The area affected by sturzstrom in the Friulian Dolomites as the place to learn and understand the strength of natural forces and consequences for the natural environment and local communities

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Abstract

This paper illustrates several geosites related to giant landslide – a sturzstrom – from the Vajont Valley in Friulian Dolomites (Italy) that is considered to be one of the greatest natural disasters from mountain areas in modern times. Because this natural disaster affected the large area, we offer a tourist route with five sites along the fragments of two valleys (Piave and Vajont valleys) to get to know the geological and geomorphological context of this event, caused partly by imprudent human activity. Presented sites are easily accessible and exhibits high education and cognitive value both in the field of natural and social issues. The tourists can realize here the enormity of the natural forces, their strength and consequences both for the natural environment and local communities.

Keywords: Vajont landslide, Dolomites, Heritage, Geotourism

Introduction

Landslides are phenomenon resulting from a wide range of ground movements. In mountainous areas landslides may have a form of rockslides, rock and debris avalanches or debris flows. The most important causative factors of landslides resulted from complex features and processes are lithology, tectonics, slope relief and shape, as well as seismicity, climate, and finally human activity (e.g. Heim, 1932; Zischinsky, 1966; Solonenko, 1977; Hutchinson, 1988; Evans & Clague, 1994).

An unstable slope after years of slow creeping and long-lasting deformation of a mountainside, it may shift several kilometres within minutes to generate a giant landslide – a sturzstrom – one of the most powerful natural hazards on Earth (Hsü, 1975, 1978). Such events have occurred in Europe every few decades (Kilburn & Pasuto, 2003). The effects of such events can be dramatic, and energy released during one sturzstrom can be comparable to that from the largest recorded volcanic eruptions (Williams & McBirney, 1979).

More than 55 years ago, one of the biggest landslides in Europe caused by geoengineering catastrophe took place in the Northern Italy, about 80 km north of Venice, in the municipality Erto and Casso, in region Friuli-Venezia Giulia (Fig. 1). On 9 October 1963, at 10.39 pm., after a week of heavy rains, a mass of approximately 270–300 million m^3 of rock debris slipped into an artificial lake confined by the highest dam in the world which has been ever constructed before. This landslide generated a displacement wave that spilled as much as 245 m above the dam (e.g. Kilburn & Petley, 2003; Wolter et al., 2014). The flood wave dropped into the Piave Valley destroying the town of Longarone and other villages located upstream and downstream, killing near 2,000 people (Wolter et al., 2014). The Vajont landslide is considered to be one of the most catastrophic slope failures or sturzstrom. It is now an excellent place for understanding and study complex mechanisms of landslides generated on rock slopes. It is also a place of one of the most famous natural disasters in modern history, where tourists interested in geology can realize the enormity of the forces of nature, and strive to understand the causes of these phenomena and teach how to prevent them in the future.

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Fig. 1 *Location of the Vajont landslide and the Piave River (map after https://maps-for-free.com)*

Location and morphology of the Vajont Valley

The Vajont Valley is situated in the Friulian Dolomites of the Southern Alps (Fig. 1). It is located between Toc Mt (1921 m a.s.l.) and Zerten Mt (1883 m a.s.l.) on the north, and Sterpezza Mt (2215 m a.s.l.), Fortezza Mt (2101 m a.s.l.) and Lodina Mt (2020 m a.s.l.) on the south, and is presently dewatering by the Vajont River, a left tributary of the Piave River. The valley has a broad and deep morphology, and a very narrow valley mouth (Fig. 2). It is now closed by disused dam (coordinates: 46°16′02″N 12°19′44″E). Below the dam site, the Vajont Valley has a character of a gorge, a few meters wide and over 100 m deep. The valley was formed by glacial and fluvial downcutting (e.g. Kilburn & Petley, 2003). The morphology of the gorge before the year 1963 was formed by re-incision of the Vajont River through the 200 m thick toe of the ancient landslide that had slid from the Toc Mt and blocked the valley (e.g. Ward & Day, 2011).

