Landslides
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Engineering geomorphological characterisation of the Vajont Slide, Italy, and a new interpretation of the chronology and evolution of the landslide

Abstract Although the 1963 Vajont Slide in Italy has been extensively studied for over 50 years, its regional geological and geomorphological context has been neglected. In this paper, we use field observations and remote sensing data to elucidate the interaction between endogenic and exogenic processes that brought the north slope of Monte Toc to failure. We present the first detailed pre- and post-failure engineering geomorphology maps of the slide area. The maps delineate two main landslide blocks, several sub-blocks, compressional and extensional zones, and secondary failures in the deposit. The maps provide new insights into the kinematics, dynamics and evolution of the slide. Finally, we discuss the origin of Vajont Gorge and a prehistoric failure that occurred at the same location as the 1963 slide. We propose, as part of a newly developed multi-stage landscape evolution sequence, that the prehistoric failure was a deep-seated gravitational slope deformation (sackung) that initiated during deglaciation and continued to slowly move until the catastrophic failure in 1963. We argue that the gorge was created by these deep-seated slow movements.

Keywords Vajont Slide · Engineering geomorphology · Regional geomorphology · Endogenic processes · Exogenic processes · Sackung · Rock slope damage

Introduction

The 1963 Vajont Slide, which resulted from catastrophic failure of the north slope of Monte Toc into Vajont Reservoir in northeast Italy (Fig. 1), is one of the best-studied landslides in the world, with over 200 publications addressing its geological, geotechnical and social aspects. The 250 million m^3 rockslide generated a 50 million m^3 displacement wave that flooded the town of Longarone and other villages, killing almost 2000 people. Over the past 50 years, researchers have investigated the structure, lithology, hydrogeology, kinematics, dynamics and impacts of the slide (for an overview, see Genevois and Ghirotti 2005; Superchi et al. 2010; and Paronuzzi and Bolla 2012).

Notwithstanding this remarkable research effort, only Giudici and Semenza (1960), Carloni and Mazzanti (1964a, b), Rossi and Semenza (1964, 1965), Selli and Trevisan (1964), Broili (1967), Semenza (1965), Hendron and Patton (1985) and Guerricchio and Melidoro (1986) mentioned the geomorphological setting of the slide. Broili (1967) described the morphology of the 1963 failure surface, including irregularities related to folds and faults, as well as the role of clay in the failure, ultimately dismissing its importance. He also derived movement directions in different parts of the slide based on sliding surface orientation and determined a general NNE movement of the sliding mass. Hendron and Patton (1985) produced the first geomorphological map of the slope based on 1960 air photographs. They illustrated scarps, depressions and areas of movement, and noted that a prehistoric failure, first described by Giudici and Semenza (1960), could have been recognised on air photographs prior to 1961. An unpublished report, which describes hazards and risk in Vajont Valley, includes maps illustrating geomorphological features (Colleselli 2005). Only Guerricchio and Melidoro (1986), however, focussed exclusively on the geomorphology of Vajont Valley. They highlighted the complexity of the geologic evolution of the valley and provided sketches and maps of processes and landforms, including prehistoric and recent mass movements, watersheds and drainage. Furthermore, they interpreted the geomorphological features present on the northern slope of Monte Toc as the results of tectonic décollement during uplift of Monte Toc and subsequent gravitational deformations superimposed on the preceding Wurmian glacial landforms. They attributed the arcuate trend of the valley to multiple landslide-damming events.

This paper describes features in the valley that brought the north slope of Monte Toc to failure. We describe the mechanisms, kinematics and dynamics of the failure using detailed engineering geomorphological maps. Our approach is based on structural geology and engineering geomorphology (following Fookes et al. 2005, 2007; Griffiths et al. 2012) and the interactions between these disciplines. We adopt an approach similar to those of Gerber and Scheidegger (1969), Whalley (1974) and Leith (2012) by focussing on endogenic and exogenic processes. Leith (2012) defines endogenic processes as those stressing a rock mass due to the Earth's geodynamic system (e.g. tectonics, isostasy, volcanism) and exogenic processes as those stressing a rock mass due to climate (e.g. weathering, landsliding, and glacial and fluvial erosion). In this paper, we include anthropic activities such as construction, mining, agriculture, and horticulture as exogenic processes. We contribute to the body of literature on the slide by: (1) summarising the geomorphic features of the Vajont Valley, (2) providing engineering geomorphological maps of the north slope of Monte Toc before and after the 1963 catastrophe, (3) discussing the interactions between endogenic and exogenic processes that conditioned the north slope of Monte Toc for failure, and (4) commenting on the mechanism of the slide.

Context of the Vajont slide

The 1963 Vajont Slide involved limestones of the Fonzaso and Socchèr formations. Thin clayey interbeds, hypothesised to be of volcanic origin (Bernoulli and Peters 1970) and intercalated within cherty micritic limestone beds of the Fonzaso Formation, are presumably closely associated with the sliding surface. These clay layers are the weakest strata in the stratigraphic sequence and are

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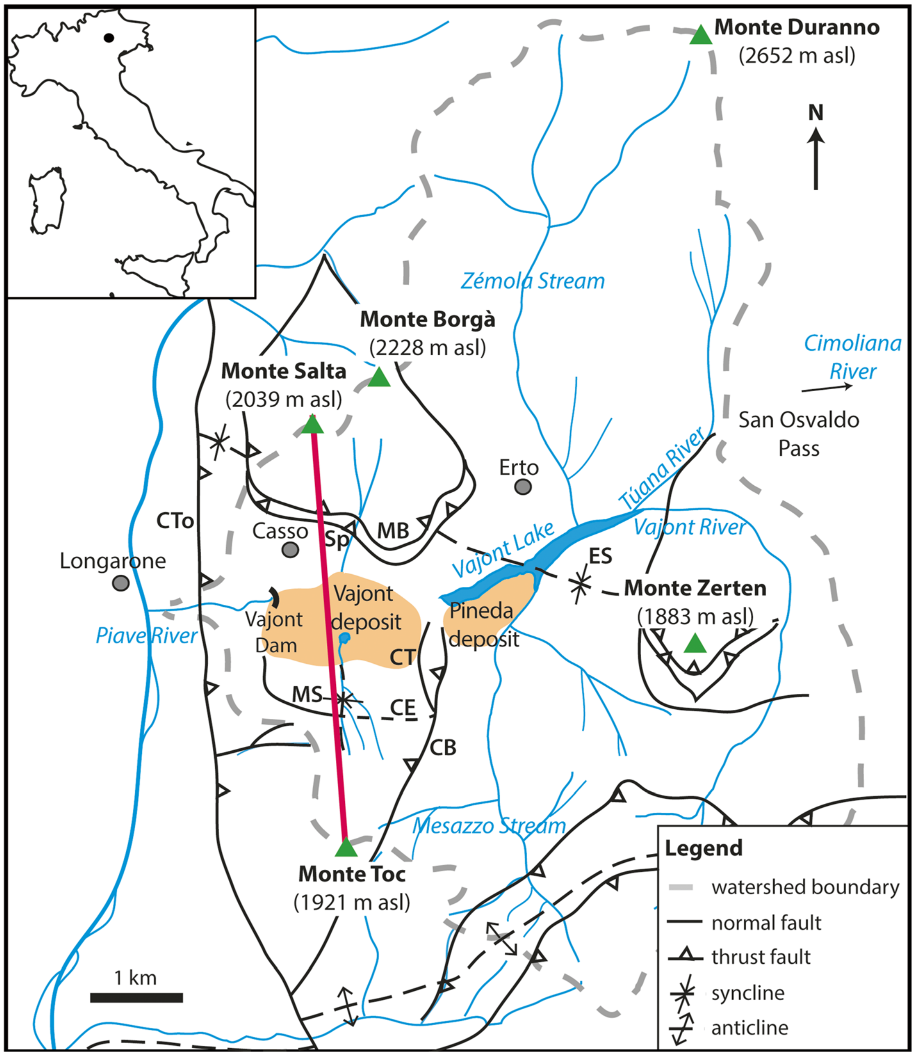

Fig. 1 Setting of the Vajont Slide in northeast Italy. *CB* Croda Bianca Thrust, *CT* Col Tramontin Fault, *CE* Col delle Erghene Fault, *CTo* Col delle Tosatte Fault, *MB* Monte Borgà Thrust, *Sp* Spesse Thrust, *ES* Erto Syncline, *MS* Massalezza Syncline. *Red line* indicates location of the cross section in Fig. 2 (modified from Massironi et al. 2013)

overlain by some of the strongest rocks in the valley, those of the Socchèr formation (Wolter 2014). Figure 2 illustrates the stratigraphic sequence at Vajont.

