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The prehistoric Vajont rockslide: An updated geological model

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ABSTRACT

This study presents the detailed reconstruction of the entire structure of the prehistoric Vajont rockslide (about 270–300 million m^3 of rocks and debris) for the first time, describing the complex geometry and the characteristic superimposition of distinct rigid blocks on a very thick shear zone. The prehistoric Vajont rockslide was characterized by an enormous 'en masse' motion of a rigid overlying rock mass (100–130 m thick) that moved downslope, sliding onto a very thick shear zone (40–50 m thick, on average) made up of a chaotic assemblage of blocks, limestone angular gravel, and high plasticity clays (montmorillonitic clays). Coarse loose sediments, still exposed on the 9 October 1963 detachment surface, are always associated with large blocks made of strongly fractured rock masses (Fonzaso Formation: middle-upper Jurassic) preserving the stratification. The blocks of stratified and folded limestone sequences appear to be 'sheared off' from the underlying bedrock and can be considered as displaced rock masses planed off by the motion of the overlying rigid rock mass ('rock mass shavings'). The prehistoric Vajont rockslide was characterized by a multistage failure with a marked retrogressive evolution. The first rupture (Pian del Toc block) rapidly destabilized the upper slope, mobilizing a second rock mass block (Pian della Pozza block) that, in turn, determined the multiple rupture of the revealed shear zone material (Massalezza lobe). Even if the exact timing of the different phases is not known, the entire multistaged failure process was very rapid. At the end of the multistage retrogressive failure, the slope morphology of the northern toe of Mt. Toc was drastically changed and the large failed rock mass settled into the preexisting Vajont Valley assuming the unusual chair-like geometry.

The Vajont rockslide represents a very significant example on how a complex geological situation, if not adequately analyzed and reconstructed, can lead to dangerous misinterpretations or even to erroneous engineering–geological and geotechnical models. Accurate fieldwork and modern technologies can be fundamental in solving such a very intriguing 'geological puzzle.'

1. Introduction

On 9 October 1963 at 10:39 p.m. (GMT + 1), an enormous mass (about 270–300 million m^3) of rocks and debris slid into the Vajont reservoir provoking a giant wave that overflowed the dam, destroying the village of Longarone and killing about 2000 people (Fig. 1). This event is considered the most disastrous rockslide ever to occur in European territory (Schuster, 1996), and for this reason it represents an important case history for scientists and researchers dealing with large rockslides and/or reservoir-induced slope failures. Owing to its scientific complexity, the Vajont rockslide event is often regarded as a milestone in rock slope stability studies, and it has also been considered as the starting point for the development of modern rock mechanics and rock engineering (Hoek, 2007). Despite the great scientific interest related to this catastrophic episode, many geological, hydrogeological, and geotechnical aspects of the Vajont rockslide still remain unexplained (Paronuzzi, 2009a).

The name 'Vajont' (Fig. 1) is used in this paper (the exact pronunciation in English is 'Vaiont') according to the current Italian toponymy, whereas other authors formerly utilized both Vajont and Vaiont. In certain cases, even the same author utilized both spelling of the name in different papers: as for example Semenza (Giudici and Semenza, 1960; Semenza, 1965, 2001, 2010) and Müller (1964, 1968, 1987). Even recently the well-known catastrophic rockslide has been reported as Vajont (Kilburn and Petley, 2003; Paronuzzi, 2009b) and as the Vaiont landslide (Genevois and Ghirotti, 2005; Alonso and Pinyol, 2010; Superchi et al., 2010).

The bibliographical archive on the Vajont rockslide currently includes more than 120 scientific papers and technical reports (Superchi et al., 2010), starting from the first studies carried out at the time of the dam construction (Giudici and Semenza, 1960) to the latest historical reviews (Semenza and Ghirotti, 2000; Genevois and Ghirotti, 2005; Ghirotti, 2006) and recent papers on specific topics (Alonso and Pinyol, 2010; Pinyol and Alonso, 2010; Ferri et al., 2011a,b). If one examines the extensive bibliography on the Vajont rockslide, we see that most well-known research papers are written in the English language, but some Italian papers were published immediately after the 1963 catastrophe containing important geological descriptions that are often unavailable

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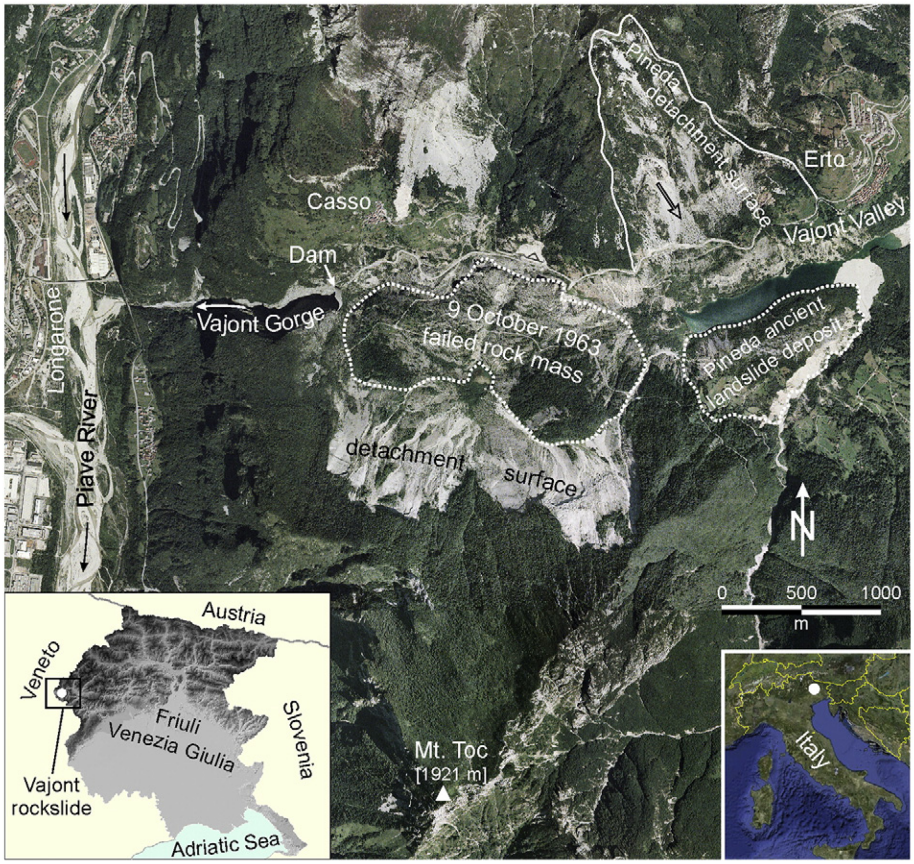

Fig. 1. Orthophoto (date: 6 August 1998) showing the Mt. Toc massif (at the bottom), the final stretch of the Vajont Valley with the Vajont rockslide area (in the central part), and the main Piave Valley (on the left).

to international researchers. As a consequence, the adopted geotechnical and hydrogeological models do not very often consider some important geological evidence that is mainly reported in papers written in the Italian language. A 'gap' exists between the geological studies carried out essentially by Italian researchers, first of all by Edoardo Semenza (the geologist who was the son of the dam designer, Carlo Semenza) and the subsequent geotechnical investigations aimed at the mechanical reconstruction of the catastrophic 1963 rockslide. On the other hand, poor understanding of the geological conditions occurring on the Mt. Toc slope before the disaster has a determining influence on the mechanical reconstruction and on related slope stability back-analyses.

Among numerous scientific papers dealing with the Vajont rockslide, some fundamental works are of note: the special issue dedicated to the first geological studies on the Vajont rockslide, written immediately after the disaster (Selli and Trevisan, 1964); two comprehensive papers written by Müller (1964, 1968) focusing on the main geotechnical and hydrogeological features of the rockslide, including a review of the performed slope stability back-analyses (Müller, 1968); the geological map of the Vajont rockslide, before and after the 9 October 1963 catastrophe, surveyed immediately after the landslide and published for the first time in 1965 (Rossi and Semenza); the book by Hendron and Patton (1985), previously published as a technical report (Hendron and Patton, 1983), containing the most complete scientific review of the Vajont rockslide and including some new geological data surveyed on the detachment surface. The work of Hendron and Patton (1985) represents, without doubt, the most exhaustive research project conducted on the Vajont rockslide because geological, hydrogeological (rainfalls and reservoir level fluctuations), and geotechnical aspects (i.e., the main properties of the clay layers) were examined. More recently, the original photographic documentation taken by Edoardo Semenza during his field investigations (1957–1965, mainly) was made available to the public in a digital format (Masè et al., 2004). Semenza's photographic archive is fundamental for the objective reexamination of main geomorphological and geological features that were visible on the field before the dramatic 1963 slope failure.

From a conceptual viewpoint, the main aspect of the geological interpretation of the Vajont rockslide is the presence of an ancient failed rock mass located on the northern toe of Mt. Toc. The occurrence of an ancient failed rock mass (palaeoslide) was hypothesized in 1959 by Edoardo Semenza after the identification of the paramount outcrop of 'Colle Isolato' (Semenza, 2001, 2010), as reported in his first technical report (Giudici and Semenza, 1960) ordered by SADE (i.e., the dam owner) and delivered to the dam designers on June 1960. Unfortunately, the hypothesis of an ancient failed rock mass or 'prehistoric rockslide' of Mt. Toc was not accepted by all the scientists and engineers involved in the stability analyses, either during the dam construction (the consultant geologists Giorgio Dal Piaz and Francesco Penta) or in the years following the catastrophe. For example, Leopold Müller, the main geotechnical investigator of the Vajont rockslide, did not share Semenza's opinion on the prehistoric Vajont or Mt. Toc rockslide and no reference to this topic was made in his first papers (Müller, 1964, 1968). On the contrary, Müller argued that the hypothesis of a prehistoric failed rock mass represented a contrasting feature to the proposed progressive rupture mechanism for the 1963 slope failure (Müller, 1968).

As a consequence, most geotechnical analyses performed after the 1963 rockslide (Jäger, 1965a,b; Skempton, 1966; Kenney, 1967; Nonveiller, 1967a, 1968; Jäger, 1968; Chowdhury, 1978) considered the geological reconstruction formulated by Müller (1964), assuming a first-time failure along a single basal surface as having a bilinear or curvilinear shape. Three new geological cross sections (coded as 2, 5, and 10A sections) of the Mt. Toc slope were carried out in 1980 by Rossi and Semenza and were later inserted and published into the fundamental work of Hendron and Patton (1985). Some important differences appear when compared to previous geological interpretations, and these include two distinctive bottom failure surfaces (an older and a younger one — 9 October 1963 — rupture surface), the subdivision of the prehistoric rock mass in 3–4 individual blocks separated by distinct internal curvilinear failure surfaces, and some 'tectonized' material located at the bottom in the post-failure section 10A. Internal deformation and damage of the Vajont rockslide mass were also considered by other authors like Mencl (1966), who hypothesized the development of a transitory yield zone in the form of a Prandtl prism with tension cracks and shear planes. The progressive development of an oblique master joint within the rock mass was also postulated as a consequence of a sequential failure mechanism (Trollope, 1980) owing to the unusual bilinear basal rupture surface (chair-like shape) of the Vajont rockslide.

Today, the problem of the prehistoric rockslide of Mt. Toc can still be considered an open question because fundamental aspects are substantially unknown or not defined in detail, such as geometry, kinematics, internal structure (rock damage, fracturing, folding), age, and possible reactivations of the palaeoslide. Most of these features have to be ascertained before starting the hydrogeological and geotechnical modeling of the catastrophic 1963 slope failure. Otherwise, the slope stability back-analyses performed may be greatly conditioned by the adoption of an inadequate engineering–geological model. The occurrence of many contradictory aspects or poorly explained features (antecedent surface movements, progressive failure mechanism, en masse movement, no disintegration of the mobilized rock mass, high velocity of the 1963 rockslide) confirms the necessity for a reexamination of engineering–geological characteristics related to the Vajont rockslide.