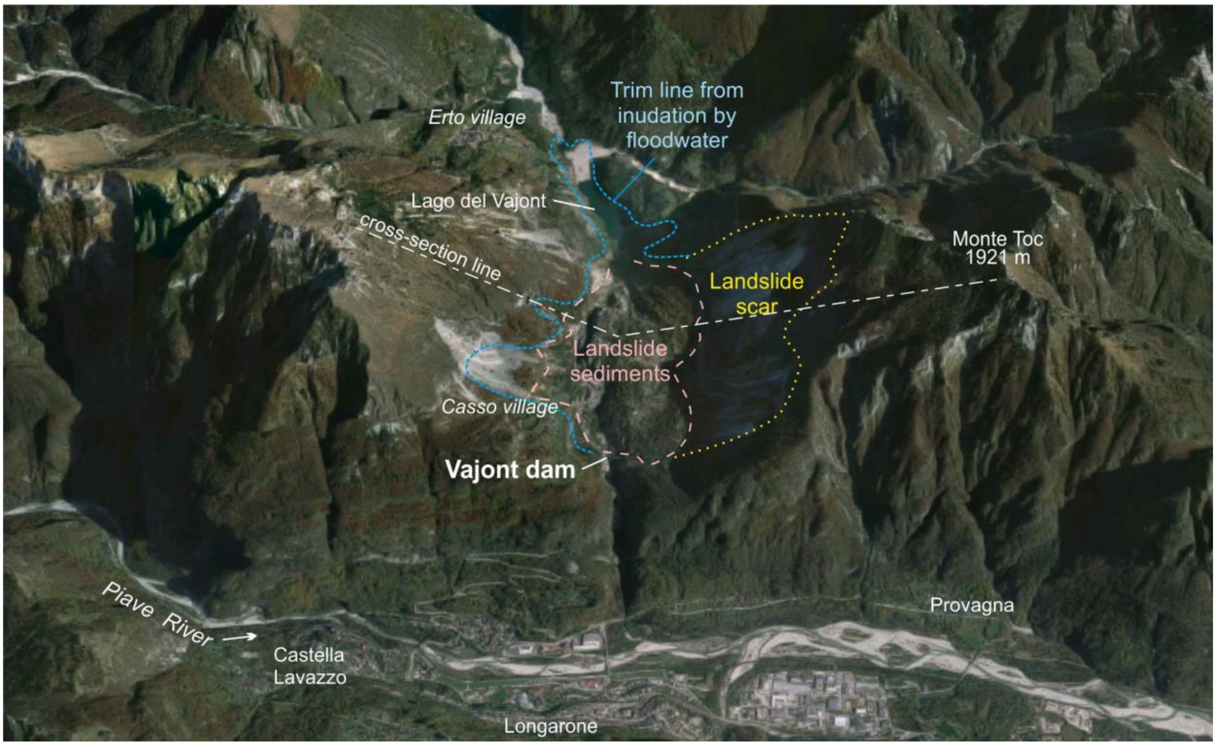

Fig. 2 *Google Maps image of lower part of the Vajont Valley displaying narrow gorge at the mouth, restricted by dam built during 1956–1959, and flat floor covered by colluvial sediments from the slide at 9th October 1963*

Geological setting

The oldest rocks that build the Vajont Valley and surrounding mounts consist of Mesosoic sequence of predominately calcareous deposits, which are limestones interbedded with clays and marls (Riva et al., 1990) (Fig. 3). The stratigraphic succession in the cross-section from the Piave River to Vajont River contains the Soverzene Formation (Lower and Middle Liassic), the Igne Formation (Upper Liassic), the Vajont Limestone Formation (Middle Jurassic), the Socchér Formation (or Biancone Formation; Upper Jurassic–Lower Cretaceous), the Scaglia Rossa Formation (Upper Cretaceous–Lower Paleocene), the Marne di Erto (Paleocene), and the Flysch Formation (Eocene).

The Middle Jurassic Vajont Limestone Formation provides spectacular outcrops at the S–E flank of the Toc Mt and at the dam site. These are predominantly thick bedded limestones with some breccia.

These Jurassic to Palaeogene sequence is locally covered by late Quaternary moraines caused by series of glaciations (Castiglioni, 1940), and by Holocene slope and channel deposits. Several Prehistoric landslides dammed occasionally the Vajont River, altering the valley floor and inducing lacustrine and deltaic deposition.

The Jurassic–Palaeogene sequence in this area consists of tectonic structures dominated by a series of predominantly E–W folds. One of them is the asymmetrical Erto syncline which is occupied by the Vajont Valley. The southern limb of this syncline includes Toc Mt. The folds are cut by N–S faults, including the Costa delle Ortiche lineament, which crosses the Vajont Valley near the eastern edge of the 1963 slide. On the northern bank of the valley, Mesozoic sequence thrust over the Scaglia Rossa Formation. Prior to the landslide in 1963, the contact between Vajont Limestone Formation and a series of red marls and marly limestones of the Scaglia Rossa Formation was visible.