The tectonic and structural evolution of the region has had a major influence on the geomorphic history of the E-W-oriented Vajont Valley. Several compressional events preceded and accompanied the formation of the Southern Alps. The WSW-vergent Dinaric phase of deformation created folds with N-S-oriented hinges during the Eocene (Ravagnan 2011). The recently mapped Massalezza Syncline, associated with this deformation, is oriented roughly N-S and forms the bowl shape of the 1963 failure scar (Fig. 3). Vajont Valley follows the Erto Syncline, a recumbent fold with a hinge plunging approximately 20° E-ESE. This structure probably formed during the Miocene Neoalpine deformation phase. The refolded southern limb of the Erto Syncline coincides with the hanging wall of the Belluno Thrust and with the asymmetric Belluno Anticline, whereas the northern limb is stretched and overturned under the Monte Borgá and Spesse thrusts (Massironi et al. 2013). Dip slopes occur on both the south and north walls of the valley and contribute to the initiation of large landslides. The southern refolded limb of the Erto Syncline, for example, is the site of the prehistoric and 1963 failures and is responsible for the characteristic chair shape of the north slope of Monte Toc (Fig. 3). The deformation that produced the Erto and Massalezza fold systems created complex interference patterns in the sliding zone of the Vajont scar (Ravagnan 2011; Massironi et al. 2013; Wolter et al. 2014).

Faulting has also affected the Vajont Valley landscape (Fig. 1). The mouth of the valley intersects the N-S-trending Col delle Tosatte Fault, a reverse fault dipping to the east (Massironi et al. 2013). Faults within the Vajont Slide area include the Col delle Erghene and Col Tramontin faults. The E-W-trending, normal Col delle Erghene Fault acted as a rear release surface on the west side of the 1963 failure. The Col Tramontin Fault is the eastern lateral release surface of the slide and is a minor splay of the Croda Bianca reverse fault.

Longitudinal and transverse profiles drawn, respectively, along and perpendicular to Vajont River show how the river profile changes downstream (Wolter 2014). The valley is narrow and V-shaped in its headwaters (0–7 km from the source), but broad and

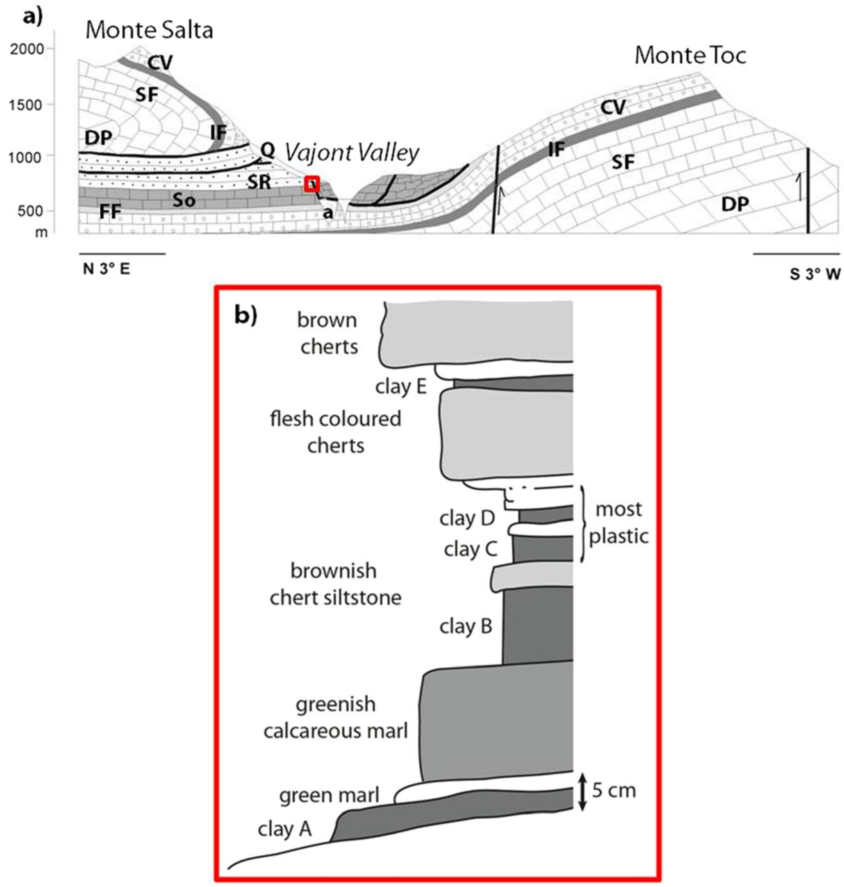

Fig. 2 Stratigraphy of the Vajont Valley area. **a** N-S cross section of units found in Vajont Valley (see Fig. 1 for location of section) (modified from Genevois and Ghirotti 2005). *DP* Triassic Dolomia Principale, *SF* Jurassic Soverzene Formation, *IF* Jurassic Igne Formation, *CV* Jurassic Calcare del Vajont (Vajont Limestone), *FF* Jurassic Fonzaso Formation, *So* Jurassic-Cretaceous Socchèr Formation, *SR* Cretaceous Scaglia Rossa, *Q* Quaternary sediments, *a* Quaternary alluvial gravels. *Red outline* indicates where Hendron and Patton (1985) described the stratigraphy in **b**, which is the detail of units involved in the sliding zone of the 1963 Vajont Slide (modified from Hendron and Patton 1985)

U-shaped or parabolic downstream (8–12 km from the source). The narrow Vajont Gorge, with an E-W trend, forms the lowest 1-km-long reach of the valley. The Vajont Slide occurred in the widest part of the valley and partially infilled the gorge.

Hendron and Patton (1985), Besio (1986), and Fabbri et al. (2013) summarise the hydrogeological conditions in Vajont Valley, with emphasis on the north slope of Monte Toc. Fabbri et al. (2013) note the importance of karst in controlling groundwater flow and supplying deep aquifers. One of three piezometers installed in the sliding mass on the north slope of Monte Toc before the catastrophic 1963 failure indicated the presence of a pressurised groundwater system controlled by impermeable clay layers or shear zones resulting from the prehistoric Vajont failure. Hendron and Patton (1985) suggest the presence of an inclined multilayer artesian aquifer system at and below the surface of sliding: an upper groundwater table in the highly fractured rock mass above the basal clay-rich zone, which was hydrologically linked to the reservoir; and another groundwater table at and below the sliding surface directly reflecting changes in infiltration rates due to rainfall or snowmelt on the upper slopes of Monte Toc and farther south in the Val Gallina watershed.

The glacial history of the Piave region is poorly known, as the record has been largely obscured by erosion, subsequent mass movements and karst development, especially in Vajont Valley. Evidence of glaciation during the most recent Pleistocene glacial stage (marine oxygen isotope stage 2) includes morainal and glaciofluvial deposits on the lower slopes of valleys, fresh cirques, and U-shaped valleys (Colleselli 2005). Pellegrini et al. (2005) and Carton et al. (2009) suggest at least three phases of retreat of the Piave glacier between about 18 and 17 ka. A small glacier probably occupied Vajont Valley during the late Pleistocene (Castiglioni 1940), separated from other valley glaciers by nunataks. Downstream of the dam the Vajont Valley enters the Piave Valley with a vertical drop of 260 m.

Methods

This paper combines field observations and measurements with aerial photograph interpretation and engineering geomorphology mapping. Following Geological Society of London (1982) guidelines, we created detailed maps of the Vajont Slide based on air photographs and field observations to evaluate pre- and post-1963 processes that have shaped the landscape and to better understand the 1963 event. First, we created morphological maps, showing breaks and changes in slope only (no interpretation of landforms or processes). Then, we produced morphogenetic maps to show interpretations of morphologic features and processes as related to