This paper reports the first results of a comprehensive research project on the Vajont rockslide that was started in 2000 with a study aimed at establishing the residual geological risk of the area. Most of the geological data was acquired later, with a detailed survey of the detachment surface and failed rock mass that was carried out over five years (2006–2010). Within this study, the extensive bibliography on the Vajont slide was critically reexamined (in the Italian and in the English languages), photographic documentation taken by Edoardo Semenza was back-analyzed, and several soil and rock samples were collected on the detachment surface for laboratory characterization. Newly acquired geological data was employed to establish an updated engineering–geological model of the Vajont rockslide (Paronuzzi, 2009b; Paronuzzi and Bolla, in press). This model constitutes the basic reference for a combined seepage–stability modeling that has been carried out and will be presented in subsequent technical papers.

2. Controversial aspects and debated questions

The Vajont rockslide has many engineering–geological aspects that have been interpreted in different manners and/or strongly debated by various authors. Some of them are reported here and briefly discussed to emphasize the most critical points of past geological and geotechnical interpretations. The following 10 items are particularly important:

- occurrence of clay layers;
- basal rupture surface;
- geometry and internal structure of the prehistoric Mt. Toc rockslide;
- karstic features of Mt. Toc massif;
- characteristics and behavior of groundwater;
- progressive failure mechanism;
- different slope responses during various filling stages of the reservoir;
- drastic change from slow surface movements (cm/d) to the final collapse (m/s);
- 'en masse' motion mode and preservation of the entire rock mass structure; and
- extraordinary high translation velocity (15–30 m/s) of the 9 October 1963 rockslide.

The occurrence of clay layers at the base of the failed rock mass was a controversial question and was especially confuted by Müller because he believed that clay material, in a strict sense, cannot occur within a limestone rock mass dated to middle Jurassic (Müller, 1968). On the other hand, various clay samples were collected on the detachment surface soon after the 1963 rockslide and then analyzed in the laboratory, showing high plasticity properties and low shear strength characteristics. The debated question of clay beds was later definitively resolved as a consequence of the detailed geological survey carried out on the detachment surface (Hendron and Patton, 1985), and several clayey beds were sampled: intercalated within the limestone layers (bedrock) and mixed with loose sediments (matrix-supported angular gravel). Clay interbeds characterize the currently defined 'Fonzaso Formation' (lower-middle Jurassic), i.e., the cherty limestone and marly limestone sequence involved in the basal rupture. Today, the occurrence of high plasticity clay layers is universally recognized and is considered a determining factor for the triggering of the Vajont rockslide. Investigations on microstructural, mineralogical, and strength properties of Vajont clay layers have recently been carried out in order to determine values of the coefficient of friction appropriate to dynamic features of the landslide (Tika and Hutchinson, 1999; Ferri et al., 2011a,b).

Generally, the bottom rupture surface of the Vajont rockslide is assumed to be single, with the typical bilinear pattern or chair-like shape. This particular shape is characterized by an upper inclined joint (the 'back' of the chair) and a lower nearly horizontal joint (the 'seat'). Most geological and geotechnical cross sections intersecting the toe of Mt. Toc took into consideration such a chair-like failure surface. The geometry of the upper third of the whole failure surface was determined on the basis of exposed detachment planes. On the contrary, the remaining lower two thirds of the whole failure surface were assumed by taking into consideration the stratigraphical records of a number of boreholes carried out on the mobilized rock mass after the 1963 catastrophe. Rockslides characterized by a failure surface with a chair-like shape are rather rare, and this unusual feature was attributed to a supposed synclinal geological structure occurring along the Vajont Valley.

In most cases, geotechnical models used in slope stability analyses took into consideration a single failure surface, but some geological cross sections drawn later (Rossi and Semenza, 1985) hypothesized two distinct failure surfaces. In this case, an older, overlying, failure surface caused by the prehistoric rockslide is taken into account; and this discontinuity is well differentiated from the underlying rupture attributed to the 1963 paroxysmal event. This geological interpretation also considers the formation of heavily fractured rocks ('tectonized rocks') along the detachment surface as a consequence of the 9 October 1963 rockslide (Rossi and Semenza, 1985: section 10A 'after slide'). The occurrence of a preexisting rupture surface, in accordance with the hypothesis of a prehistoric dormant rockslide, has a decisive consequence on geotechnical modeling because it implies that residual shear strength has to be mobilized on the rupture plane before the catastrophic collapse. In the same way, the presence of cataclastic rocks along the bottom failure surface can strongly influence both the mechanical behavior of the rock mass and the hydrogeological model of the slope. Therefore, all these geological aspects of the Vajont rockslide have to be investigated in detail and ascertained before implementing the geotechnical modeling.

The existence of the prehistoric Mt. Toc rockslide, as already mentioned, is decisive for the analysis of the antecedent slope instability and the final disruptive rock sliding. For this reason the prehistoric rockslide has to be correctly identified and significant documentary evidence for its existence has to be supplied. The hypothesis by Giudici and Semenza (1960) that a prehistoric slope failure occurred at the northern toe of Mt. Toc was strongly disputed by other geologists and engineers because the supposed rockslide mass denoted an extraordinary unitary aspect preserving all primary features such as stratification joints and sin-sedimentary folds (slumpings). Interestingly, the 1963 rockslide motion occurred with similar characteristics: the mobilized rock mass did not disintegrate, and the large 'rock slab' slid onto the opposite valley side after passing over the Vajont Gorge. Rockslides rarely exhibit such behavior because failed rock masses normally disintegrate, forming an accumulation of blocks and debris as occurred during the first impoundment stage of the reservoir (shallow precursory rockslides failed into the reservoir in March and in November 1960, Müller, 1964; Semenza, 2001, 2010).

Karstic features of Mt. Toc massif have been considered an important geological factor for the analysis of the Vajont rockslide since the earliest studies (Kiersch, 1964) and therefore are often considered in the hydrogeological models of the surrounding area (Semenza and Dal Cin, 1967). This karstic circulation scheme was accepted in most subsequent interpretations (Hendron and Patton, 1985). Nevertheless, a recent field survey carried out on the Mt. Toc relief, on the detachment surface and in proximity to the dam, seems to reconsider the influence of karstic processes on the Vajont rockslide. In fact, the involved rock mass, i.e., the 'Calcare del Vajont' Formation (middle Jurassic) is formed by massive oolitic limestone and only exhibits scarce evidence of karstic processes and morphologies. Surface karstic landforms are rare and poorly expressed. Analogously, the typical underground karstic features (horizontally or vertically developed caves) and the karstic springs are practically absent in the area.

One of the most debated questions of the Vajont rockslide concerns the characteristics of the water table within the slope and the related behavior of groundwater in relation to heavy rainfalls and to the fluctuations of the reservoir level. Basic information on the hydrogeological behavior of the northern toe of Mt. Toc was acquired by means of four piezometers (P1, P2, P3, and P4) that were installed on the slope from April to November 1961. Piezometer P4 went out of order shortly after installation, and the measurements of the water table level were only executed in the remaining piezometric tubes (P1, P2, and P3). Since July 1962, the level of the water table within the slope was effectively equal to the reservoir level, confirming the high permeability of the toe material. The high permeability of the unstable rock slope was already emphasized by initial studies carried out after the catastrophe (Selli and Trevisan, 1964), and a mean value of $k = 1.2 \times 10^{-4}$ m/s was back-calculated by Müller (1968). Such a permeability value is not realistic for rock masses characterized by thin-stratified limestone layers alternated with clayey interbeds, marls, and marly limestone like the geological formations constituting the northern toe of Mt. Toc.

During the initial period of measurements, i.e., until February 1962, the piezometers P1 and P2 exhibited a considerably higher level of groundwater compared to the reservoir level, up to 50 m (P1) or 100 m (P2) higher. On the basis of these elevated groundwater levels, Hendron and Patton (1985) hypothesized the presence of an artesian water table within the bedrock underlying the unstable rock mass. According to these authors, the bottom sequence made up of alternated layers of cherty limestone and clayey interbeds "results in a near classic case of an inclined multiple-layer artesian aquifer system at and below the surface of sliding" (Hendron and Patton, 1985, p. 93). The artesian groundwater, confined by low permeable clay seams of the Fonzaso Formation, in theory would be refilled by upslope precipitation and snow melt involving the Mt. Toc karstic massif that dominates the lower unstable slope. No recent experimental data and/or *in situ* measurements have confirmed this hypothesis, so the hydrogeological reconstruction of the Mt. Toc slope and the relationships with the reservoir fluctuations still have to be ascertained.

Most slope stability back-analyses assumed a simplified hydrogeological model of the failed slope considering, as a rule, the groundwater level within the slope as equal to the reservoir level. These simplified models substantially considered two specific hydrogeological scenarios of the northern slope of Mt. Toc: (i) at the moment of the perimetrical crack appearance in late October–early November 1960; and (ii) at the final collapse on 9 October 1963 (Nonveiller, 1965; Mencl, 1966; Nonveiller, 1967a; Kenney, 1967; Müller, 1968). No combined slope seepage–stability analyses were carried out in previous geotechnical studies.

A progressive failure mechanism was considered by many researchers (Müller, 1964; Kenney, 1967; Nonveiller, 1967b; Chowdhury, 1978; Voight, 1988; Kilburn and Petley, 2003) to explain the change in the mechanical behavior of the unstable slope and the final collapse. This implies progressive damage of the rock mass during the preparatory period, coupled with an increase in the fracturing of the intact rock that leads to the formation of the ultimate failure surface. Müller (1968) observed that such a failure mechanism was in contrast with the hypothesis of a prehistoric rockslide because this assumes a preexisting failure surface that was already defined before the collapse. According to this interpretation, a progressive failure mechanism cannot coexist with the hypothesis of the prehistoric Mt. Toc rockslide; and this problematic question is still unsolved.

During repeated filling and drawdown cycles of the Vajont reservoir, the northern toe of Mt. Toc showed strong differences in its behavior. Slope instability phenomena, evidenced by rockslides at the front and generalized increase of surface movement rates, characterized the impounding phases; whereas drawdown operations (first and second drawdown procedures) generally resulted in an improvement of the slope stability conditions. This slope behavior changed dramatically during the last (third) drawdown procedure as slope movements increased progressively until the final catastrophic rockslide was triggered. The abrupt change from low surface movements to sudden failure on 9 October 1963 was generally explained as a consequence of a progressive failure mechanism (Müller, 1964, 1968). In addition, during the reservoir filling procedures, a particular type of behavior was observed as described by Müller (1964, p. 178): "the movements generally had a higher velocity only if a new portion was wetted for the first time whereas they remained always smaller than the previous one if a layer once wetted was flooded a second time." This led to the so-called 'first-time wetting theory', which gave to the scientists, engineers, and authorities the erroneous belief that the Mt. Toc slope instability could be controlled by hydraulic operations. The first-time wetting theory has neither physical nor mechanical fundamental groundings. The final accelerating movement of the sliding mass that resulted in the catastrophic collapse on 9 October 1963 has recently been investigated by analyzing the surface displacements from some benchmarks located on the Vajont unstable mass. This was carried out in order to understand the failure mechanism or to predict the final slope failure (Voight, 1988; Kilburn and Petley, 2003; Helmstetter et al., 2004; Veveakis et al., 2007).

The occurrence of the prehistoric Vajont rockslide mass was discussed because of the unusual unitary aspect of the supposed failed rock mass. Rockslides rarely denote such en masse motion mode, but this characteristic feature has already been recognized in certain large rock slope failures involving sedimentary rocks such as the Flims rockslide (Poschinger et al., 2006), as well as the Waikaremoana (Davies et al., 2006) and the Abbotsford (Hancox, 2008) 'block slides' that occurred in New Zealand. However, the absence of a generalized disintegration process involving the rock mass during the sliding phase implies the existence of a particular failure phenomenon allowing for such unusual mechanical behavior. Only the detailed geological and mechanical characterization of the prehistoric rockslide can explain this particular type of rock slope failure.