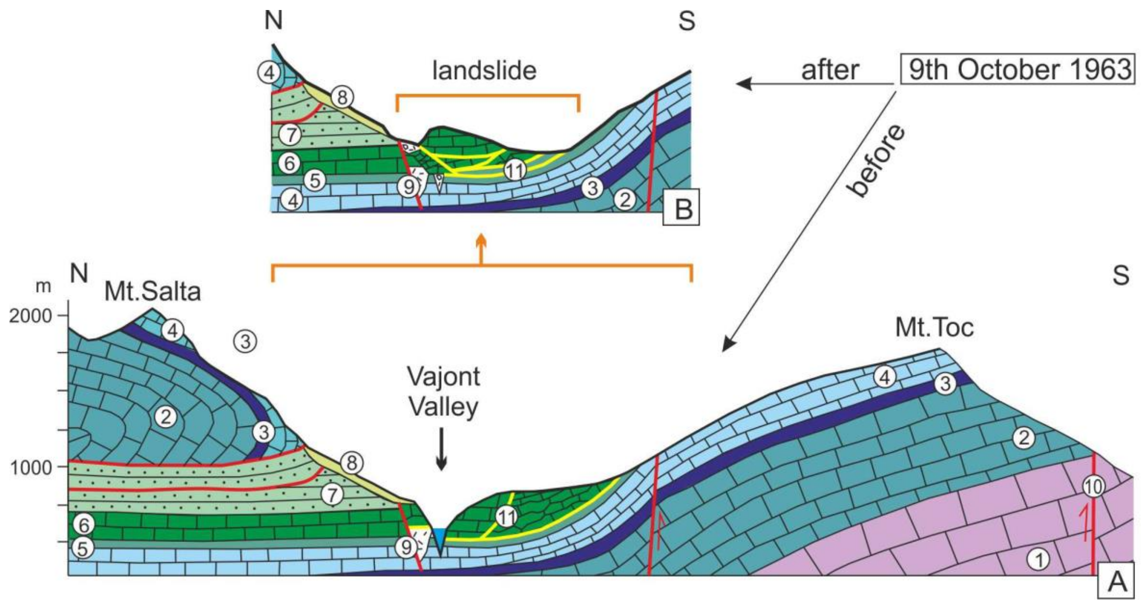

Fig. 3 North to south geological section across the Vajont Valley showing the Vajont Gorge and the position of the ancient landslide before and after 9th October 1963 (after Semenza & Ghirotti, 2000); 1 – Main Dolomite (Upper Triassic), 2 – Sowerzene Formation (thin beds of gray cherty limestone alternating with thin beds of reddish sandy marl; Lower Jurassic), 3 – Igne Formation (white to reddish, platy to very thin-bedded limestone with some siliceous beds; clay seams are common along the bedding planes limestones; Lower Jurassic), 4 – Vaiont Limestone Formation (medium- to thick-bedded grey limestone; Middle Jurassic), 5 – Ammonitico Rosso (red nodular limestone) and Fonzaso Formation (siliceous limestone and calcareous turbidites; Upper Jurassic), 6 – Soccher Limestone Formation (Upper Jurassic–Lower Cretaceous), 7 – Scaglia Rossa Formation (red thin beds of marl alternating with pink thin-bedded limestone; Upper Cretaceous–Palaeogene), 8 – Quaternary deposits, 9 – alluvial gravels, 10 – faults and overthrusts, 11 – failure surfaces of landslides

History of Dam construction

A previous project of a dam was undertaken in 1925 (Semenza & Ghirotti, 2000). The first proposed location of the dam was at the bridge at Casso, about 1500 m upstream of the site where the Vajont dam was finally built, to avoid possible problems with landslides. However, the construction of the dam in those places was discussed because difficulties connected with geology. In the proposed place, the Cretaceous limestones of the Socchér Formation was not enough solid to dam construction as the Middle Jurassic Vajont Lmst. Formation located downstream. After the second world war, the Vajont Valley was again taking into consideration as a potential site for construction of a hydroelectric power station. The construction of the dam began in 1956 and was completed in 1960. It was the highest doubly curved arch dam in the world, rising 262 m above the valley floor. The dam was located within the Jurassic limestones of the Vajont Lmst. Formation. The dam had a maximum level of water storage equal to 722.5 m a.s.l. It created a reservoir which was able to accommodate up to 169 million cubic meters of water.

The designers and constructors of the dam believed that any occurrence of deep-seated landslides in the close vicinity of newly created dam were extremely unlikely (e.g. Kilburn & Petley, 2003). The previous geological recognition shows that the valley walls consisted of very firm *in situ* rock with a high modulus of elasticity and without weak layers. Additionally, the rock formed an asymmetric syncline, which was expected to be a natural refraining of slope movement.