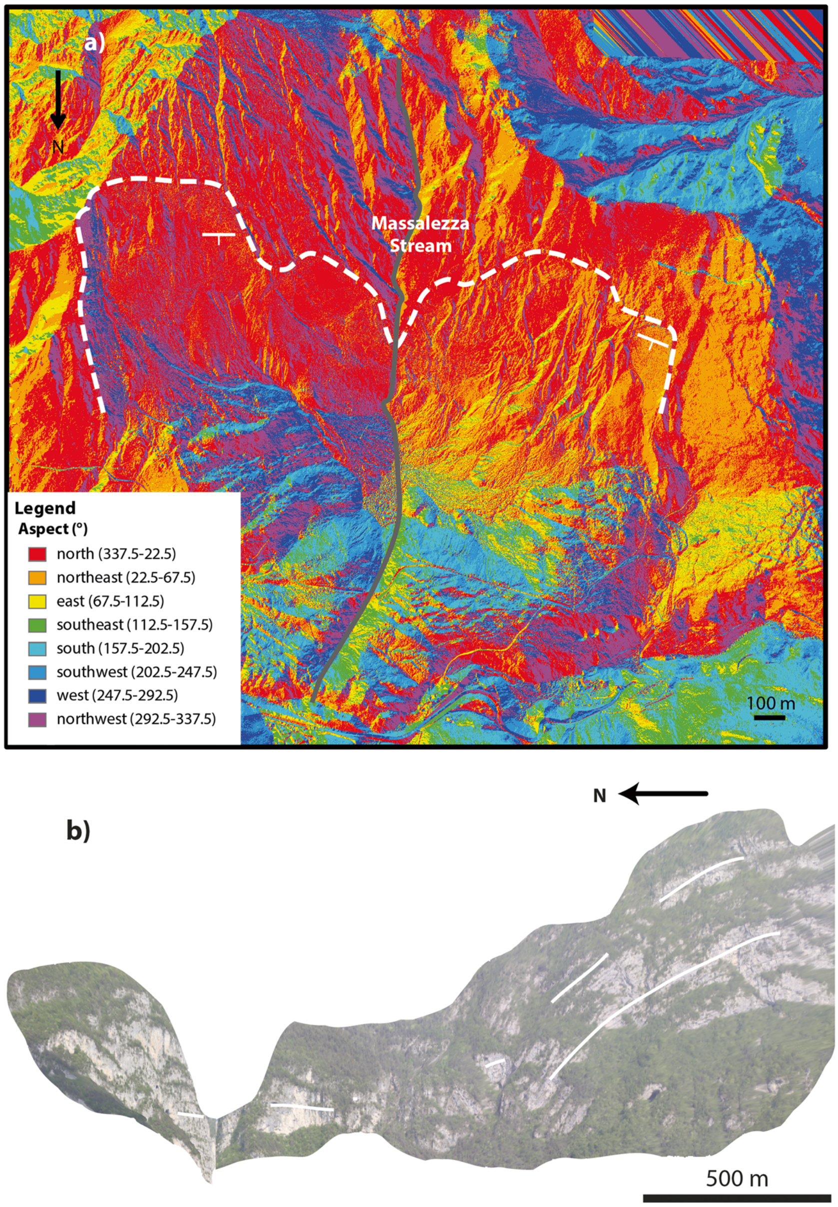

Fig. 3 **a** Aspect map of the slide area, demonstrating the bowl shape of the failure scar due to the Massalezza Syncline. *White curve* outlines the failure scar, and *symbols* indicate orientation of strata. **b** Long-range photogrammetric model of the refolded chair-like limb of the Erto Syncline taken from Longarone ($f = 50$ mm)

the Vajont Slide. We made a field map based on the present morphology in 2011 by surveying changes in slope with a compass and clinometer along transects oriented roughly N-S and spaced 50 m apart (Fig. 4). Below, we summarise observations based on the maps, including description of landforms and processes active before and after the 1963 event. Note that it is difficult to differentiate between shear and extension lineations on air photographs; hence, these were grouped into one feature class on the 1963 map.

Results

1960 map

The 1960 map (Fig. 5) shows the morphology of the north slope of Monte Toc before the 1963 failure. The largest features on the south wall of Vajont Valley are gently sloping (areas with slope angles less than 25°), discontinuous benches (Table 1, Figs. 5 and 6). Most of the benches occur in two clusters, one near the top of the slope and another at the toe of the slope; there are fewer benches in the mid-slope position. The Pian della Pozza (Bench 5; approximately 208 000 m^2), the largest and most distinctive bench with the exception of the Pineda deposit, tilts gently into the slope. In contrast, Bench 6 (approximately 132,000 m^2) dips downslope.

Steep scarps (>45°) and extensional lineations are present on both sides of the Massalezza Gully and cluster near the developing headscarp of the instability (Figs. 5 and 7). The two most prominent scarps, each longer than 200 m, are oriented WNW-ESE and are located in the upper slope area west of the gully;

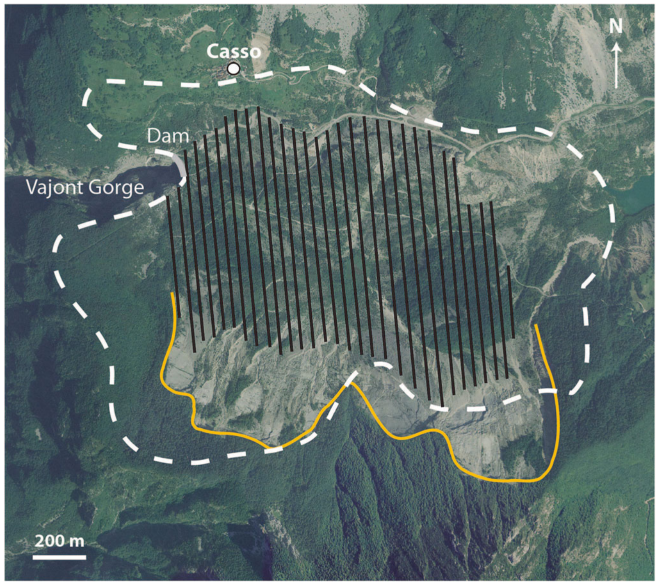

Fig. 4 Location of topographic transects used to document changes in slope below Monte Toc and to assist in creating a detailed field engineering geology map of the Vajont Slide. *Dashed white curve* delineates the area mapped in the field, and solid golden curve indicates the slide headscarp (modified from Wolter et al. 2013)

they are located along the trace of the Col delle Erghene Fault. A third scarp, with a length of 300 m and a similar orientation, is present east of the gully. These three scarps delineate the 1963 headscarp, which first appeared as an M-shaped tension crack in October 1960. A smaller scarp (75 m long), on the Pian della Pozza at the toe of the slope, is likely related to the incipient November 1960 failure. Minor scarps also appear on the east side of the slope.

Three depressions are present within the unstable rock mass. The smallest depression (220 m long) is located just downslope of Bench 12. The largest depression (700 m long, 100 m wide, and about 15 m deep) is located at the rear of the Pian della Pozza.

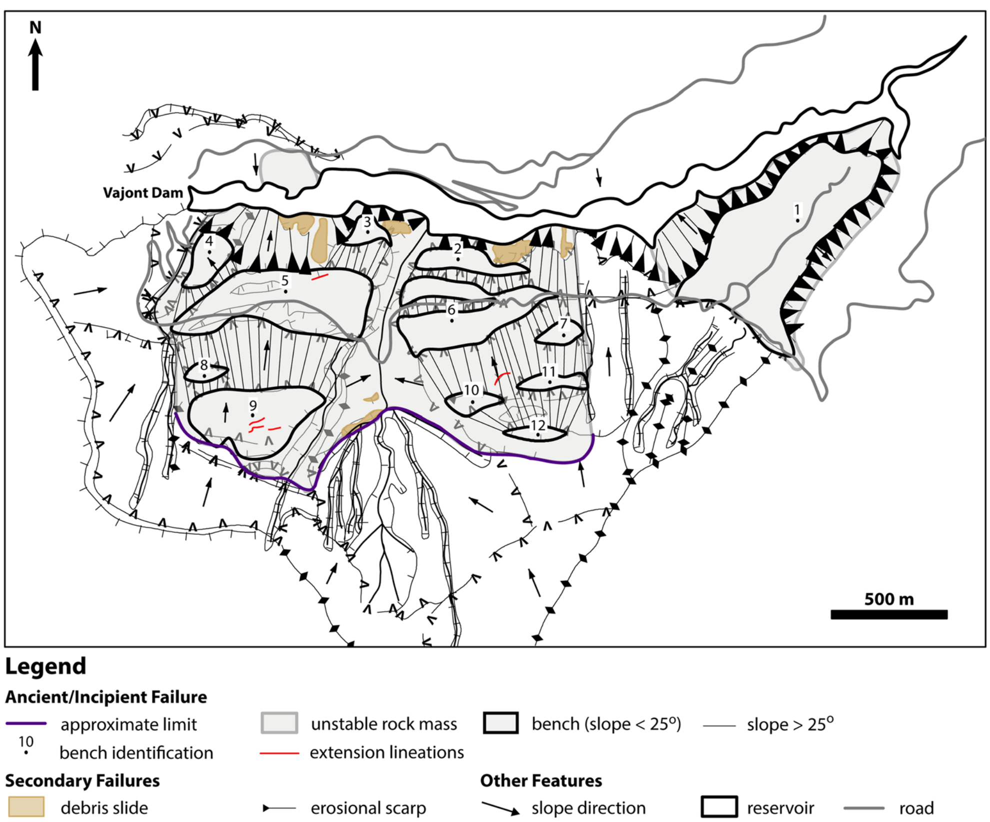

Fig. 5 Pre-slide morphological and morphogenetic map based on an interpretation of 1960 aerial photographs