The extraordinary high translation velocity (15–30 m/s) of the 9 October 1963 collapse was certainly the most unexpected feature of the Vajont rockslide. Today, and also in the past, this behavior was essentially interpreted as a consequence of thermal processes occurring along the deep basal failure surface (Voight and Faust, 1982; Nonveiller, 1992; Pinyol and Alonso, 2010). Interestingly, traditional analyses of the catastrophic rockslide motion have always considered a single failure surface made up of a homogeneous material (generally high plasticity clay), but field evidence has clearly demonstrated that the basal detachment surface was characterized by a stepped pattern involving various materials (limestone and marly limestone strata, clay interbeds, clay lenses, angular gravel, etc.).

The geological aspects briefly summarized above emphasize the extraordinary complexity of the 1963 Vajont rockslide. At the same time, the number of debated questions push us to direct a great deal of effort into the geological reconstruction of the prehistoric Mt. Toc rockslide because, without adequate knowledge of the preexisting conditions, no realistic slope stability back-analyses of the 9 October 1963 collapse can be performed. It is time to go back and reanalyze topical geological aspects, returning to the field to implement an updated engineering–geological model based on newly acquired data and sustained by innovative rock mechanical interpretations.

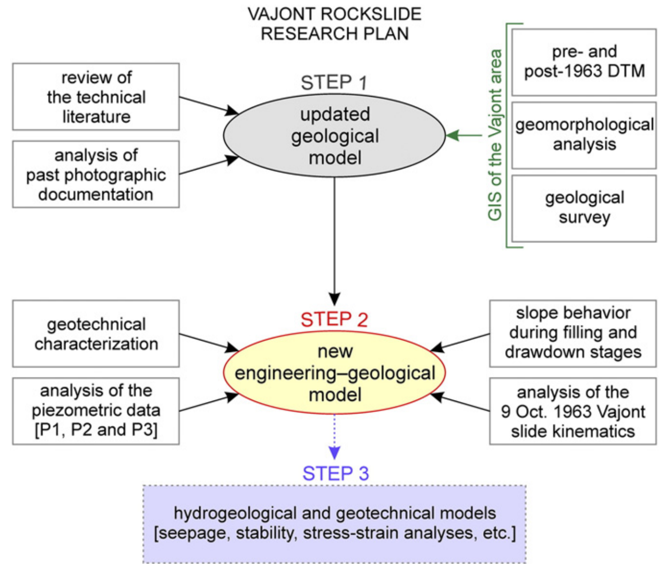

Fig. 2. Flow chart showing the main steps followed in this research on the Vajont rockslide.

3. Materials and methods

Comprehensive research into the Vajont rockslide extended over several years and included the following main steps: the critical review of the abundant geological and technical literature, the detailed back-analysis of the photographic documentation taken by Edoardo Semenza in 1957–1965, the implementation of two digital terrain models (DTM) describing the study area before and after the 9 October 1963 catastrophe, and finally a new geological and geotechnical survey (2006–2010) of the detachment surface and of the failed rock mass. All this data was then used to establish an updated engineering–geological model (Fig. 2) capable of explaining both the antecedent behavior of the slope and the conclusive collapse.

The accurate reexamination of the detailed photographic archive of Edoardo Semenza (Fig. 2) has made possible a critical review of many significant outcrops that have now disappeared or were drastically modified by the 1963 rockslide. In most cases, the geological features of these outcrops have already been reported in various technical reports, papers, and books written by Semenza (Giudici and Semenza, 1960; Semenza, 1965, 2001, 2010); but these descriptions obviously reflect his geological interpretation. This unique photographic documentation was utilized to schematize past lithostratigraphical field evidence estimating the thickness of involved sedimentary sequences and identifying main rock mass units as differentiated by Rossi and Semenza (1965). Particular attention was paid to the analysis of the basal rupture surface and to the so-called 'mylonitic rocks,' as evidenced by old photographs.

Topographic features of the Mt. Toc slope and of the surrounding area were defined by implementing two specific digital terrain models (DTM). The older DTM (Fig. 3), illustrating the slope situation before the 1963 rockslide, was created by digitizing the elevation lines reported on the 1:5000 geological map drawn by Rossi and Semenza (1965). The detailed original scale, especially when compared to the traditional topographic maps used at that time for geological purposes, allows for an adequate representation of main slope characteristics. The antecedent DTM obtained using this procedure is characterized by a mean density of about 1 point per 170 m^2, that is to say, one topographical point for a square surface having a side of 13 m. Obviously modern acquired DTM models are of a greater quality, but this base map represents the best topographical data available today for reconstructing the past Vajont Valley morphology (Fig. 3).

On the contrary, the topographical data of the present morphological situation came from the regional numerical cartography (Technical Map of the Friuli Venezia Giulia region, published on the scale 1:5000 but acquired with 1:2000 comparable topographical quality requirements). The *x,y,z* data sets of the ground surface points, recently acquired (September 2000), were used to produce the post-1963 DTM of the Vajont area (Fig. 4), which is better quality (mean surface density of points: about 1 point per 10 m^2) compared to the pre-1963 terrain map. Pre- and post-1963 DTM models were employed to extract the slope profiles required for the implementation of some new geological cross sections. The manipulation of the topographical data and related DTMs was obtained by using the software Surfer®, from Golden Software Inc. For the geographical and geomorphological analysis of the Vajont Basin, an orthophoto taken on 6 August 1998 was also used (cartographical archive of the Friuli Venezia Giulia region) (Fig. 1).

The recent engineering–geological survey was performed on the large 1963 detachment surface (Fig. 5) and on the failed rock mass. The surveyed trails were recorded by means of a GPS device for storing all related geographical information and the outcrops of particular importance were specifically coded and positioned. Many waypoints were identified in the field and a number of samples, both rocks and loose soils, were collected. Sampled materials were later analyzed in the laboratory for petrographical and geotechnical characterization. Only fundamental data from collected samples and tested rocks are summarized in this paper.

Bedrock outcrops were characterized by measuring the orientation of both the stratification and the fracture joints. Stratification joints and intact rock surfaces were also tested by traditional Schmidt Hammer field procedures, and some rock samples were tested using point load apparatus in the lab. Rock mass characteristics and intact rock data were then employed for a mechanical characterization of involved rock masses.

Important observations were also made on the internal structure of the rock mass, and significant structural data was acquired for the first time on deformed rock strata. Finally, many striations were identified and measured on the basal rupture surface and on the eastern lateral detachment surface. All this newly acquired geological data constitutes the basis for the reexamination of the Vajont rockslide.

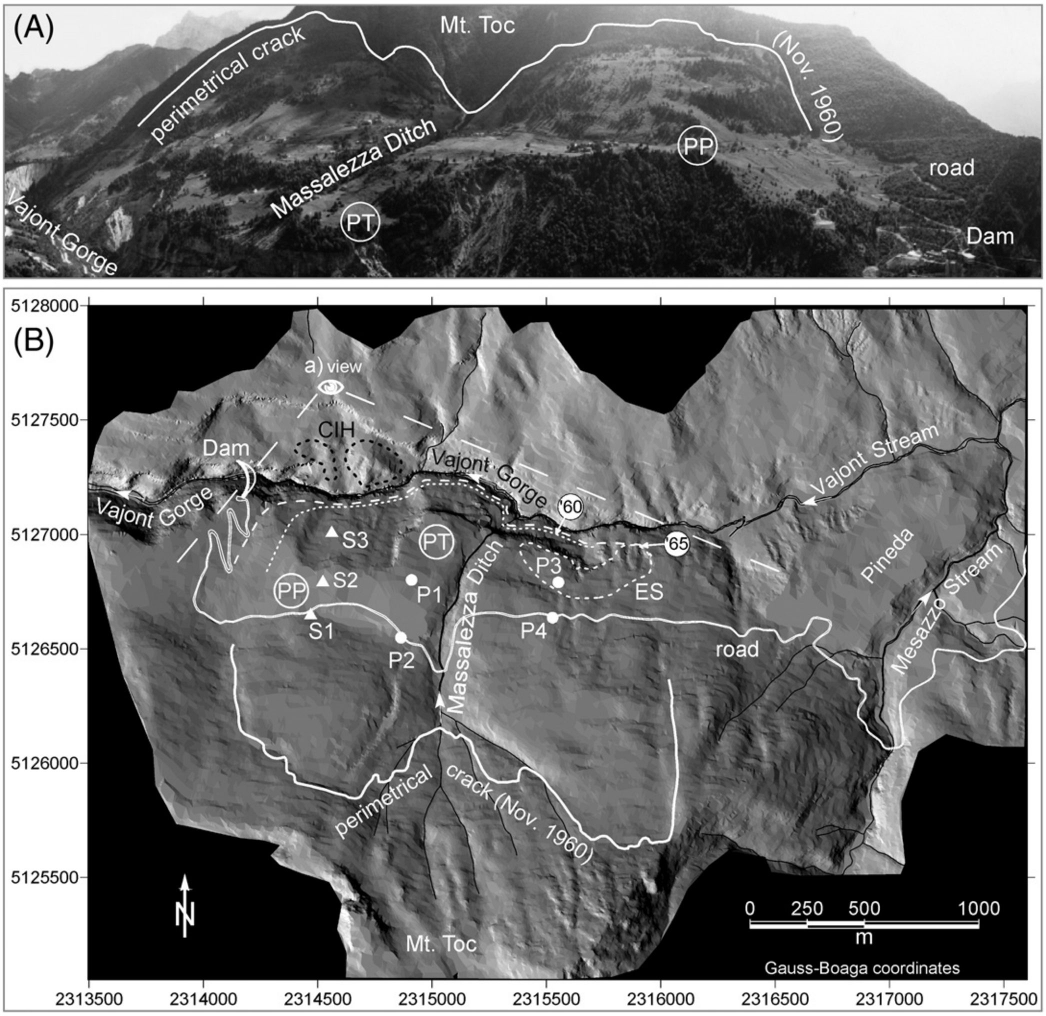

Fig. 3. (A) Front view of the pre-1963 topography of Mt. Toc (by Edoardo Semenza, 1 September 1959, modified from Masè et al., 2004, photo GS_26) and (B) digital terrain model (data density: about 1 point per 170 m^2) of the prehistoric Mt. Toc rockslide mass before 9 October 1963. PP: Pian della Pozza Terrace; PT: Pian del Toc Terrace; ES: Eastern Spreading (Semenza, 2001, 2010); CIH: Colle Isolato Hill; P1, P2, P3, P4: piezometers; S1, S2, S3: boreholes. Note the two hypothesized outlines of the sliding surface along the prehistoric rockslide front: '60 = according to Giudici and Semenza, 1960; '65 = according to Rossi and Semenza, 1965.

The most significant outcrops, especially along the basal detachment surface, were accurately prepared before the sampling procedure: the surface debris and the soil cover were always eliminated, and most stratigraphical contacts were cleaned and highlighted. After this preparation, the outcrop was coded, photographed, and drawn. The coded samples refer to a specific site or waypoint accurately located on the reference map. The geological surface data was then stored in a GIS database specifically implemented for the Vajont area. This GIS was finally utilized to build an updated engineering–geological map (Fig. 2).

4. The updated geological framework

Since the first studies conducted by Semenza and his co-workers (Giudici and Semenza, 1960; Rossi and Semenza, 1965), present day geological knowledge on the Vajont Valley has improved, from lithostratigraphical and structural points of view. Important modifications have concerned the lithostratigraphical terminology because some new geological formations have recently been coded (Commissione Italiana di Stratigrafia, 2002) and attributed to the rock masses involved in the 1963 rockslide.