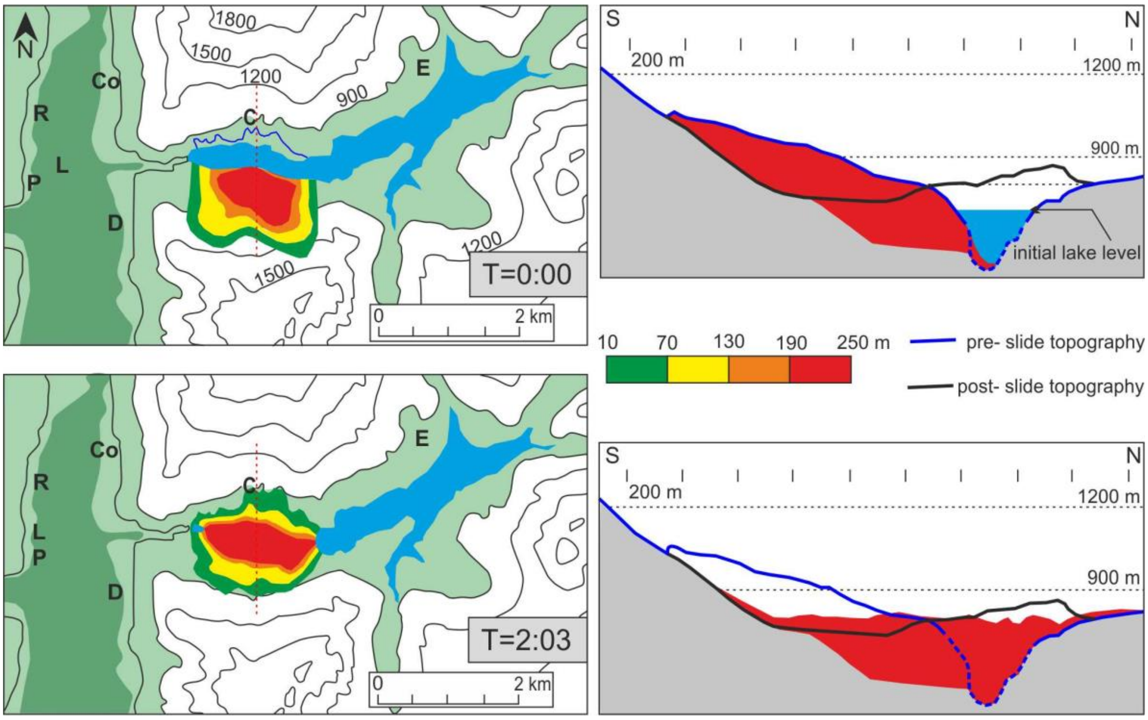

Fig. 4 *Landslide simulation at T=0:00 and 2:03 in the Vajont Valley (redrawn after Ward & Day, 2011; simplified). Two map view panels: at the left – contour landslide thickness; at the right – corresponding S–N landslide cross sections along central transect (red dotted line). Abbreviations of villages: C – Casso, Co – Codissago, D – Dogna, E – Erto, L – Longarone, P – Pirago, R – Roggia*

The signs of disaster

On the 22 March 1959, an unexpected landslide took place in the valley of the Maè River, the next tributary of the Piave River, neighboring to the Vajont Valley. The failure happened during the second filling of the artificial reservoir at Pontesei. Final fall was preceded by small movements, occurred a few days before. The landslide was very rapid. It generated a wave which flowed over the top of the dam by a few metres, however without any serious damage in the Piave Valley below. At that time, the Vajont dam was already at final stage of construction. Despite the landslide that occurred in valley of the Maè River, filling of the Vajont reservoir began in February 1960. However, this accident realized the need of further verification, whether there was any possibility of landslides on the slopes above the Vajont reservoir (Semenza & Ghirotti, 2000). The special technical study programme was initiated in July 1959 to monitoring of slope stability around the Vajont reservoir. The observations were carried on during almost three years until the day of disaster. These detailed investigations led to the identification of previously unknown details of Vajont Valley's geology. One of them were deposits of many ancient landslides located along the valley (Semenza & Ghirotti, 2000). The areas located upstream the dam as Pian del Toc and the Pian della Pozza were recognized as potentially dangerous.

The several events of instability of Toc Mt. slopes preceded the final catastrophe (Müller, 1964; Hendron & Patton, 1985; Kilburn & Petley, 2003). By October 1960, when the depth of the reservoir had reached 170 m, joints opened along distance of 2 km across Mt Toc c. 500–600 m above the valley floor. On 4th November, when the depth of the reservoir reached 180 m, the slid of 700,000 m^3 of material took place from the flank of Mt Toc into the lake. It was inferred that elevating of water level in the Vajont reservoir was the key destabilizing factor that caused the raise of water pore pressure in the flanks of Mt Toc generating mass movements and creeping of the material. It was assumed that lowering of the reservoir's level resulting in cessation of slope movement. Between April and May of 1963, the depth of the reservoir was rapidly increased from about 195 up to 230 m, and then reached 240 m by mid-July. Such elevation of water depth induced movement of slope up to 0.5 cm per day. Although the water level increased only to 245 m by early September, slope velocity accelerated to 3.5 cm per day. By early September, the water depth in the Vajont reservoir reached 245 m. In the same time the slide velocity had accelerated to 3.5 cm per day. It became apparent that the slope is being undermined. Although, during late September through early October the water level were systematically lowering up to 235 m, slope movements continued to accelerate to more than 20 cm per day, caused final crush at night on 9th October 1963 (Fig. 4).

Approximately 270 million cubic meters of material slid into the dam reservoir, generating a huge wave that has been estimated to have reached a height of about 105 meters above the dam (*Cremonesi et al., 2016*). Due to the irregular terrain topography, the wave did not reach the same elevation around the reservoir observing the contour of destroyed vegetation. The maximum range of deposits consisting colluvium reach 900 m a.s.l. in the western part of the Vajont Valley (Ward & Day, 2011).

Geotourist route

Because this natural disaster affected the large area containing a part of the Piave Valley on a distance of c. 1.5 km and a part of the Vajont Valley on a distance about 4 km, we offer a tourist route along this two valleys to get to know the geological and geomorphological context of this event, caused partly by imprudent human activity.