Table 1 Characteristics of the gently sloping benches evident on the 1960 air photographs

ID[a]	Elevation (m asl)	Length (m)	Width (m)	Area (m^2)	Angle (°)
1	739	3194	120	384,407	23
2	761	1182	33	38,481	22
3	763	633	27	17,352	17
4	774	774	45	34,907	17
5	839	2250	93	208,205	13
6	864	2750	48	131,661	18
7	951	538	30	15,886	25
8	961	476	24	11,442	25
9	1071	1653	84	138,966	22
10	1077	611	30	18,199	18
11	1088	740	25	18,146	18
12	1191	620	22	13,404	23

[a] ID numbers correspond to those in Fig. 5

1963 and 2011 maps

The extent of the 1963 landslide is shown on the post-slide 1963 and 2011 maps (Figs. 8 and 9). The landslide, from headscarp to deposit toe, is approximately 1.8 km wide and 1.5 km long. The debris front forms a conspicuous 60-m high, 1.5-km long cliff on the floor of the former Vajont Reservoir. It follows the pre-failure gorge, with a protrusion to the north near Massalezza Gully. The debris did not impact the opposite valley wall; rather reservoir water prevented the debris front from moving all the way across the valley. The influence of the reservoir is also evident from the distribution of surviving pre-1963 vegetation on the debris. Most of the slide deposit was washed by the large displacement wave, leaving a bare surface. However, undisturbed 1963 vegetation is evident. For example, the Bosco Antico ("old forest") is preserved in the southwest corner of the debris (Fig. 10).

The headscarp is asymmetric—it is tallest (nearly 100 m) next to the Col Tramontin Fault along the east boundary of the landslide. Another area of the headscarp that is taller than average (approximately 25 m high) is near the west boundary of the landslide and coincides with the Col delle Erghene Fault (Fig. 1). Most of the remainder of the headscarp has little relief (<10 m) and is subparallel to bedding.

Ridges and shear/extensional lineations within the blocks provide information on movement directions, with ridges assumed perpendicular and lineations roughly parallel or oblique to displacement. Figure 11a, b illustrates the lengths and orientations of the ridges and lineations, respectively, on the 1963 map. Most ridges are hundreds of metres long, and the lineations are tens of metres long; the longest ridge is 400 m and the longest lineation is 130 m. The average trend of the ridges is E-W, whereas the average trend of the lineations is NE-SW.

Discussion

Interpretation of engineering geomorphological maps

1960 map

Active processes in 1960 included gullying, fluvial erosion, and shallow slope failures on gully walls and at the toe of the slope along the newly filled Vajont Reservoir. Gently sloping benches,

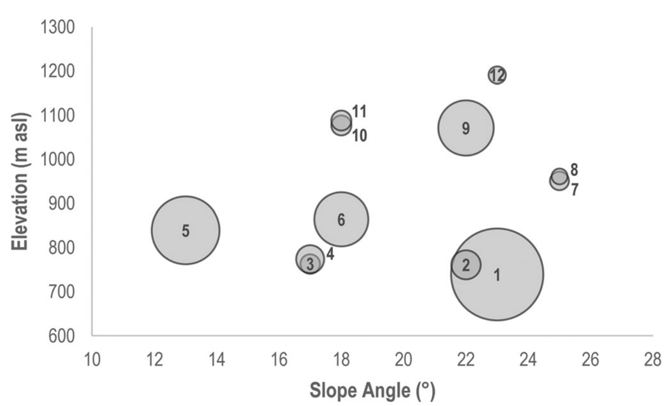

Fig. 6 Graphical representation of bench characteristics (elevation, slope angle and area), as labelled in Fig. 5 (see Table 1 for values). The sizes of the data points indicate bench area

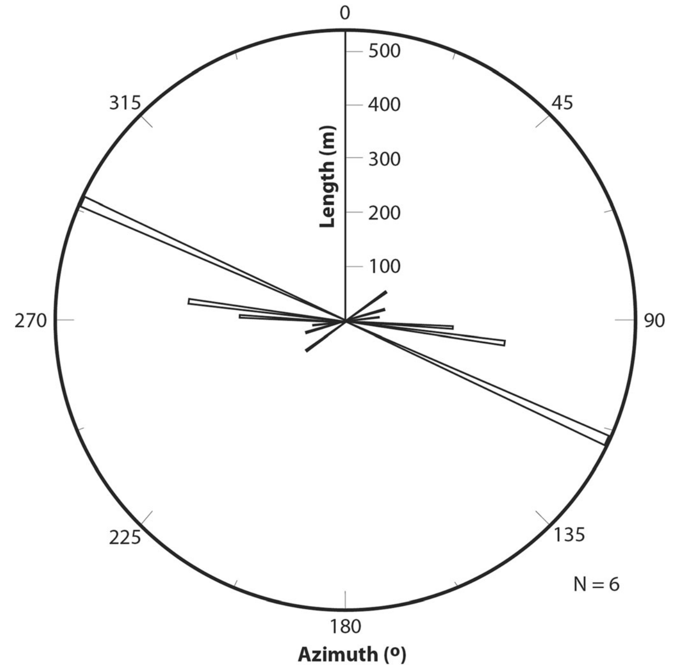

Fig. 7 Polar plot of scarps and extension lineations mapped on the 1960 air photographs, showing lineation strikes and lengths. The three longer scarps correspond to the headscarp of the 1963 failure, whereas the smaller lineations are within the unstable rock mass

scarps, ridges, depressions and hummocky terrain are evidence of a long history of movement of the north slope of Monte Toc. Also, evident is an incipient landslide, which subsequently entered the reservoir in November 1960. The eroded Pineda and Colle Isolato deposits indicate the complex history of landsliding in the valley. There is no evidence of a headscarp delimiting a large pre-existing failure on the north side of Monte Toc in the photographs.

Several features observed in the 1960 map have implications for the evolution of the northern slope of Monte Toc. For example, comparison of the orientations of benches 5 and 6 across the

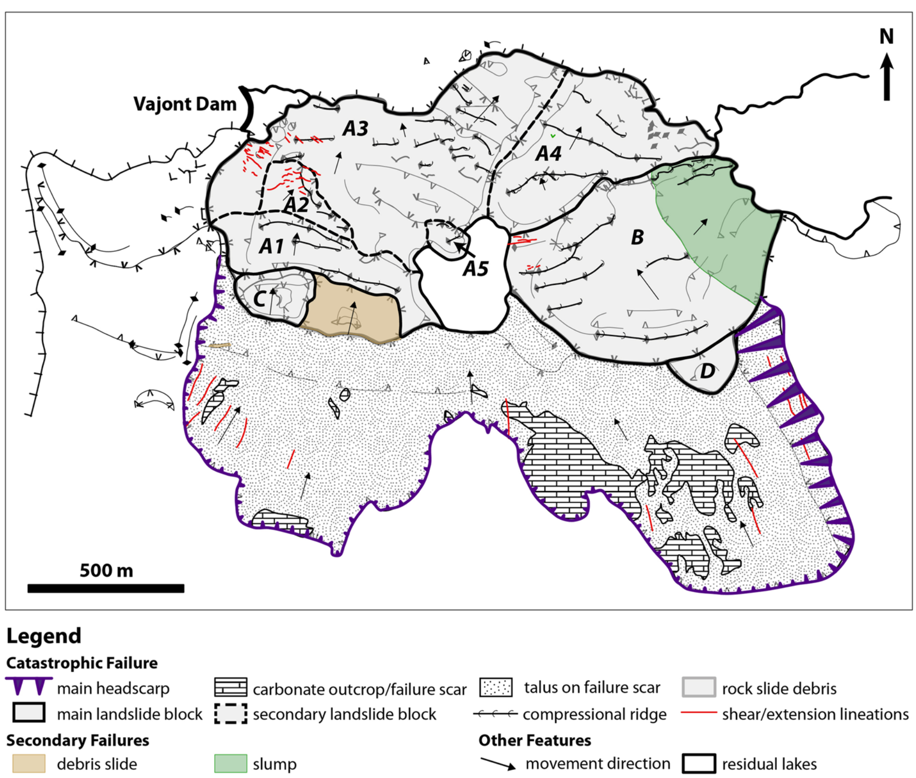

Fig. 8 Post-slide morphological and morphogenetic map based on an interpretation of 1963 aerial photographs. *Letters* indicate blocks and sub-blocks discussed in the text