The lithostratigraphical sequence occurring at the northern toe of Mt. Toc includes presently (Carulli, 2006) the following four geological formations, from the top to the bottom (Fig. 6, Mt. Toc sequence):

(4) the Biancone Formation (lower–upper Cretaceous): thickness ≅ 130–150 m;
(3) the Rosso Ammonitico superiore Formation (upper Jurassic): thickness ≅ 1–10 m;
(2) the Fonzaso Formation (middle-upper Jurassic): thickness ≅ 60–70 m;
(1) the Calcare del Vajont Formation (middle Jurassic): thickness ≅ 350–370 m.

In the past, the geological formations differentiated above as items 2, 3, and 4 were described all together under the name of the 'Calcare di Soccher' Formation and are frequently identified by this terminology. The 1963 mobilized rock mass involved a complex cherty limestone and marly limestone sequence dating from middle-upper Jurassic to upper Cretaceous, including Fonzaso, Rosso Ammonitico superiore, and Biancone Formations. The clay seams of the Fonzaso Formation are thin to very thin interstrata (0.1–5 cm, essentially), and are considered deep-sea sediments having a mixed sedimentary–volcanic origin (Bosellini et al., 1981).

The whole stratigraphical sequence involved in the 1963 slope failure reached a maximum thickness of about 180–190 m, but this value does not correspond to the maximum thickness of the failed rock mass owing to the thickening of the bottom shear zone and to the filling of the Vajont Gorge. In this area, for the 1963 rockslide a

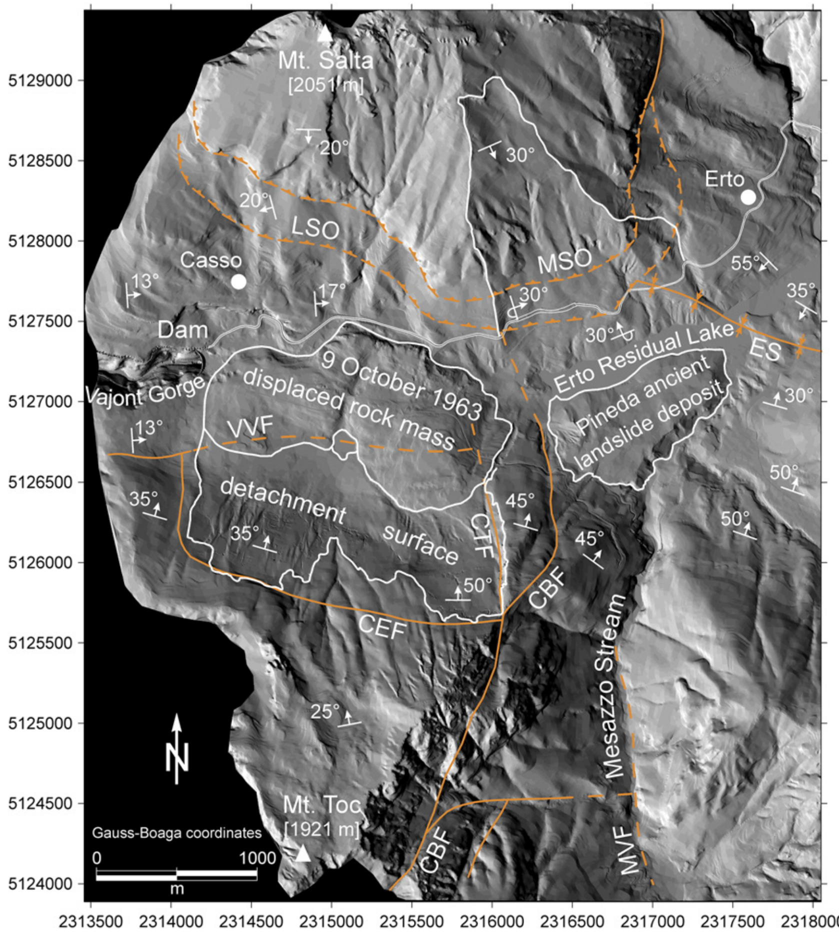

Fig. 4. Digital terrain model (data density: about 1 point per 10 m^2) of the Vajont rockslide area after 9 October 1963, with main tectonic discontinuities and strata attitudes. CBF: Croda Bianca Fault; CTF: Col Tramontin Fault; CEF: Col delle Erghene Fault; VVF: Vajont Valley Fault; MVF: Mesazzo Valley Fault; LSO: Le Spesse Overthrust; MSO: Mount Salta Overthrust; ES: Erto Syncline.

maximum thickness of about 330–350 m has been estimated by comparing the two DTMs (pre- and post-1963 slope profiles).

As noted above, the deepest stratigraphical layers involved in the basal rupture of the Vajont rockslide belong to the basal cherty limestone sequence of the Fonzaso Formation (Fig. 5). The underlying Calcare del Vajont Formation, constituted by massive oolitic limestone (1–5 m thick), was never involved in the basal failure; and this was clearly confirmed by the stratigraphical records of many boreholes carried out after the 1963 catastrophe (Broili, 1967; Martinis, 1978). The stratigraphical logs of the borings also proved that the main rupture surface developed essentially 25–30 m above the underlying stratigraphical contact between the Fonzaso and the Calcare del Vajont Formations.

The whole limestone sequence involved in the 1963 rockslide was subdivided by Rossi and Semenza (1965) into eight rock mass units, from *ma* to *f* (Fig. 6). These lithological units were identified on the field and reported on the geological map that was published immediately after the catastrophe (Rossi and Semenza, 1965). The main geological features of these rock mass units are the following (from top to bottom):

- *f* unit (Biancone Formation): marly limestone layers alternated with thin strata of green and red marls. Prevailing chert is red or dark brown. Variable total thickness from 20–25 m (left Vajont side) to 40–45 m (right Vajont side).
- *e* unit (Biancone Formation): limestone strata intercalated with cherty limestone, including nodules of white or light grey chert. Thickness: 25–30 m.
- *d* unit (Biancone Formation): marly limestone with nodules of red chert characterized in the middle part by a massive layer formed by a calcareous conglomerate that was often excavated for quarrying purposes ('Marmo di Castellavazzo'). Thickness: 15–20 m.
- *c* unit (Biancone Formation): thin-stratified limestone sequence formed by thin layers (5–10 cm thick) of grey-colored limestone intercalated with marly limestone, including nodules of black chert. Variable thickness from 10 m (right Vajont side) to 25–30 m (left Vajont side).
- *b* unit (Biancone Formation): very compact and characteristic thick layer (2–10 m) of calcareous conglomerate. This lithological unit, very recognizable on the field, was utilized during the geological survey as an important lithostratigraphical marker for reconstructing the geological structure of the left valley side (Mt. Toc slope) before the 1963 catastrophe.
- *a″* unit (Biancone and Rosso Ammonitico superiore Formations): micritic limestone, marly limestone, and marls; light grey, green, or reddish-colored with red chert. At the bottom of the sequence, a thin succession of grey or light red nodular limestone occurs and has a very variable thickness (1–10 m) that was deposited at the end of the Jurassic period (upper Kimmeridgian–lower Titonian). Thickness: 40–50 m.
- *a′* unit (Fonzaso Formation): grey or light red nodular limestone forming thicker layered limestone sequences (30–40 cm thick) with single strata sometimes reaching a thickness of 100–150 cm. The limestone layers are locally separated by thin beds of red marl. Thickness: 25–30 m.

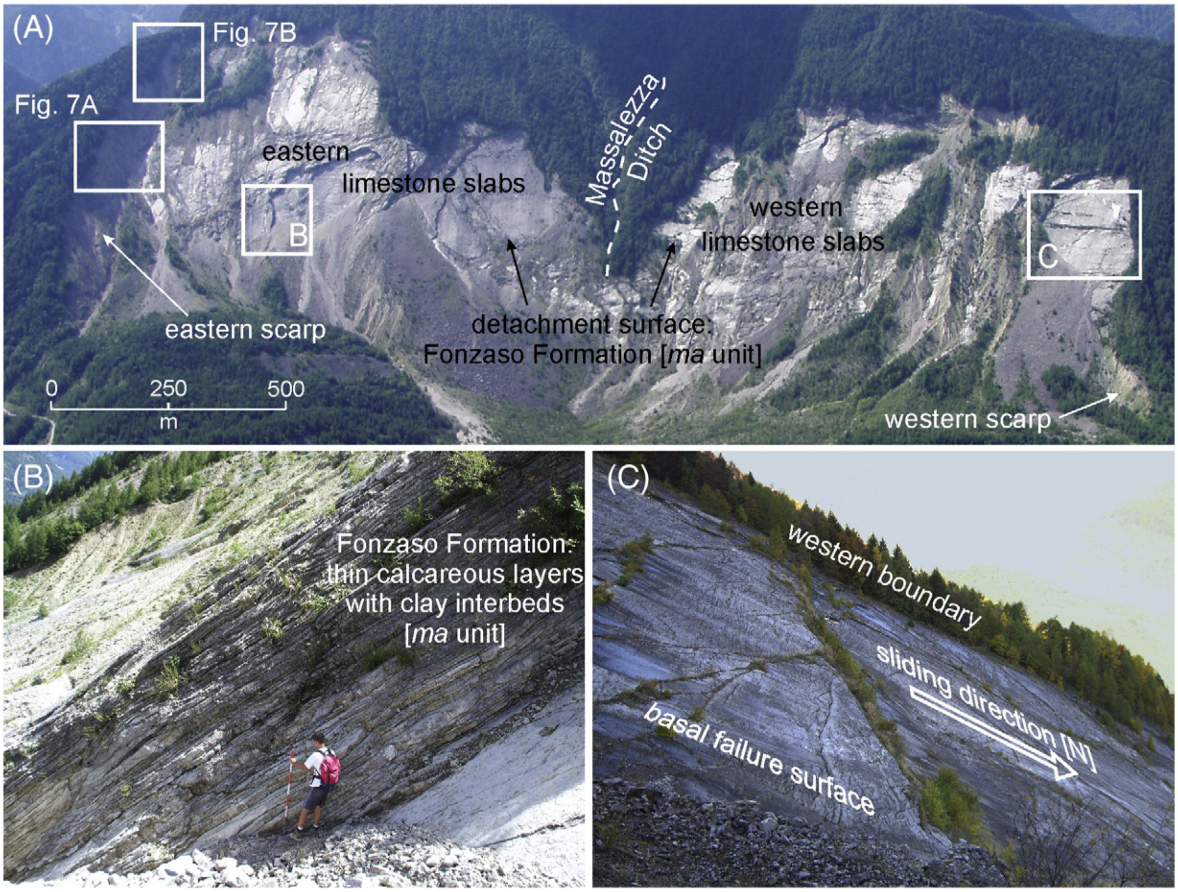

Fig. 5. Detachment plane of the Vajont rockslide: (A) the sliding surface mainly corresponds to the stratification planes of the Fonzaso Formation (top of *ma* unit); (B) stepped geometry of the basal detachment surface; (C) limestone stratification joints of the bedrock dipping northward (35°, on average) in proximity to the western border.

- *ma* unit (Fonzaso Formation): thin-stratified (1–10 cm) and slab-shaped limestone sequence characterized by abundant nodules of dark brown or black chert and frequent thin intercalations of yellowish-brown or green clays (0.1–5 cm, essentially). Thickness: 40–50 m.

This basic lithostratigraphical subdivision formulated for the Vajont rockslide can still be considered valid and was substantially confirmed by other geological research (Carloni and Mazzanti, 1964; Rossi, 1968; Martinis, 1978), except for some more detailed chronological attributions. In this study, the previously described units *ma-f* were assumed as reference units for the reconstruction of the entire lithostratigraphical succession, both for the right valley side (the so-called 'Casso sequence') and the left Vajont bank (the 'Mt. Toc sequence'). The stratigraphy of the opposite Vajont Valley sides was accurately compared by means of the original fieldwork (Figs. 5 and 7) and by the back-analysis of the historical photographic documentation (Fig. 8). The result of this integrated reexamination is the stratigraphical reconstruction summarized in the columns reported in Fig. 6. The stratigraphical column of the Mt. Toc sequence also represents an important shear zone at the base of the Vajont rockslide, depicted here for the first time and absent in the Casso sequence, which will be described in detail in the next section.