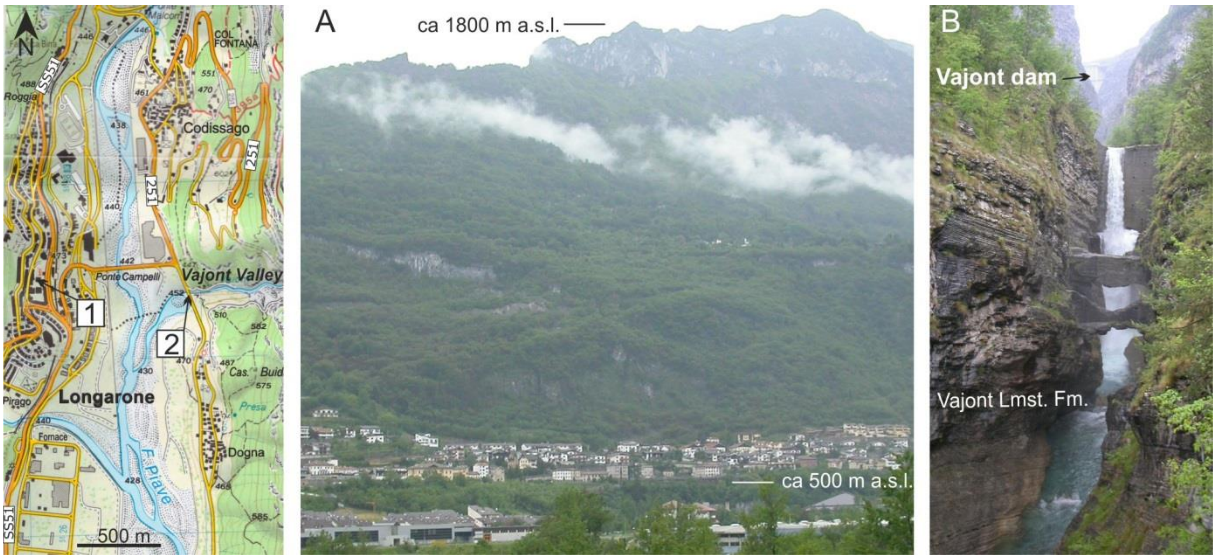

Fig. 5 *Map of the Longarone village with location of The Longarone Vajont Museum – Moments of History (point 1 on tourist road). (A) View point from the left side of the Piave River on the Longarone village. (B) View from the road via Dogna (30 m above the bottom of the Piave River – point 2 of the tourist route) on the Vajont Gorge with the dam visible at the top; the gorge is cut in thick-bedded grey limestone of the Vaiont Limestone Formation (Middle Jurassic). Photo by: M. Bąk; Map after Carta Topographica per escusionisti in scale 1:25,000 (Foglio Blatt 021 – Dolomiti di sinistra Piave) edited by TABACCO.*

Point 1 – Longarone village

We suggest start our journey at Longarone village, situated on the banks of the Piave River (35 km north from Belluno), along the SS51 road linking Belluno to Cortina d'Ampezzo (Fig. 5), close to the borders of Veneto with Friuli-Venezia Giulia. The Longarone was known during Roman times. The municipality of Longarone was established by Napoleon Bonaparte in 1806 (http://www.longarone.net; 03.03.2019). A large part of Longarone was located in the immediate path of the wave of mud and water which swept into the Piave Valley through the Vajont Gorge and above it, falling from several hundred meters high during the Vajont disaster. More than 1450 inhabitants of Longarone – victims of the disaster (from the total number of 1909) – are buried at the Vajont Victims Cemetery of Fortogna. Longarone was rebuilt between 1967 and 1975 (e.g. Mugnano & Carnelli, 2016). We offer a visit to the Attimi Di Storia Museo Longarone Vajont (Piazza Gonzaga, 1). This allows you to see the size of the disaster in the Piave valley in the photographs.

Point 2 – gorge of Vajont Valley

The road to the Vajont Valley begins at the Strada Statale 51 di Alemagna (SS51) in the suburbs of Longarone. Just behind the road sign designating the beginning of the Longarone town, our journey takes us on the righthand side of SS51, to a road junction that is signposted "diga del Vajont". About 500 m past this road junction, there is a bridge over the Piave River (Fig. 5). Turning right sight behind the bridge we are on the Via Dogna street. After 200 meters we approach to small bridge over the Vajont River, right at its mouth to the Piave River. Deeply incised gorge ending the Vajont Valley is visible at the opposite side to the Piave River. Here the roadcuts expose flat-lying, thin-bedded, partly silicified limestones of Igne Formation, overlaid by grey limestones belonging to the Socchér Limestone Formation (Figs 3 & 5B). Uppermost part of concrete construction of the Vajont Dam is visible from this place.