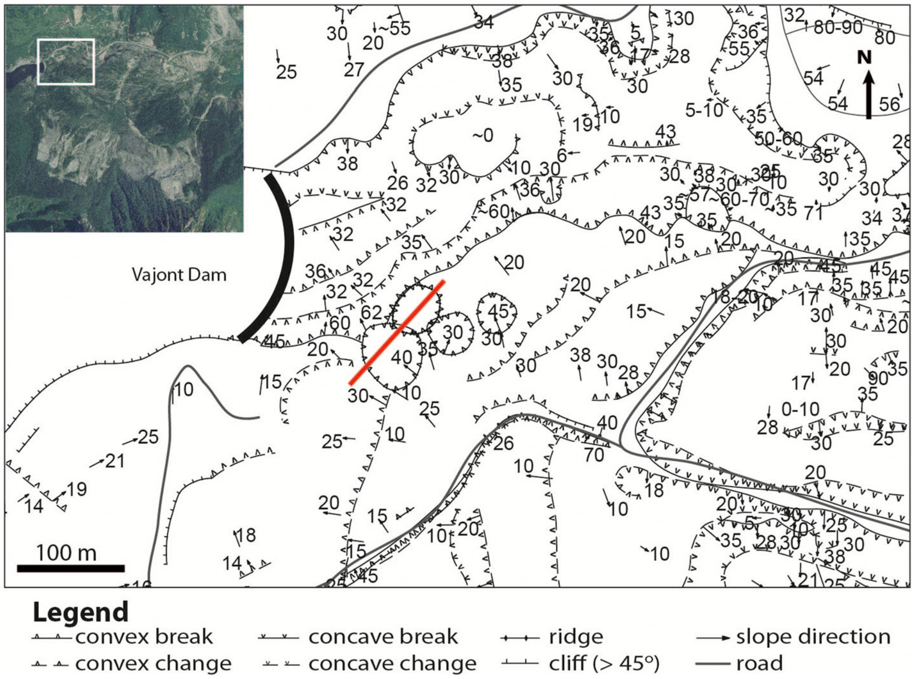

Fig. 9 Sample of the 2011 field morphological map. *Red line* indicates location of the section shown in Fig. 13

Massalezza Gully indicates that, although at similar elevations, they were not connected before erosion of the gully. This observation implies that blocks on the east and west sides of the Massalezza Gully had moved independently prior to the 1963 failure. Semenza (2010) originally thought that the largest depression at the rear of Pian della Pozza might have been the headscarp of the prehistoric failure, but after further fieldwork he revised his interpretation and concluded that the prehistoric slide limit was farther upslope. Other authors, such as Hendron and Patton (1985) and Guerricchio and Melidoro (1987), have suggested that this and other depressions are evidence of gravitational movements, overprinted by dissolution. We interpret this depression as a possible product of sackung and karst processes, as evidenced by its elongated morphology.

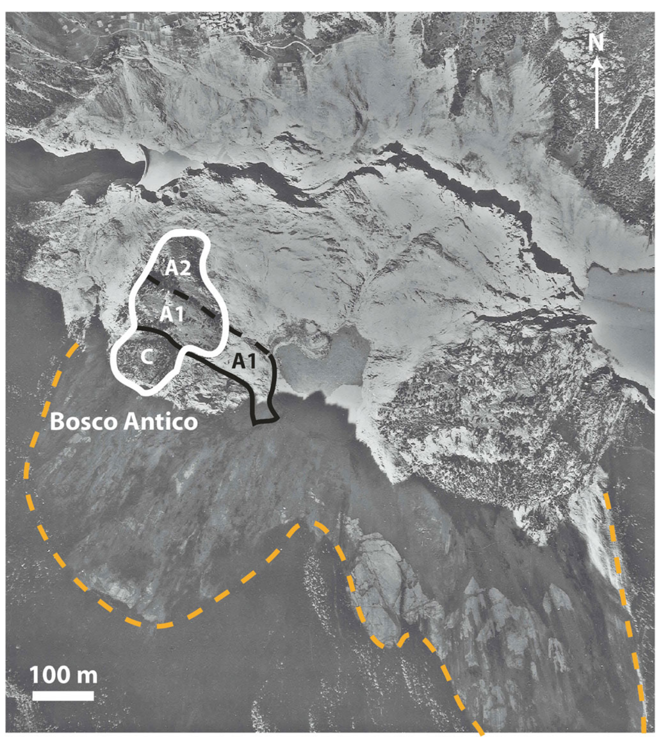

Fig. 10 Bosco Antico (old forest) preserved on blocks A1, A2 and C, showing that the displacement wave did not wash over this area

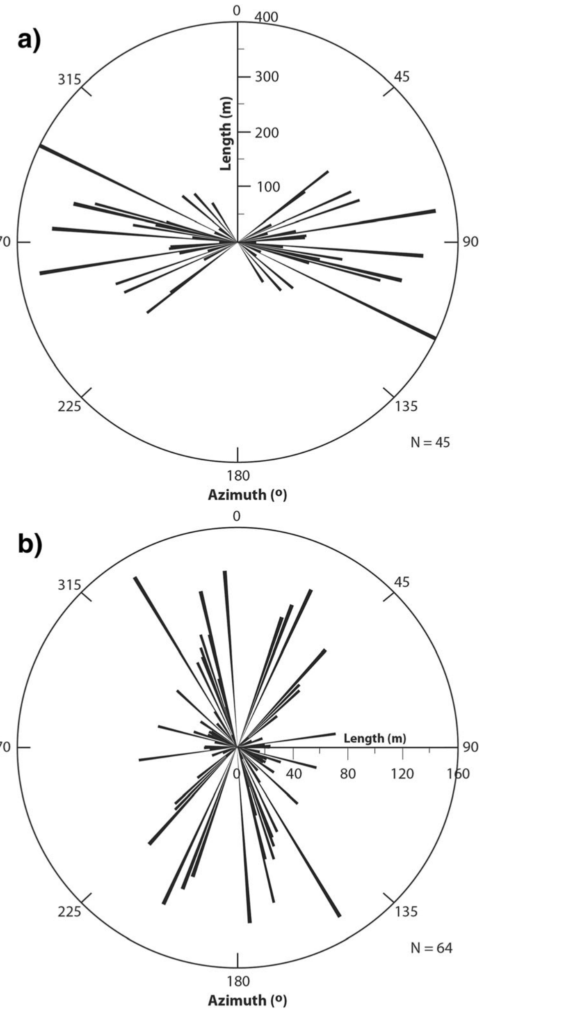

Fig. 11 Rosette diagrams of **a** ridge and **b** shear/extensional lineations observed on the 1963 map, showing the trends of the features and their lengths

1963 and 2011 maps

Much of the slide deposit remained remarkably intact, preserving stratigraphy and, in some areas, even vegetation. Several authors (e.g., Superchi 2012; Bistacchi et al. 2013) have suggested that two main blocks were involved in the 1963 event—a larger west block (block A in Fig. 8) including the Massalezza Gully and a smaller east block (block B) that overrode the west block. These blocks are distinct on the 1963 air photographs and have volumes, respectively, of 181 million m^3 and 43 million m^3 (Superchi 2012). We identified two smaller (<100 m long) blocks (C and D in Fig. 8) higher up on the failure scar. In addition, the west block itself is divisible into five sub-blocks (blocks A1 to A5); differences in the morphology and orientation of ridges on the two sides of the Massalezza Gully indicate that the gully marks a NE-SW oriented, 1-km-long intrablock boundary. Similarly, steep slopes in the southwest corner of the west block may mark boundaries between sub-blocks. Trenches observed in the field and evident on the 2011 map support these 1963 air photograph interpretations.

The orientations of the ridges and lineations in the deposits suggest movement directions to the N and NE, respectively. The orientations of the features indicate that blocks A and C moved N to NE and blocks B and D moved to the NNW (Fig. 8). These movement directions agree generally with Broili's (1967) interpretation, in which most movement vectors are oriented N.

Some of the ridges and lineations formed after block A came to rest due to interactions between blocks A and B. For example, the ENE-WSW-trending ridge on block A4 east of the Massalezza Gully and north of the residual lake (Fig. 8) indicates movement in a NNW direction, which contrasts with the general N to NNE movement direction of the west block. This ridge may have formed in response to collision between blocks A and B.