The reconstructed stratigraphy emphasizes the considerable resemblance between the two limestone sequences occurring on opposite sides of the Vajont Valley, but also certain thickness differences between the corresponding units can be noted (Fig. 6). For this reason, in the past, the Casso sequence was assumed to be the lithostratigraphical reference (Rossi, 1968) for the geological study of the large rock mass mobilized by the catastrophic 1963 slide. The described *ma-f* units were also used for the mechanical characterization of the rock masses involved in the 9 October 1963 collapse. In fact, main lithological subdivisions are quite adequate for the mechanical analysis of the failed rock mass.

Some geological aspects played an important role in the basic failure mechanism of the rockslide and therefore should be pointed out. High plasticity clay interbeds characterize the top sequence of the *ma* unit, immediately before the passage to the overlying *a′* unit (Fig. 6), including several thin layers (0.1–5 cm, essentially) made up of yellowish and green montmorillonitic clays. The basal detachment surface mainly involved these thin-stratified cherty limestone layers (1–10 cm, essentially) alternated with high plasticity clayey interbeds (*ma* unit). The entire limestone sequence, from the Fonzaso Formation up to the top of the Biancone Formation, is formed by thinly stratified limestone layers (1–10 cm thick, in most cases) with the exception of some thicker strata made of massive conglomerate (*b* unit and the intermediate layer of *d* unit) or the thicker limestone layers characterizing the *a′* unit.

It is also important to consider the tectonic framework of the Vajont area, examining in detail the major faults that were the determining factors for the geological release of the prehistoric Mt. Toc rockslide. The first geological study (Boyer, 1913) interpreted the Vajont Valley as a classic example of a synclinal structure located along the axis of the valley and defined as the 'Erto Syncline.' In fact, at that time the geologic interpretation based on the continuity of the deformed rock masses prevailed (alternate syncline–anticline structures), and main tectonic discontinuities (faults and/or overthrusts) were rarely considered. Nevertheless, the geological map published after the 1963 rockslide-induced disaster (Rossi and Semenza, 1965) for the first time showed some important tectonic

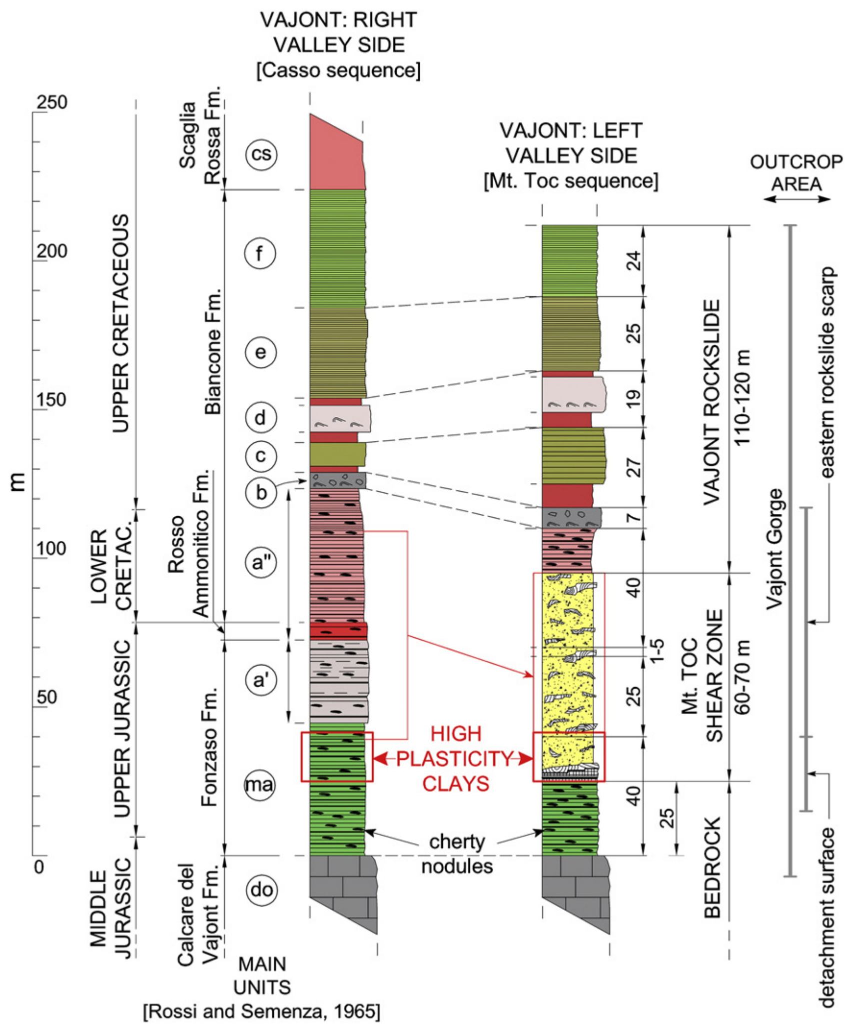

Fig. 6. Updated lithostratigraphic columns of both sides of the Vajont Valley. The most characteristic geological element of the Mt. Toc sequence is the presence of a thick shear zone (yellow unit), recognized for the first time in this study.

lines occurring at the border of the unstable Mt. Toc slope and limiting the failed rock mass. These important faults acted as decisive geological releases for the unstable rock mass, predetermining the lateral margins (east and west releases) and the upslope boundary (southern limit).

The faults intersecting the Mt. Toc massif were later characterized in detail (Riva et al., 1990) so that we have, at present, a more complete knowledge of the main faults and tectonic lines occurring in the area (Fig. 4). The southwestern border of the prehistoric rockslide is defined by the 'Col delle Erghene' Fault (CEF), whereas the eastern margin is determined by the 'Col Tramontin' Fault (CTF), a N–S trending subsidiary fault associated with the principal adjacent 'Croda Bianca' Fault (CBF). These three faults practically delimited the entire prehistoric Mt. Toc rockslide: the CEF plane is characterized by a predominately E–W trend, while the CTF and CBF developed according to a main N–S direction. All these faults are characterized by near vertical or steep planes.

In addition to these main faults, another tectonic line defined as the 'Vajont Valley' Fault (VVF in Fig. 4) was identified during this work at the northern toe of the unstable area of Mt. Toc. This fault strikes parallel to the axis of the Vajont Valley and is visible in proximity to the left abutment of the Vajont Dam, in correspondence to a marked morphological change of the slope. The Vajont Valley Fault involved the basal sequence of the Fonzaso Formation (*ma* unit) and the underlying Calcare del Vajont Formation. A segment of this important tectonic contact was reported on two geological maps published after the 1963 catastrophe (Rossi and Semenza, 1965; Martinis, 1978).

5. The shear zone

The identification of a thick (40–50 m, on average) shear zone located at the base of the prehistoric Vajont rockslide represents the main scientific discovery of the previously described research project on the 1963 Vajont slide. In fact, no previous geological interpretations and related geotechnical models ever considered the existence of strongly fractured rock material interposed between the upper rigid mobilized rock mass and the underlying stable bedrock (lower sequence of the *ma* unit, Fonzaso Formation) (Fig. 6). As a consequence, conventional geotechnical models performed in the past assumed, as a rule, a single basal rupture surface characterized by limestone layers and/or high plasticity clay interbeds. Only some geological interpretations presented later (see the geological cross sections 2, 5, and 10A drawn by Rossi and Semenza, 1985) considered two clearly differentiated rupture surfaces, i.e., the prehistoric and the 9 October 1963 detachment plane and also hypothesized some 'tectonized' rocks originated by the 1963 final movement. In the following section, the main features (geometry, geological structure, grain size, and stratigraphical characteristics) of the shear zone characterizing the base of the prehistoric Vajont rockslide are described in detail.

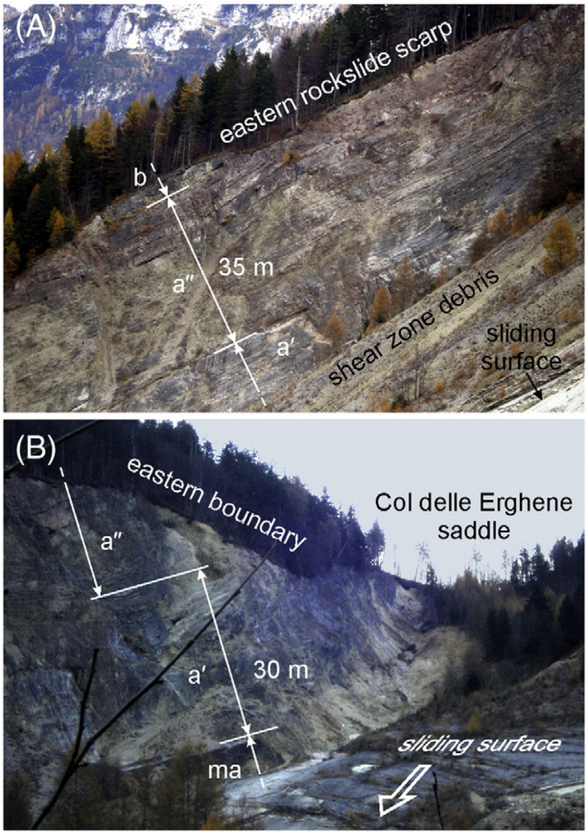

Fig. 7. Eastern limit of the 1963 Vajont rockslide showing the high rock scarp on which the main rock mass units (top of *ma*, *a*′, and *a*″) involved in the formation of the shear zone are visible. Photographic details refer to the middle (A) and upper (B) parts of the rock scarp. Estimated thicknesses were used to reconstruct the Mt. Toc sequence of Fig. 6.

Heavily fractured rocks, defined as 'mylonitic rocks' (Giudici and Semenza, 1960; Semenza, 1965) or 'cataclastic rocks' (Semenza, 2001, 2010), were formerly identified by Semenza along the western gully of the Massalezza Stream during the survey performed on the upper unstable Mt. Toc slope. A number of photographs taken by Semenza on 29 July 1960 (Masè et al., 2004) supply the documentary evidence for the existence of a considerable thickness (30–35 m) of debris material, chaotically structured, overlying a practically undeformed, thin-bedded limestone bedrock (Fig. 9). The good-quality pictures testify to the occurrence of many rock blocks, frequently 1–10 m in size but sometimes bigger, chaotically included within a gravelly matrix made up of angular limestone fragments. The basal contact with the undeformed bedrock (*ma* unit of the Fonzaso Formation) is abrupt and no transitional units appear. Surprisingly, this extraordinary field evidence outcropping in the Massalezza Gully was never taken into consideration as the primary argument for the existence of a thick shear zone underlying the prehistoric slide mass. This probably depended on poor mechanical knowledge about the possible formation of a shear zone at the bottom of large rockslides (100–200 m thick). In fact, at that time the formation of cataclastic rocks was exclusively related to the presence of fault surfaces and was interpreted by Semenza (1965, 2001, 2010) in this manner. This geological interpretation was also applied in the fundamental work of Hendron and Patton (1985).

Angular limestone gravel mixed with rock blocks (belonging to the *a*″ unit of the Biancone Formation) were also identified at the paramount Colle Isolato outcrop on the right side of the Vajont Valley. About 5–10 m of loose sediments, i.e., gravel mixed with a sandy matrix and some subrounded pebbles, are present under a heavily deformed and fractured rock mass (about 80–100 m thick). The contact surface between the mobilized rock mass and the underlying gravel occurred at an elevation of about 590–595 m. This outcrop was interpreted by Semenza as the geological evidence of an enormous rockslide that had failed from the left side, filling the palaeo Vajont Valley and burying the previously deposited stream sediments. According to this interpretation, the gravel material present at the base of the prehistoric rockslide was essentially attributed to alluvial processes, and no reference was made to the possible relationships with rock disintegration induced by the basal shear failure mechanism.

