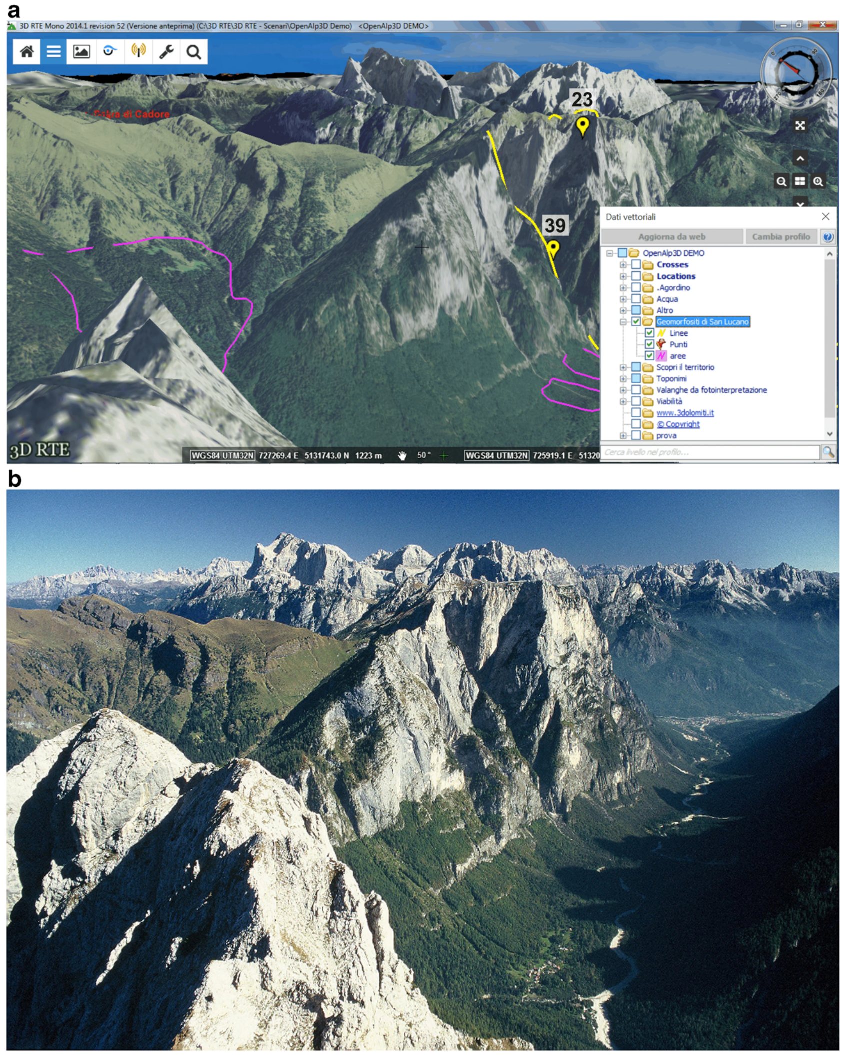


Fig. 7 Boral of Lagunaz, a sub-vertical transcurrent fault, oriented N-S (geomorphosite no. 39) and the "Inclined plane" (geomorphosite no. 23). Virtual (**a**) and real (**b**) images. *Yellow line* geomorphosite with linear extension, *closed purple line* geomorphosite with extended area

tourist information and to plan excursions to places of geological interest. Indeed, the user can explore highly realistic virtual places (Aldighieri et al. 2012) and access all the pictures and textual information associated with such area of interest. With the use of this geological and geomorphological content, the local community can contribute in the communication process as the importance of the geomorphosites conservation. Thanks to its multithematic approach, the platform also becomes the collector of scientific contributions relating to the territory and a showcase of its historical and cultural heritage. This dual function is the starting point for the creation of 'places of collective identity'. Each person or institution that connects to the system becomes a user that can contribute to its expansion by describing and placing new sites based on their knowledge. Each person is recognised as part of the territory in which they live or want to explore. In this way, they can promote tourism that enriches the land and the people.

Although today all services are offered as app or web-GIS, web technology currently does not yet support a true 3D terrain model for a navigation especially using high-resolution maps (regional technical maps and orthophotos). This is the reason for choosing a hybrid system (in situ + Web) with which the degree of realism achieved by the tool is essential for understanding the scientific and aesthetic value of the geological heritage and the importance of preserving it.

During the year of implementation, the procedures for setting up the database have undergone important changes related to user response to the proposal platform—including the registered massive use of the application Openalpmaps on mobile. As a result, we started to improve the system and allow compilers to access and post photos and details even from smartphones. Following these improvements, the database of the platform Openalpmaps (www.openalpmaps.it) can now be updated more quickly, even if the user cannot display 3D images.

In addition, in order to improve further their efficiency, the tools should be tested in their specific context (Martin 2014). The educational value of this platform was tested at the Mining Institute Follador (Agordo) where it was considered to be a useful tool to support teaching in geology and geomorphology through the use of a 'computerised platform.'

In such an environment during lessons, students can navigate on a 3D model (5 × 5 m cell), choose different maps (topographic, geological, geomorphological, etc.), recognise the geological sites and geomorphosites and delimit them by drawing points, lines and areas to improve understanding. The tool has been also tested by experts for design studies and for land use planning, etc. For example, Openalp 3D is used to update the database that allows the user to highlight areas potentially affected by avalanches (i.e. the Localization Map of Probable Avalanche (CLPV), produced by the Avalanche Centre of Arabba, Belluno for the study and prevention of risk in skiing areas.

Conclusions and Perspectives

As discussed above, Openalp 3D is an efficient tool for in-depth analysis of landforms and a good resource for educational and research purposes on geomorphosites.

Information is dynamically managed: the end user, after log in, can download whatever they need. Users can download not only the elements of interest that have been previously uploaded on the project server but also different future scenarios that will be applied in Openalp 3D. The tool can be used online or offline and it comprises a 3D cartographic background with recorded elements of interest (points, lines and polygons), with an aim of assisting the planning of itineraries of interest. The platform enables the easy creation of a 3D motion picture, with dynamic descriptions of places and itineraries (www.3drte.com). Furthermore, Openalp 3D has been creating by the Local Action Group (GAL) of the Northern Belluno Area, a 'network' in which each user also becomes an active participant and can enrich the platform with information resulting from his/her experience, including pictures, video, routes of all kinds, as well as natural and historical heritage information.

Most users, however, consult and update the information contained in Openalp 3D via the smartphone application "OpenalpMaps"—which, presumably, is destined to become the preferred solution. There is still, at the same cost, a significant gap between the hardware graphics performance of PC and smartphone, which is not reflected in the software. It is only a matter of time, however, before this problem is resolved, and within a few years, the convergence between PC and smartphone will be complete. For this reason, for now, the use of 3D graphical utilities will remain confined to a niche of people with a medium–high technical level or Local Authorities and for educational and research purposes—while the general public will continue to interact with 2D information and updates dependent on the difficulty of data transmission across the Internet network.

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