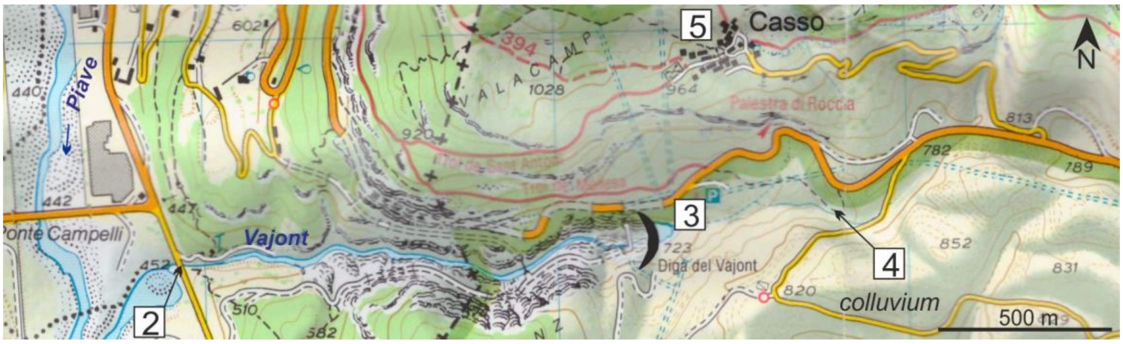

Fig. 6 *Map presenting the Vajont Valley with stops described in the text. Map after Carta Topographica per escusionisti in scale 1:25,000 (Foglio Blatt 021 – Dolomiti di sinistra Piave) edited by TABACCO.*

Crossing the tunnel and galleries through the Mt Salta massif

From the bridge on the Vajont creek, we return Via Dogna (about 200 m) to the intersection with the road No. 251 and follow it through the narrow terrace of the Piave River towards Codissago village. After that the winding road climbs on the Mt Salta massive. The roadcuts along the road expose the Upper Jurassic through the Lower Cretaceous sequence, predominately consisting of limestones and marls. Going up we successively passing complex of siliceous limestones and calcareous turbidites of the Fonzaso Formation, which in places is seen to overlie by a red limestone of the Ammonitico Rosso, and in succession, by the light gray "Maiolica" limestones of the Socchér Limestone Formation. The medium to thick-bedded grey limestones belonging to the Vajont Limestone Formation are visible in the distance on the right-hand and left-hand side of the road.

After about 5 kilometers we enter the tunnel (Fig. 6) which leads directly to the Vajont Valley. The tunnel is hollow in the rocks belonging to the Socchér Limestone Formation. The final section of the tunnel has a character of gallery, where through openings is possible to observe the grey limestones belong to the Vajont Limestone Formation on the slopes of the Mt Toc, located near the Vajont Dam. The tunnel derives up the Vajont Gorge, directly on the dam crest level, which is visible on the right side of the road after passing the tunnel. After about 200 m we enter next part of the tunnel called San Antonio Tunnel which is 168 m long. Outside the tunnels there is a most steep and rocky part of the Vajont Gorge. This is a alpine climbing area. One of the alpine climbing routes on this rocky wall was stated in October 2015 as a different way to remember the Vajont disaster (https://www.guidedolomiti.com/en/news-en/ferrata/ferrata-del-vajont-ferrata-della-memoria/25433; opened 20.03.2019). At the tunnel entrance we can observe in a distance behind, a scar of the landslide from 9 October 1963 situated on the northern slope of the Mt Toc.

Fig. 7 *Vajont Dam with S. Antonio memorial chapel visible from the parking site on the northern slopes of the valley with bottom and slopes covered by colluvial deposits (point 3 of the tourist route); Photo by: M. Bąk*

Point 3 – the Vajont dam and San Antonio memorial church

About 150 m past the San Antonio Tunnel, on the right, is a parking place just at the small church, located near the dam. To reach the dam, visitors is advised to go 200 m from this parking using the footpath (Fig. 6). The dam, which is still standing intact is open for visitors. It is also possible to take a guided visit**.** Near the dam there is an information point, where one can also get the ticket for visiting. Going to the dam we pass the memorial chapel dedicated to San Antonio (Fig. 7). The Church commemorates the tragic death of 64 employees who were present in areas adjacent to the dam on the night of October 9 (https://www.progettodighe.it/forum/viewtopic.php?t=800; opened 20.03.2019). The church was design in 1967 and was built in the following year.

Fig. 8 *Various packages of colluvial material at the valley bottom visible along the road from the Vajont Dam to Casso. Note brecciated marls of the Scaglia Rossa Formation (B) and rolled package of the Sowerzene Formation (D); total thickness of colluvial sediments (not visible on photographs) is estimated at around 250–300 m. Photos by: K. Bąk*

Point 4 – Colluvial sediments at the bottom of the Vajont Valley

An escarpment visible behind the dam and church consists a thick colluvium of the landslide from 9 October 1963. About 200 m past the church, on the right is a next parking place, which provides the opportunity to leave a car or a touristic coach and go on the opposite site to see deposits of colluvium (Fig. 8). The rock mass consists of course and loose sediments, always associated with large blocks made of strongly fractured rock masses (Fonzaso Formation: The Middle–Upper Jurassic) preserving the stratification. These features are important for recognition of the sediments of the latest landside from deposits of prehistoric events, which are common on the Vajont Valley area (e.g. Paronuzzi & Bolla, 2012).