The spatial distribution of the ridges and lineations indicates where the most deformation and corresponding damage occurred in the deposit. Figure 12 shows areas of interpreted extension and compression based on the ridges and lineations still visible on the 2011 map. We assume that sinuous ridges are caused by compression and reverse faulting, whereas linear ridges are related to normal faulting (cf. Shea and van Wyk de Vries 2008). Ridges are most common near the fronts of blocks and sub-blocks and in weaker areas of the debris. The ridges in block B are larger than those in block A, with amplitudes of decametres versus metres, suggesting more deformation. Lineations cluster in the Col Tramontin Fault area, block A2, and at the fronts of blocks A3 and B (Figs. 8 and 12). The Col Tramontin lineations, as well as a few lineations in sediments resting on the failure scar, appear to have been produced by shearing. The NNE-oriented lineations in the material near the Col Tramontin shear zone indicate that the failed mass sheared to the north, rather than extending away from the fault to the west. Lineations in block A2 are oblique to the movement direction and, based on field observations of trenches, are extensional.

Comparison of Figs. 8 and 12 further highlights the evolution of the deposit since 1963. The deposit has extended northward into the gorge, southward into the hollow behind the debris front next to the residual lake, and eastward into Vajont Lake. Block C is not present in Fig. 12 and may have been disturbed and transported with sediment moving down the failure scar. A new rockfall deposit from the east-central failure scar covers part of block B.

The 1963 and 2011 maps show that many of the same processes operating in 1960 have remained active, but at different locations. Processes that operated within the 1963 slide mass include piping and ponding. Metre- to decametre-scale, circular depressions at the debris front were formed by piping. An obvious cluster of 20- to 30-m-deep depressions appeared a few days after the 1963 slide (Fig. 13; Semenza 1965). New ponds formed on and adjacent to the slide debris in three places after the failure. Reservoir water surged over most of the slide deposit immediately after the failure and left a shallow lake in the large depression behind the debris front at the hinge of the chair-shaped failure surface. This lake and the one remaining behind the dam after failure have since filled with sediment. Vajont Lake, whose intake is 1.5 km upstream of the slide debris, has also decreased in size due to sedimentation.

Many of the gullies that were active in 1960 are now inactive. Material is still failing at the toe of the slope, but sediment resting on the exposed failure scar farther up the slope is also failing in response to the dramatic change caused by the Vajont Slide. Large amounts of material have accumulated in talus cones in the hinge zone of the refolded limb of the Erto Syncline (Wolter

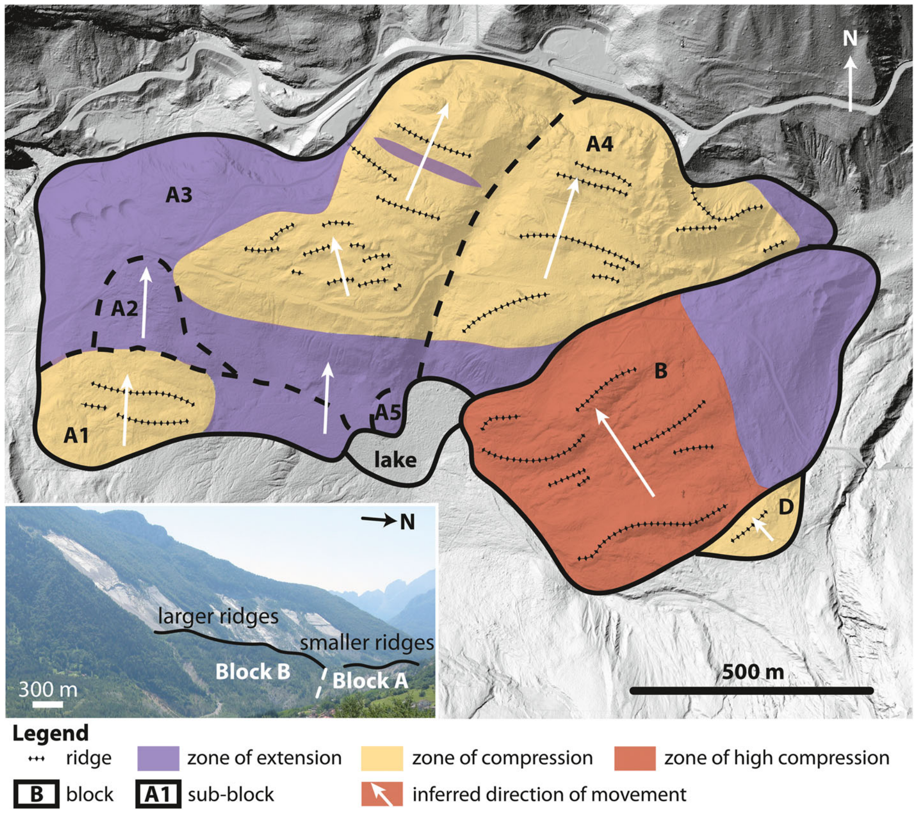

Fig. 12 Map of compressional and extensional areas within the Vajont Slide deposit, based on recent remote sensing imagery. Movement directions are indicated by *arrows*. *Block labels* correspond to those in Fig. 8. Note that block C has been eroded since 1963. *Inset* shows size differences between ridges within blocks A and B

et al. 2014). Another area of active erosion is the Col Tramontin Fault, where a gully has formed between the fault and the slide scar. Large amounts of debris have moved along this gully into Vajont Lake. Rills have also formed in weak material in the shear zone, with intervening sharp pinnacles metres to tens of metres high (Fig. 14).

Humans have lived in Vajont Valley and modified its slopes for thousands of years. The natural landscape has been altered by agriculture, road building, and settlement. Since 1963, parts of the slide mass have been levelled, new roads have been constructed across it, and material has been moved and removed. The Vajont River no longer erodes the toe of the slope, as it flows through the bypass tunnel constructed in 1961.

Interaction between endogenic and exogenic processes and a new hypothesis for the Vajont failure

We have mentioned the endogenic and exogenic processes that have shaped Vajont Valley and the north slope of Monte Toc. Figure 15 highlights the specific causal and triggering factors, framed in an interaction matrix (cf. Hudson 1992). Each variable in the matrix (along the diagonal, with colours representing endogenic (red) and exogenic (green) processes) affects other variables, and is in turn influenced by them.

Causal factors include both endogenic and exogenic processes. Triggering factors—heavy precipitation and reservoir level fluctuations—are exogenic. The influence of past seismicity is unknown, but earthquakes undoubtedly had some effect on the

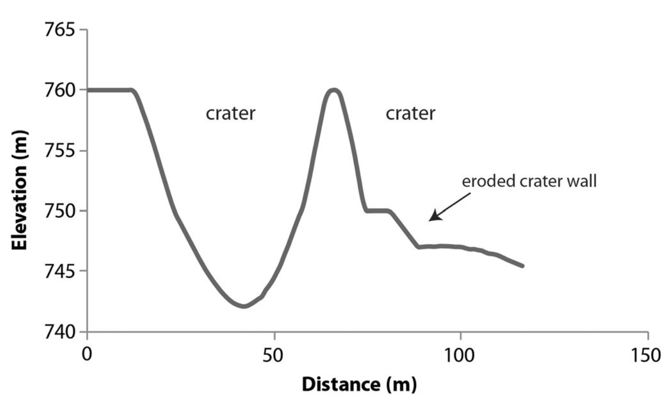

Fig. 13 Section through the largest of the craters at the front of the 1963 slide debris, near the dam. Section location is the red line in Fig. 9

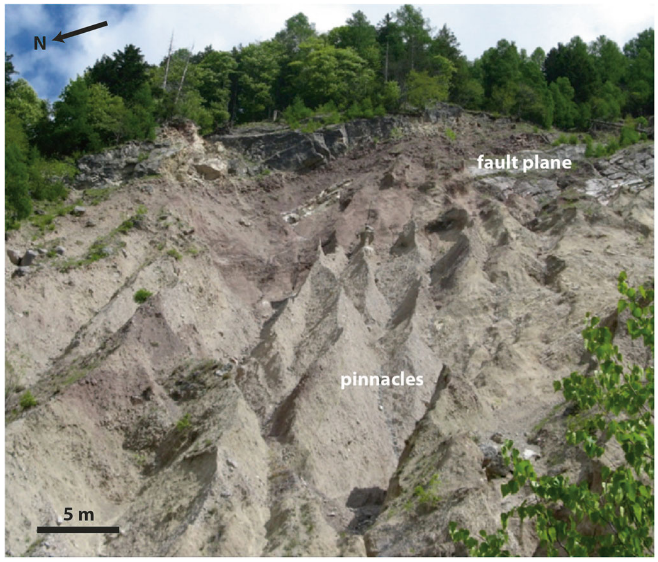

Fig. 14 Pinnacles of remaining sediment and weak rock material at the Col Tramontin Fault