On the other hand, angular gravel and cataclastic rocks were often recognized during the geological survey of the unstable area, on the upper slope and on the steep rock walls limiting the southern bank of the Vajont Gorge ('Pian del Toc' and 'Pian della Pozza' terraced areas). Angular limestone gravel constituted a wide debris belt located along the base of steep rock slopes characterizing the front of the prehistoric mobilized rock mass. Owing to their position, these loose sediments were interpreted by Semenza as debris scree or talus deposits (see the geological map by Rossi and Semenza, 1965) originating as a consequence of small rockfalls from overlying steep walls. The debris belt surrounded the entire rockslide front, developing essentially from the 550- to 650-m contour lines. The maximum thickness of the cataclastic rocks mapped in the Vajont Gorge can be estimated at about 70–80 m, clearly decreasing eastward (20–30 m). The reported maximum values reflect

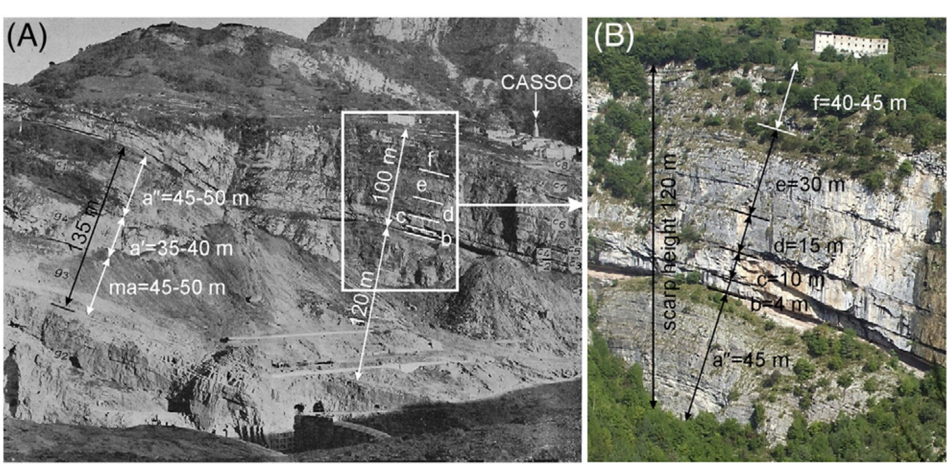

Fig. 8. (A) Right side of the Vajont Valley above the dam site photographed a short time after the 1963 rockslide (modified from Carloni and Mazzanti, 1964). (B) Closeup of the characteristic stratigraphical succession of the Casso Homocline as currently visible. Main rock mass units are coded according to Rossi and Semenza (1965). Mean strata attitude (dip direction/dip): 080°/14°.

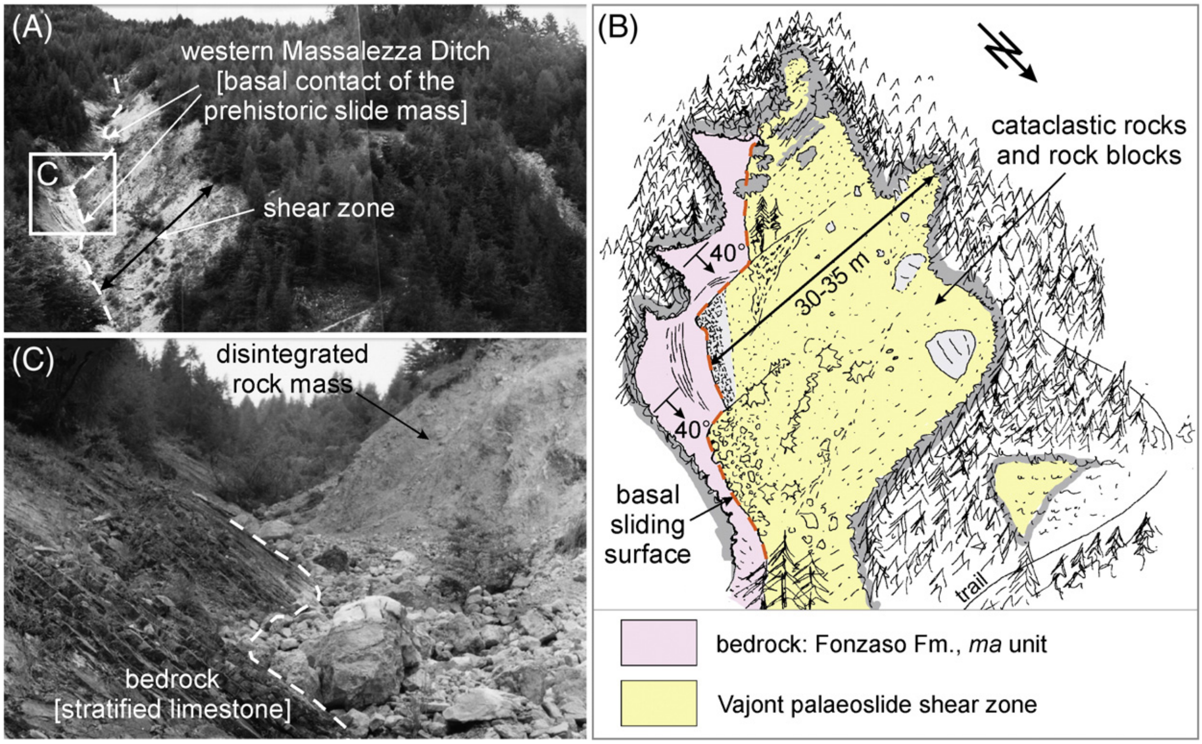

Fig. 9. (A) Fractured rocks and debris of the shear zone outcropping in the western branch of the Massalezza Ditch, as photographed by Edoardo Semenza on 2 August 1960 (modified from Masè et al., 2004, photo S2_7); (B) its schematic drawing, and (C) detail of the basal contact between *in situ* rock mass (top of *ma* unit) and the basal shear zone (by Edoardo Semenza, 29 July 1960, modified from Masè et al., 2004, photo S2_4).

the thickness increase owing to the filling of the palaeo Vajont Valley and do not correspond to the true value of the primary shear zone. On the basis of this data, the thickness of the bottom shear zone can be evaluated as ranging from 20–30 m (upper slope) to 60–70 m (lower slope) with a mean value of about 40–50 m (Fig. 6).

In reality, many significant outcrops clearly demonstrate the presence of angular gravel mixed with blocks under the prehistoric displaced rock mass, particularly the spectacular cross section visible on the eastern edge of the Pian del Toc Terrace (Fig. 10). This lateral scarp, caused by the erosion of a small debris gully, showed the internal structure of the front of the prehistoric Vajont slide, analogously to the western edge located on the opposite side (Fig. 11). Along the eastern edge of the Pian del Toc Terrace, the abrupt superimposition of a heavily fractured rock mass overlying some characteristic loose materials made up of angular gravel and limestone blocks was clearly visible. The sharp contact between the displaced rock mass and the underlying debris was characterized by a marked stepped failure surface with alternated flat (25–35°) and steep (80–90°) segments (Fig. 10). A very similar situation was visible on the opposite western edge of the Pian del Toc Terrace where a rigid block of fractured and faulted rock mass rested on some isolated outcrops of angular debris (Fig. 11). In this case, the direct contact between the mobilized rock mass and the cataclastic rocks was not properly visible as in the eastern edge. Angular gravel and cataclastic rocks were also identified above the debris gully located at the eastern edge of the Pian del Toc Terrace. This outcrop, interpreted by Semenza (2001, 2010) as an 'eastern spreading' of the prehistoric rockslide, demonstrates the superimposition of loose materials and heavily fractured rocks overlying the prehistoric rockslide mass (Fig. 12).

This very important field evidence showing the presence of a shear zone at the base of the prehistoric Mt. Toc rockslide was confirmed by additional data directly acquired on the giant detachment surface on the slope after the disastrous 1963 slide. The detailed geological survey performed on the detachment plane resulted in the identification of a number of relicts of the primary shear zone, still resting on the main failure surface (Fig. 5). The maximum residual thickness of the sheared materials can be estimated at about 10–12 m (Figs. 13 and 14A).

The relicts of the primary shear zone appear on the field as a debris cover that can be effectively mistaken for surface cover deposits on preliminary examination. Nevertheless, if analyzed in detail, this debris material exhibits several particular features and cannot in any way be compared to the traditional surface slope deposits. First of all, the limestone angular gravel is always strictly associated with large blocks made of strongly fractured and heavily folded rock masses still preserving the stratification (Fig. 15). The great pieces of heavily stratified rock masses are generally completely 'packed' into the debris material so that they appear as wrapped by the angular gravel. In most cases, the isolated blocks exhibit a marked internal deformation with syncline or anticline folds presenting a typical wavelength of 1–3 m (Fig. 13D). The blocks of stratified and folded limestone sequences appear to be 'sheared off' from the underlying bedrock and can be considered as displaced rock masses planed off by the motion of the overlying rigid rock mass ('rock mass shavings'). Stratified rock masses and bigger blocks are often heavily fractured, denoting extensional and shear fractures (Figs. 15 and 16A). These features suggest that the formation of the thick shear zone involves the ductile deformation of the thin-stratified limestone sequence and the brittle fracturing of the stronger limestone layers.

The most characteristic debris material of the shear zone is the limestone angular gravel supported by a sandy matrix (Group 3 in Fig. 17), but some examples of angular gravel show a typical openwork structure with abundant voids (Fig. 15B). Rock pieces are essentially made up of angular fragments of limestone, cherty limestone, and chert. Most of the chert fragments are reddish or tan-colored, often giving an evident reddish coloring to the debris (Figs. 13 and 14). Recognized rock types also include marly limestone, green marls, and calcareous breccias (Fig. 16). All these rock types, except for the breccias, characterize the top of the lower unit (*ma*) of the Fonzaso Formation. The breccias recognized on the detachment surface originated in the past through the cementation of the limestone angular gravel of the shear zone.

When stratification is preserved, the presence of isolated, thin lenses of yellowish, grey, and green clay is clearly visible. Clayey interbeds occur in correspondence to the 1963 main rupture surface (Fig. 16B) and within the displaced rock masses or are intercalated within the angular gravel (Fig. 14). Most clay lenses constitute thin or very thin layers (0.1–5 cm thick, very often) alternated with cherty limestone strata and denote low continuity. Sometimes the thin clay layers appear strongly deformed and create folded lenses.

Considering its primary mean thickness (40–50 m), three main levels within the shear zone at the base of the 1963 Vajont rockslide are distinguishable: a basal, a middle, and an upper part, each one presenting a mean thickness of about 15 m. The remnants of the debris cover resting on the main detachment surface belong to the basal shear zone. This can be further divided into three subunits: B1, B2, and B3. The B1 unit rests on the lower failure surface and corresponds to the basal debris layer (0–1 m), including many thin very plastic clay lenses (Fig. 16B); the thickness of the B2 unit ranges from 1 to 5 m and includes angular limestone gravel mixed with folded rock blocks and clay lenses (Fig. 13D). Finally, the B3 unit corresponds to the upper part (5–15 m) of the shear zone material preserved on the rupture surface.