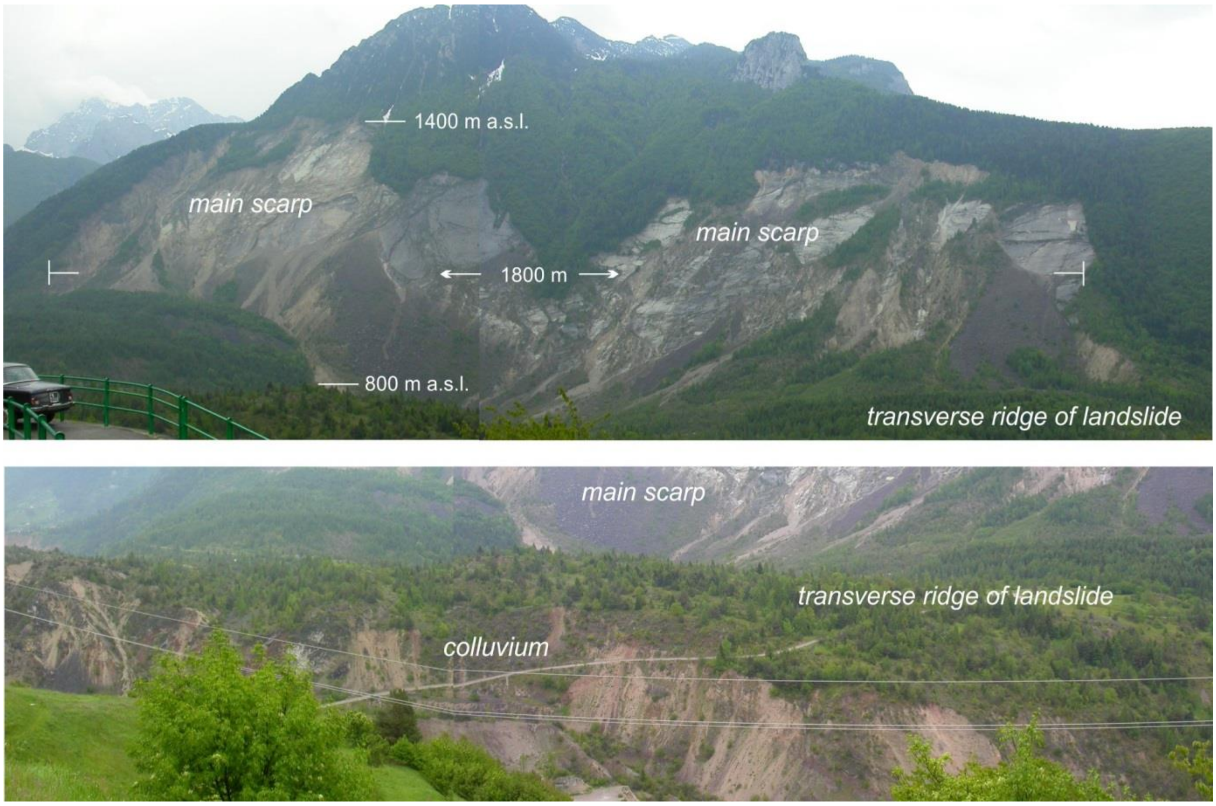

Fig. 9 *Main scarps of the landslide from 9 October 1963 on the slopes of the Mt Toc (1921 m a.s.l.) and transversal ridges at the valley bottom. Photo by: K. Bąk*

Fig. 10 *Geology of the northern slopes of the Vajont Valley above the Casso village with a fragment of the Erto Syncline built of the Middle Jurassic thick-bedded limestones (Vajont Limestone Formation) overthrusted on marls of the Upper Cretaceous Scaglia Rossa Formation. Both photos (A & B) present also stone buildings from the first half of the twentieth century that have been partly damaged in the Vajont-disaster of 1963, and was abandoned; Many years later people started to restore and re-use some of the houses, mostly as the second residence. Photos by: K. Bąk*

Point 5a – Geology of the northern slopes of the Vajont Valley near Casso village

From the parking, road leads along the scarp built of landslide debris. Above the scarp, on the right side, the slope of Mt Toc with huge landslide scar is visible in a distance. About one-kilometer past, there is road junction. Taking the left road, we can go up the hill to Casso settlement, which is situated on the southern slopes of Mt Salta. The road was rebuilt after 9 October 1963. It was cutting in the debris of landslide, which can be observed on the left and right side. Along the road to Casso these colluvial deposits are located circa 900 m a.s.l. At the lower (SW) part of the village, on the roof of the school building, a viewing platform has been built, from which there is a best panorama of the Mt Toc with main scarps of the landslide (Fig. 9).

From the upper part of the Casso, we can go on a short geological tour of tourist trail no. 393 towards the Mt. Salta. It will give you the opportunity to see two rock series that contact each other tectonically, which is very clearly emphasized in the relief of this area (Fig. 10). The village of Casso and the mountain glade above it are located on the Upper Cretaceous red marls and they contact along the thrust fault with gray limestones of the Middle Jurassic Vajont Limestone Formation, which belongs to the Erto syncline.