Vajont slope, as it is located in a seismically active area. The effect of pore water on the weak clays was particularly important in bringing the slope to the point of catastrophic failure. The clays, already affected by stress-induced damage, weathering, erosion and slow downslope movement, were further softened by infiltration of the reservoir water. Infilling and rapid drawdown of the

STRESS	stresses increased strain in the rock mass, leading to ***microcracking*** and ***damage***, especially in the clays	stresses affected joint closure/dilation and thus ***permeability*** and ***porosity***	***gravitational stress*** was a major component of erosive transport	***high stresses*** increased weathering susceptibility, especially of the clays
Erto and Massalezza synclines ***concentrated stress*** in their hinge zones; ***seismicity*** redistributed stresses	**STRUCTURE AND LITHOLOGY**	shear zones influenced ***flow paths***, and ***reduced*** or ***increased*** permeability	shear zones, folds, and faults controlled the ***kinematics*** and ***behaviour*** of the Vajont Slide	***sheared*** and ***folded zones*** and ***clays*** more prone to weathering
pore water pressure ***decreased*** effective stress	fluctuating pore water pressures ***weakened*** rock mass, and contributed to karst formation and ***creep***	**PORE WATER**	***filling*** and ***rapid drawdown*** of the Vajont reservoir triggered the catastrophic Vajont Slide	pore water contributed to ***chemical weathering*** of rock mass (oxidation and softening of joints and shear zones)
previous mass movements and glacial action would have ***changed in situ stress*** distributions	Vajont River ***undercut*** toe of slope; glaciers ***oversteepened*** slopes and ***broadened*** valley	precipitation contributed to ***high water pressures*** in the slope	**EROSION**	erosion exposed fresh material to weathering; glacial ice caused ***brittle fracture***, ***damaged*** clays, and ***increased*** weathering susceptibility
weathering contributed to ***stress relaxation*** toward surface	weathering ***opened fractures***, especially in clay seams and shear zones	more weathered rock at surface was more highly fractured, and ***permeability increased*** here	weathering (such as temperature cycling and freeze-thaw action) ***damaged*** in situ rock mass, facilitating erosion	**WEATHERING**

Fig. 15 Interaction matrix of the endogenic (*red*) and exogenic (*green*) variables at Vajont, which, with minor alterations, could be applied to similar dam reservoir landslides

reservoir altered pore water pressures, and thus effective stress, influencing disturbing and resisting forces and contributing to the destabilisation of the clays and ultimately the slope.

Vajont Gorge reflects the interplay among the important and commonly complex physical processes affecting Vajont Valley. Gorges are ephemeral landscape elements that form when a stream is in disequilibrium with downstream base level, in this case the Piave River valley. What is unclear, however, is the cause of the disequilibrium. Common conditions for gorge formation include hanging valleys after deglaciation, erosion-resistant geological formations, tectonic uplift, river obstruction, and long-term, deep-seated rock slope movement causing pinching of a valley. In the Vajont case, glaciers probably deepened Piave Valley at the expense of Vajont Valley, leaving the latter hanging. The Vajont Limestone, the unit in which the gorge is incised, is stronger, and more resistant to erosion, than other surrounding units. The mouth of Vajont Valley is also located on the west limb of the Massalezza Syncline, but there is no evidence for recent movements along faults in the gorge to suggest tectonic uplift is a factor in gorge formation.

We conclude that the most likely explanation for the formation and persistence of the epigenetic gorge is mass movement, as proposed by Ouimet et al. (2008). The knickpoint associated with the gorge in the pre-reservoir valley is just upstream of the Vajont Dam. This is where Giudici and Semenza (1960) hypothesised that there was a prehistoric failure based on cataclasite, landslide remnants on the north valley slope and slope morphology. Rather than being a discrete catastrophic failure, however, we interpret the older Monte Toc landslide to be a sackung that has been active at least throughout the Holocene. Bulging of the toe of the slope would have displaced Vajont River to the north. This hypothesis also explains the lack of a distinct headscarp prior to 1963, and the hummocky terrain, scarps, depressions and basal shear zone (cataclasite) characteristic of a sackung. The only conflicting evidence is Colle Isolato and the old gorge it covers. According to Semenza (2010 and references therein), Colle Isolato ("isolated hill") comprises two smaller landslide blocks that were part of the prehistoric failure and were separated from the main deposit by fluvial incision. It is possible, however, that Colle Isolato is a separate mass that slid away from the toe of the sackung, as suggested by Broili (1967) and similar to the 1960 failure into Vajont reservoir. We suggest that the old river channel that Giudici and Semenza (1960) mapped at the mouth of the valley was blocked by the smaller failure at the toe of the south slope of Vajont Valley, and that the river subsequently avulsed southward for 500–600 m, eroding the landslide debris and creating the current channel. Farther east, a much smaller mass that Semenza (2010) identified as MC ("Masserella"), and similar to the Colle Isolato material, suggests other failures originated from the toe of the Monte Toc slope prior to the catastrophic 1963 failure.

Spatial and temporal elements of damage

Rock mass damage can significantly affect the location, size and depth of a landslide, as well as debris fragmentation and overall landslide behaviour. It is intricately linked to endogenic and exogenic processes that shape a slope. Spatial variations in structural damage are especially apparent at Vajont. Interpretation of the GSI values and discontinuity sets of Superchi (2012) and the discontinuity sets and roughness analysis presented by Wolter et al. (2014) indicate that the rock mass on the east side of the Vajont Slide (block B) is weaker than that on the west side (block A). Its failure surface also has higher roughness than block A. Rocks in the Col Tramontin area are the most damaged in the slide area. However, the rougher surfaces and lack of kinematic freedom in the east prevented the rock mass there from moving significantly before the west block failed. The centre of the failed rock mass, where the hinges of the Erto and Massalezza Synclines intersect, was highly folded. This area would have been a focus of stress in the slope—a Prandtl wedge transition zone between the active and passive blocks of the slide (Mencl 1966). Geomorphic features at Vajont are closely associated with structural damage. For example, Massalezza Gully follows the damaged hinge zone of Massalezza Syncline.

Ridges and lineations are surficial indicators of damage; at Vajont, they were present both before and after the catastrophic 1963 landslide. Prior to failure, scarps and lineations clustered at the top of the incipient landslide, suggesting intense rock mass damage at the future headscarp location. Post-failure, ridges formed in areas of compression. The ridges in block B are larger than those in block A. We thus argue that block B deformed more and was more damaged than block A. Block B material was weaker than block A material before failure, and as a result, damage was amplified in this block during emplacement.

The debris also provides evidence of subsurface differences in damage. Some zones of the debris are sheared and highly fragmented, whereas much material remained relatively intact during emplacement (Fig. 16). The highly deformed zones are the basal shear zone and secondary shears separating intact blocks. The latter were mapped by Rossi and Semenza (1965) and are still evident in the deposit today. If our hypothesis that the north slope of Monte Toc was a sackung before 1963 is correct, the basal shear zone accumulated damage for millennia before failing. Hence, both spatial and temporal damage are significant factors leading up to the Vajont Slide (Stead and Eberhardt 2013).

Interpretation of the Vajont Slide kinematics and dynamics

The field and air photograph data have implications for the kinematics and dynamics of the 1963 slide. The asymmetry of the headscarp supports Hendron and Patton's (1985) hypothesis that the failure surface stepped up to intersect the Col Tramontin Fault to the east. The greater thickness of the sliding block on the east (approximately 200 vs 50 m on the west) reflects the control exerted by the Erto and Massalezza synclines. Thus, brittle fracture and crack propagation through intact rock would have played an important role in the development of failure, particularly towards the east.

The formation of the two main blocks and five sub-blocks within the west block relates to the kinematics of the slide. To fail, the rock mass required the kinematic freedom afforded by the creation of these blocks. Had these blocks not formed, the mass would have been more stable and might not have failed at all.