The characteristic grain size distribution curves of loose sediments sampled within the basal shear zone are shown in Fig. 17. The grain size diagram shows the occurrence of three main groups of loose soils with marked differences: silty clays (Group 1), clayey silts (Group 2), and sandy gravel (Group 3). Fine soils are characterized by a high variable clay percentage ranging from 45–65% for finer sediments (silty clays) to 15–30% for clayey silts. This notable grain size variability of the fine soils explains the different geotechnical properties measured on various clay samples collected on the Vajont rockslide (Hendron and Patton, 1985). The laboratory characterization therefore indicates the presence of very variable materials within the shear zone, ranging from fine soils (medium and high plasticity clays and clayey silts) to coarser material (very angular limestone gravel mixed with blocks). The high variability of the material involved in the basal rupture is evidenced for the first time by this study. Notably, no previous geotechnical modeling of the 1963 Vajont rockslide has taken into account the presence of such a 'mélange' or 'broken formation' dominated by brittle fracturing and including angular gravels mixed with displaced stratified rock masses and thin lenses of high plasticity clays. This chaotic 'mélange' is comparable to the so-called 'block-in-matrix rocks' or 'bimrocks' in several aspects (Medley, 1994; Riedmüller et al., 2001).

6. The prehistoric Mt. Toc rockslide

The prehistoric Mt. Toc rockslide was the first large slope failure that involved the northern toe of the Mt. Toc massif in prehistoric

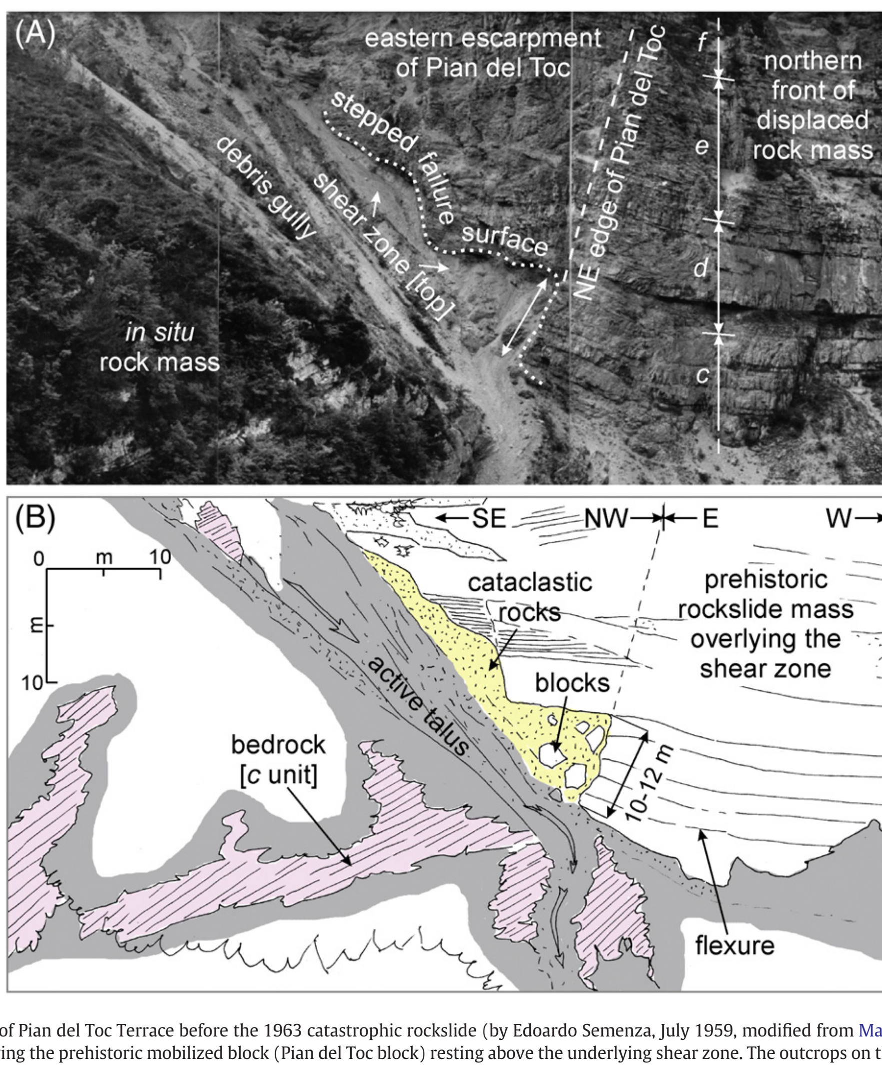

Fig. 10. (A) Northeastern edge of Pian del Toc Terrace before the 1963 catastrophic rockslide (by Edoardo Semenza, July 1959, modified from Masè et al., 2004, photo GS_39), and (B) its schematic drawing showing the prehistoric mobilized block (Pian del Toc block) resting above the underlying shear zone. The outcrops on the left are *in situ* rock masses, and the stratification is according to the Casso Homocline.

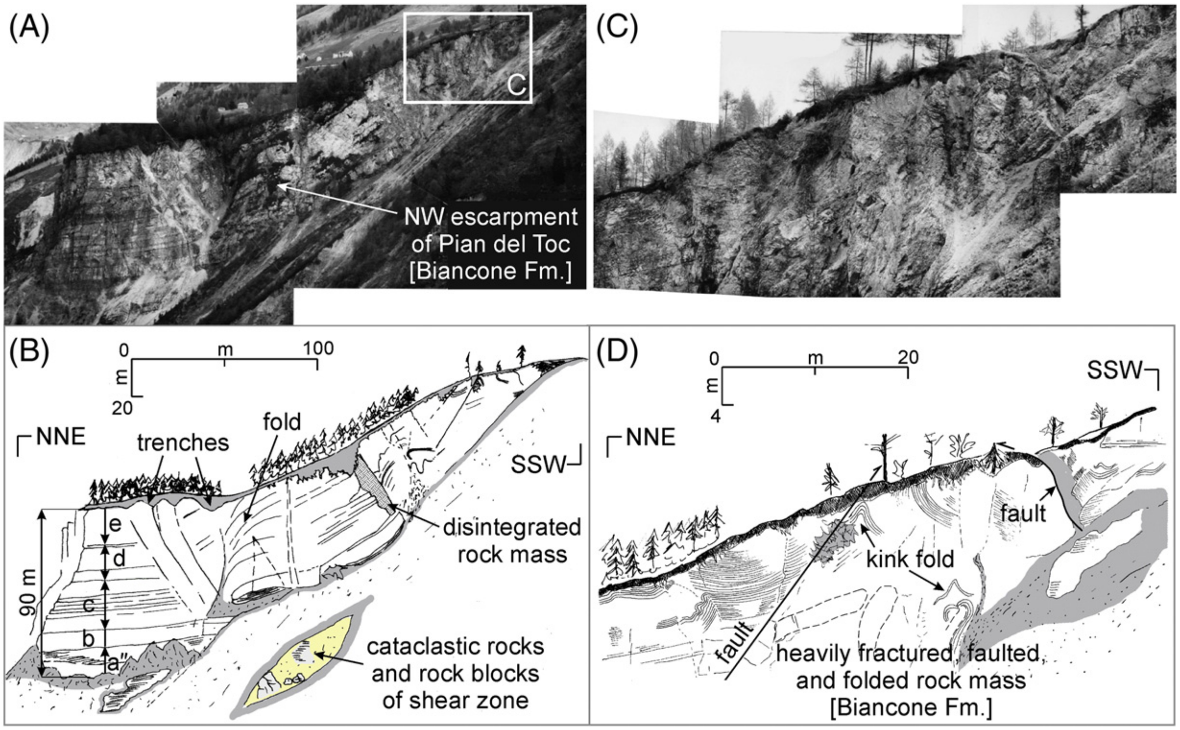

Fig. 11. (A) Northwestern unstable escarpment of Pian del Toc before 9 October 1963 (by Edoardo Semenza, April 1960, modified from Masè et al., 2004, photo GS_30), (B) its schematic drawing, (C) detail of the upper scarp (by Edoardo Semenza, April 1960, Masè et al., 2004, photo GS_31), and (D) its schematic drawing. Note the increase in fracturing, folding, and faulting of the rock mass from the left to the right (i.e., from downslope to upslope).

times, mobilizing the lower third of the entire slope (Fig. 1). An important preexistent geometrical factor for the slope instability was determined by the general strata attitude of the whole Jurassic–

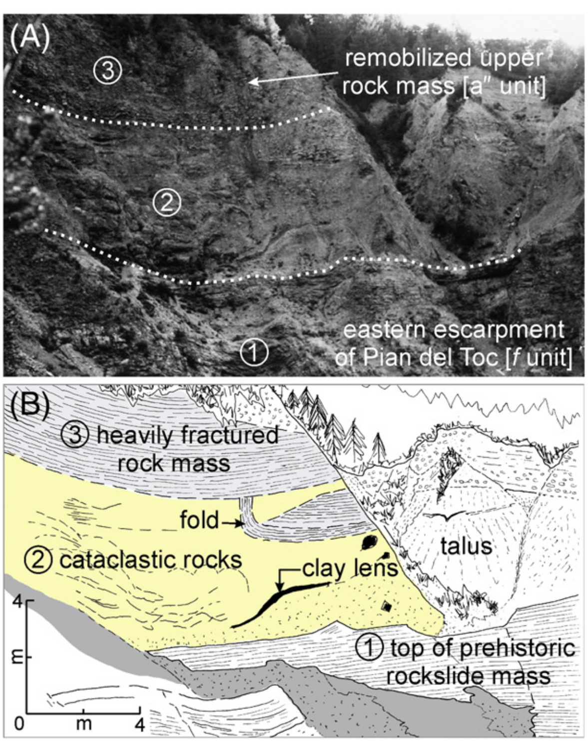

Fig. 12. (A) Remobilized rock mass, as visible prior to the 1963 Vajont landslide, interpreted by Semenza (2001; 2010) as an eastern spreading of the prehistoric rockslide (photo by Edoardo Semenza, 1 September 1959, modified from Masè et al., 2004 GS_46), and (B) its schematic drawing. The upper rock mass (units 3 and 2) slid onto the underlying, previously failed, rock block (unit 1 = Pian del Toc block).

Cretaceous sequence. In fact, on the eastern half of the slope, a dip direction toward the NNW predominates (355°/44°); whereas in the western sector, limestone layers dip toward the NNE (015°/34°) (Fig. 18). Such a situation caused the formation of a giant rock wedge whose intersection line plunged toward the NE (050°/30°). The prehistoric rockslide had an approximately rectangular shape owing to the strong influence exerted by three important faults: the Col delle Erghene Fault (southern and western limits), the Col Tramontin Fault (eastern boundary), and the Vajont Valley Fault (northern boundary) (Fig. 4). The size of the prehistoric rock slope failure was considerable: its length being about 1900–2000 m and the corresponding width about half (1000–1100 m). The entire surface of the prehistoric rockslide was ~2 km^2, and the mean thickness of the ancient failed mass can be estimated at about 150 m — giving a total volume of mobilized material close to 300 million m^3. From a chronological viewpoint, three main stages of the prehistoric Mt. Toc slope instability can be differentiated: (i) the antecedent progressive slope deformation with folding concentrated in a specific, thin-stratified rock mass bounded at the bottom by thin layers of high plasticity clays (upper sequence of *ma*); (ii) the prehistoric rock wedge failure; and (iii) the multistaged rupture followed by the propagation of failed blocks.