Point 5b – Casso and Erto villages after Vajont disaster

After visiting the Vajont Valley area the tourits may overnight in Casso or neighboring Erto village (situated 3 km east from Casso) or return to road leading back to Longarone. Both villages have long history of their settlement. Erto existed from 8th century, and Casso was stably inhabited from 14th century (Filioli Uranio, 2015). Although both villages lies very close, they have been inhabited by different ethnic group, even spoken different dialects (Beninca & Haiman, 2014). During the disaster of October 9, 1963 both villages have been partly damaged. All the inhabitants were evacuated in three days. The people were first accommodated in private houses and taverns in the surrounding areas and then had to move to the newly constructed settlement Vajont, community of Maniago (founded in 1971) about 40 km SE outside the Alps in the Friulian Plain (Zuccon, 2010). Recently, Erto and Casso are now populated again, inhabited by 328 and 26 people, respectively (http://italia.indettaglio.it; opened March 2019). Creation of the Natural Park of the Friulian Dolomites in 1996 contributed to fast revitalization of both villages. Especially, Erto Vecchio is characterized by a huge renovation boom with establishment of stores and restaurants and much more (Löffler et al., 2015, 2016). In turn, many "Cassani" who moved away still own a house in Casso village and use it as a vacation home. The return migration involving re-migrants, retirees, working and seasonal migrants, and newcomers was subject of scientific studies in both villages by Löffler et al. (2015, 2016). They showed positive impacts of second homes on a community in the remote areas of this valley. The conclusion is that without secondhome owners there would be many more "ghost towns" than there already are. First of all, they keep the buildings in good condition, and part of them even started to move back and live there all year-round.

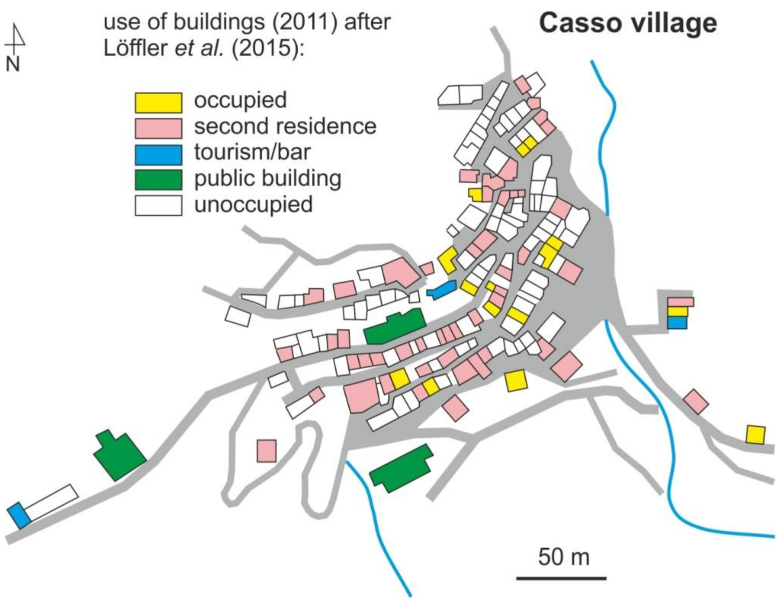

Fig. 11 Modern (2011) use of buildings in Casso village as the result of depopulation after Vajont disaster and return migration during the last 25 years; redrawn after Löffler et al. (2015), partly modified.

The educational and cognitive significance of this place

The educational and cognitive significance of the objects related to Vajont-disaster described above can be determined using both natural and social criteria. Among natural criteria, it should be emphasized: (i) the uniqueness of this geological event which was a huge tsunami inside the land, (ii) the legibility of relief forms despite the passage of over 55 years since their creation, (iii) very high representativeness of the resulting forms in the context of the interpretation of geological and geomorphological processes that contributed to the occurrence of the landslide and tsunami, and (iv) the multiplicity of scientific research in this area, which greatly enriched our knowledge about the causes and mechanisms of the formation of such geological events. They are conducted up to modern times. Among them, the research of the late professor of geology Edoardo Semenza from the University of Ferrara deserves recognition, summarized in Genevois and Ghirotti (2005).

Due to the great human tragedy and large destruction of housing infrastructure caused by this unique geological event, the above-described villages (Langarone and Casso) are places of exceptional educational and cognitive importance in the field of social issues. This applies to issues related to the reconstruction of the completely destroyed (razed to the ground) village of Lanzarone, which concerned the selection of an appropriate plan for building and choosing the architectural style of the building. These were, for the time being (60s) pioneering solutions, taking into account the opinions (through individual questionnaires) of all residents who survived this tragedy. The second very important aspect is referred to the depopulation changes in two periods of time, right after 09.10.1963 and modern times in the villages of the Vajont Valley that were completely depopulated.

Closing remarks

The Vajont sturzstrom is considered the most disastrous landslide ever in Europe which still remain unexplained for many aspects. It represents an important case history for scientists and researchers dealing with such large landslides. For this reason, the Vajont Valey is a place of great interest for geologists, hydrogeologists and geoengineerings. The *SCOPUS* bibliometric database record 86 papers related to various studies of the Vajont landslide only during the last 10 years (since 2010).

It is also a place that can be used for teaching elementary geology and geomorphology in aspects which were described in this paper. Such place may also help in understanding natural forces, their strength and consequences both for the natural environment and local communities. Additionally, it plays an educational role not only for geologists, but perhaps first and foremost for those for whom the work is associated in various ways with the development of mountain areas. The value of learning from past mistakes through understanding the causes and consequences of natural processes gives the opportunity to minimize losses related to natural disasters.

Acknowledgement

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