A possible sequence of events based on the pre- and post-failure morphologies of the Vajont slope is as follows (see Fig. 17):

1. A proto-Vajont River eroded a valley created by tectonic uplift, faulting, and folding.

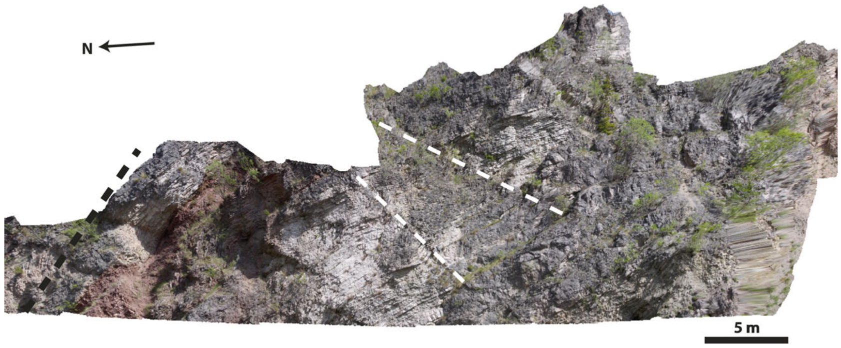

Fig. 16 Photogrammetric model of the debris front of the Vajont Slide, showing intact blocks of Soccher Formation units, separated by minor (*white dashed lines*) and major (*black dashed line*) shears ($f = 100$ mm)

2. Pleistocene glaciation deepened and widened the valley and created oversteepened valley slopes (Hutchinson and Kwan 1986).
3. Deglaciation at the close of the Pleistocene unloaded slopes, affecting in situ stresses. Vajont River re-established its course.
4. Movement began as slow, sackung-type deformation, probably during or soon after deglaciation. The sackung displaced Vajont River to the north, and the river eroded a new narrow channel.
5. A prehistoric toe failure in the western zone of the sackung possibly blocked Vajont River. This event may have been the

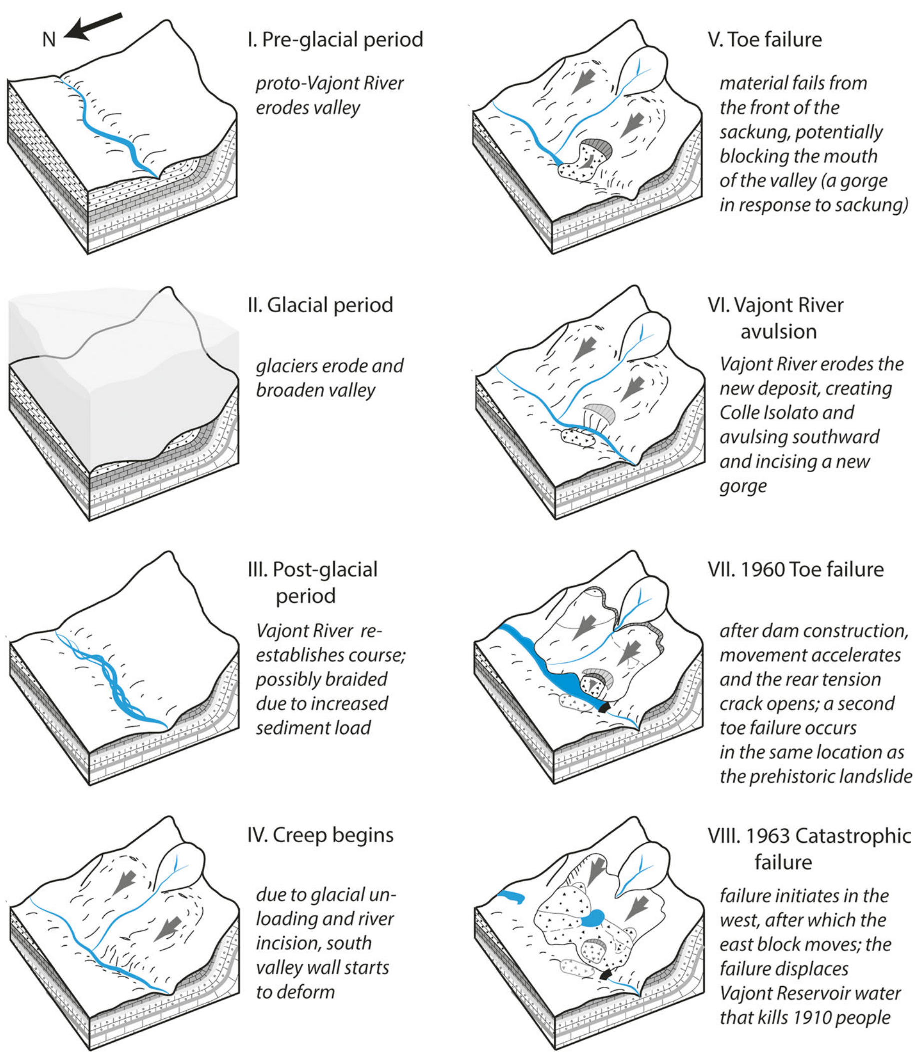

Fig. 17 Hypothesised sequence of events leading to the catastrophic failure of 1963. Stratigraphic symbols are the same as in Fig. 2a

source of Colle Isolato. Other smaller failures such as the Massarella (MC) mass had similar, although less dramatic, effects on the topography and river.

6. Vajont River avulsed southward, eroding the new landslide deposit and incising a deep narrow gorge.
7. After construction of the Vajont Dam, movement accelerated due to reservoir filling and another failure at the same location as the prehistoric landslide occurred in 1960. In the same year, the rear M-shaped tension crack opened.
8. After a period of lower movement rates, the rock mass accelerated in late 1962 due to another filling of the reservoir. This acceleration of movement was followed by a drawdown and third filling of the reservoir. The western upper blocks (blocks C, A1 and A2 in Fig. 8) acted on the lower passive material (blocks A3, A4 and A5), eventually failing and moving downslope and across the valley. Sliding of block A created kinematic freedom, allowing block B to fail and ride onto the debris of block A. Smaller blocks (blocks C and D) detached from the headscarp after the main blocks, coming to rest on the failure scar above the main deposit. Subsequent secondary failures occurred, and included landsliding of material remaining on the upper sliding surface. Drainage of the slide mass caused piping and pore water pressure dissipation.

An element of uncertainty in this sequence of events is the exact timing of emplacement relative to the displacement wave. Did the displacement wave arrive before the east block came to rest? Or afterwards? Given the short timeframe of the sequence of events, less than a minute, either is possible.

The above sequence of events compares well with Semenza's (2010) palinspastic reconstruction. The main difference is the rate of movement of the prehistoric failure. We suggest slow sackung-type movement rather than episodic catastrophic failure. The cataclasite Semenza argued to be evidence of a prehistoric catastrophic slide may have formed by slow deformation over millennia, as is common for creeping failures (e.g. Downie Slide; Kalenchuk 2010).

Why here?

The Piave region is a tectonically and geomorphically active area with many large mass movements. The Alleghe, Borta, Pineda, Fadalto, Borca di Cadore and Cinque Torri failures are notable examples (Coppola and Bromhead 2008; Dykes et al. 2013). Examination of satellite imagery shows that many mass movements in the region have occurred on dip slopes. Several are structurally controlled (Dykes et al. 2013). The stratigraphy at Vajont is not unique to that location, and other failures have occurred in clay-carbonate sequences. Glaciers occupied and eroded most valleys in the region, and stress changes due to unloading were ubiquitous. Vajont Gorge is very narrow and focuses in situ stresses, which increase strain and damage to the toe of the slope. Glacial and fluvial erosion have augmented damage in the valley; unloading changed the horizontal in situ stresses and the ratio of horizontal to vertical stresses, leading to extensional fracturing (Goodman 1980; Leith 2013, 2014). Vajont Valley is also located in an active compressional tectonic area, leading to even higher horizontal stresses. Nonetheless, these in situ stress conditions are not exclusive to Vajont Valley. Changes in reservoir levels are also common in the region, as many natural and artificial dams are present in the Piave watershed. Coppola and Bromhead (2008) investigated the stability of natural dams in the Italian Dolomites, their lasting effect on river morphology, and modification of the dams for hydroelectric power generation. They cite the 1959 Pontesei Dam failure, when filling of the reservoir reactivated an ancient landslide, as an example of landsliding related to reservoir level changes. The exact sequence of filling and slow/rapid drawdown at Vajont, however, was not repeated elsewhere.

Conclusions

The 1963 Vajont Slide occurred in a region characterised by complex structural geological and geomorphological settings. Our engineering geomorphological maps illustrate landforms and processes on the north slope of Monte Toc before and after the 1963 catastrophic landslide, allowing detailed evaluation of endogenic and exogenic causal factors, geomorphic changes and failure evolution. For example, the delineation of landslide blocks within the sliding mass; the study of interactions between endogenic (tectonic, isostatic) and exogenic (weathering, mass movement, erosional, anthropogenic) processes; and the recognition of a sackung before 1963 were possible.

We conclude that the individual factors implicated in the Vajont Slide are not unique to Monte Toc. Their combination, however, caused an unprecedented landslide with catastrophic consequences. Structural features delimited the slide and contributed to its characteristic chair shape, creating an active-passive block regime. Glacial erosion and possible debuttressing weakened the slope and changed stresses in the slope. Fluvial action undercut the toe of the slope, and the changing reservoir level and low shear strength clays triggered a catastrophic failure involving a small number of blocks that remained largely intact.

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