6.1. Ductile and brittle behavior

The prehistoric Mt. Toc rockslide was preceded by important deformation processes that involved a considerable thickness (40–50 m) of a heavily layered limestone sequence, starting from the Fonzaso Formation (top of *ma* unit) up to the older unit of the Biancone Formation (*a″* unit, for most rockslide mass). In the first phase, before the collapse, the thin-layered limestone rock mass was strongly folded and fractured. This prevailing ductile behavior caused the formation of most of the folded structures that were later displaced and included in the shear zone. These folds, made up of anticlines and synclines of a small amplitude (1–3 m) can be

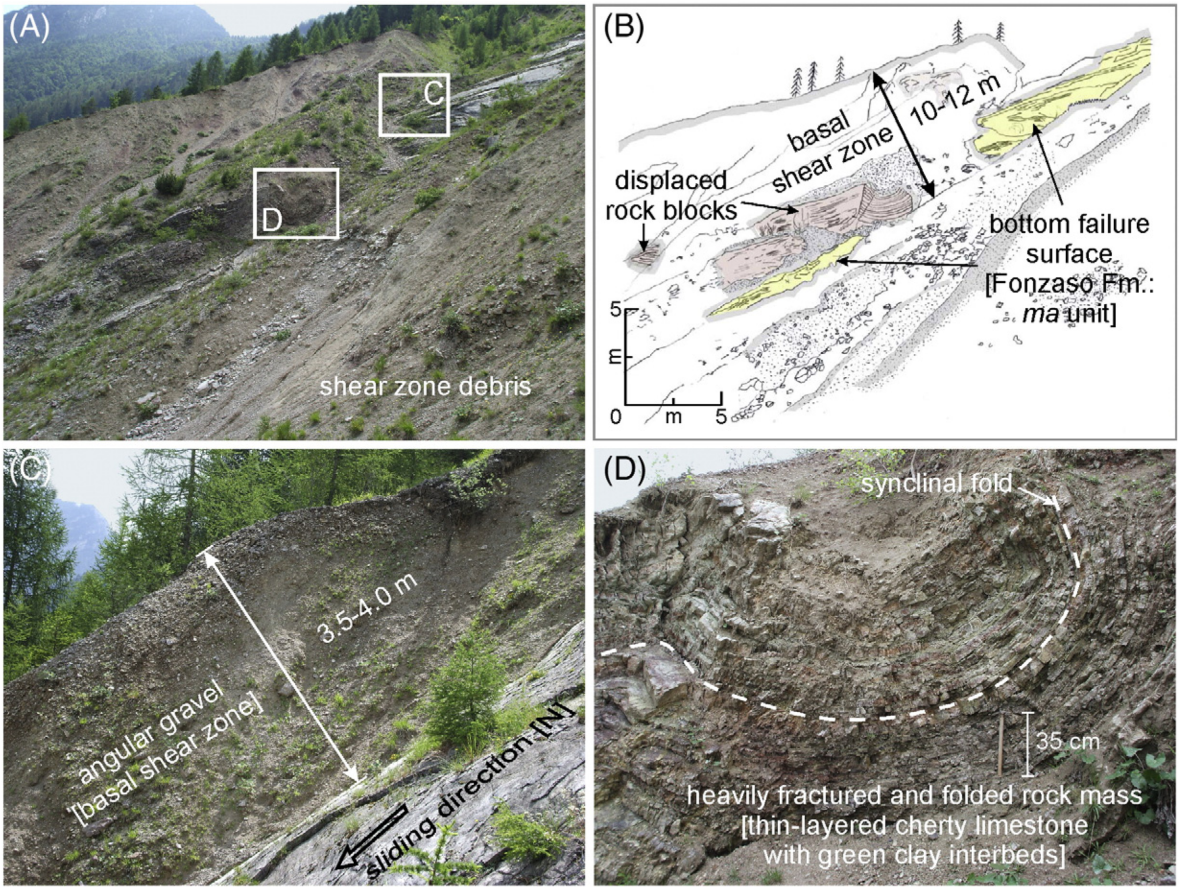

Fig. 13. The basal shear zone of the prehistoric Mt. Toc rockslide. (A) Relicts of disintegrated rock masses overlying the lower sliding surface (Fonzaso Fm.: top of *ma* unit), and (B) its schematic drawing. (C) Some details of the limestone angular gravel related to the shear zone and (D) of folded rock masses are also shown.

frequently observed at the base of the shear zone where they often give origin to small flexures, chevron folds, concentric folds, or kink-box folds (Fig. 19). Folding involves various blocks of multilayered cherty limestone sequences that mainly belong to the *ma* unit (Fig. 19A, C), but in other cases the overlying formations are also involved (Fig. 19B, D). The ductile behavior was favored by thin strata (1–5 cm, prevailingly) of clay and/or marl, alternating with well-stratified layers of cherty limestone and marly limestone.

The measured geometry of the fold relicts located in the basal shear zone shows a marked E–W orientation, with the axial planes moderately inclined (5–40°) toward the south (Fig. 19E, F). The geometrical data of most folds indicate a general slope movement toward the north, and this is consistent with the initial rock wedge geometry that was effectively constrained by the N–S striking limit owing to the eastern boundary of the Col Tramontin Fault (Fig. 4). This initial geometry was responsible for the formation of most of the folds with E–W hinge lines (set #1a in Fig. 19E, F). Folding is always associated with strong fracturing of limestone layers denoting a predominant brittle mechanism. Ductile behavior of the Mt. Toc slope — and the related progressive deformation — continued for a long time of an unknown duration until the final rock wedge collapse took place. However, considering the fluvial erosion of the front required to activate slope instability, the duration of slope deformation processes can be estimated at about 5000–10 000 years. During this time interval, slope deformation was not constant and periods with higher deformation alternated with more stable periods, depending on the climatic conditions (e.g., late Pleistocene permafrost-related processes) and the progressive deepening of the Vajont thalweg. Deformation and internal displacements probably increased progressively over time, and an initial more ductile behavior preceded a successive more brittle phase that gave origin to major rock mass fracturing forming several shear and tension joints (Fig. 20). Internal deformation and rock mass damage accumulated within the future shear zone until the first slope failure occurred.

The prehistoric slope rupture or the first-time failure involved an extensive rock wedge with a total volume of about 300 million m^3 that slid downslope, giving origin to three distinct main blocks. Owing to the primary geometry, the giant wedge rested on its eastern boundary (Col Tramontin Fault, characterized by a N–S trend) and was forced to slide toward the north during the first sliding phase (restrained sliding motion); whereas rotation toward the NE became more important during the last motion phase as a consequence of the progressive release of the sliding mass. The general sliding direction of the prehistoric rockslide mass was toward the N and NNE, and this is confirmed by many *striae* located on the basal rupture surface and on the eastern detachment rock scarp (Fig. 21). In fact, most of the geometrical data emphasizes a general sliding motion toward the N and NNE (mean ± standard deviation: 002 ± 12°) with dip ranging from 21° to 41° (mean ± standard deviation: 31 ± 6°) (Fig. 21). Considering the three-dimensional geometry of the ancient rockslide mass (Fig. 22), the prehistoric slope rupture can be described as a wedge-type failure with subsequent restrained sliding motion characterized by strong rotation toward the NE during the final phases of the block propagation. Because of their location on

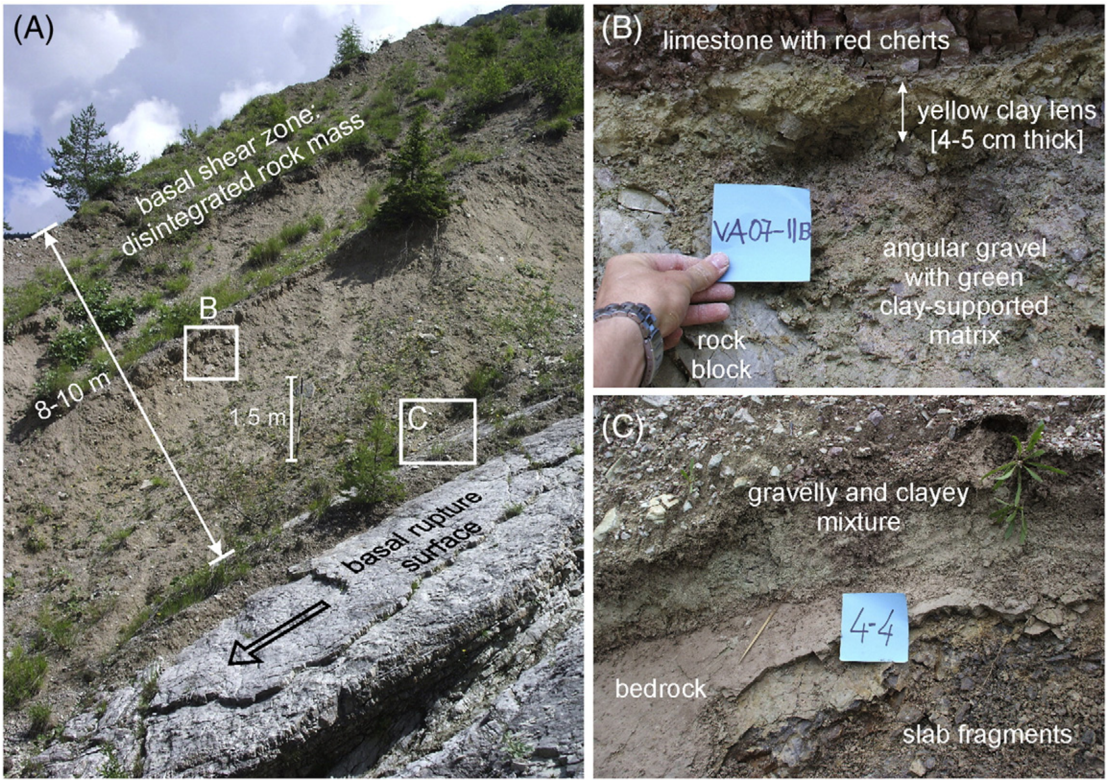

Fig. 14. (A) Basal contact of the shear zone; (B)–(C) details of two trenches showing the different materials making up the shear zone. Labels refer to the sampled materials taken for laboratory geotechnical characterization.

the upper third of the detachment surface, most of the *striae* detected can be referred to the prehistoric rockslide. The final rock wedge failure was associated with the formation of the thick shear zone above the bedrock, and the sliding motion of the overlying rigid blocks determined the development of multiple shear planes within the fractured rock mass. In this process, previously formed folds were sheared off and mobilized within the shear zone material.

6.2. En masse propagation and filling of the palaeo valley

The prehistoric rockslide mass filled a palaeo Vajont Valley, burying the alluvial sediments and impacting against the steep rock walls of the opposite side of the valley (right valley side: Casso sequence). At the eastern extremity ('Ponte di Casso' site), the failed rock mass slid over some smaller rock relief constituting the opposite slope (Fig. 23). The palaeo Vajont Valley was completely filled by the front of the rockslide for a length of about 2 km. The elevations of the ancient buried thalweg ranged from 500 m (western extremity, close to the dam: 'Ponte del Colomber' site) to 560–570 m (eastern extremity, Ponte di Casso site). The prehistoric rockslide mass also buried some stream sediments as demonstrated by the recovery of alluvial sandy deposits, about 8.2 m thick, located at an elevation range of 550–560 m in the S5C1 borehole (Martinis, 1978), which was drilled in 1965 in proximity to the northern border of the small residual lake created by the 1963 collapse. Finding grey silty-clayey sands at that depth, directly overlying the stable bedrock (*ma* unit of the Fonzaso Formation), was an unexpected discovery for which no reasonable explanation was advanced at that time (Martinis, 1978). The front of the prehistoric rockslide rested on the former valley bed, burying it; and this explains the particular chair-like shape characterizing the 9 October 1963 rupture. The 'seat' of the assumed geological cross sections corresponded to the front of the slide mass resting on the buried Vajont Valley whereas the 'back' was the primary rupture surface occurring on the ancient slope (Fig. 24).

The prehistoric Vajont rockslide was characterized by an enormous en masse motion of a rigid overlying rock mass (100–130 m thick, on average) that moved downslope, sliding onto a very thick shear zone (40–50 m thick, on average) made up of a chaotic assemblage of blocks, limestone angular gravel, and high plasticity clays (Fig. 6). The cataclastic rocks of the shear zone, including many displaced blocks (5–30 m sized boulders, frequently) of stratified rock masses (*ma*, *a′*, and *a″* units, essentially), filled the ancient valley bed reaching a maximum thickness of about 70–80 m (western edge of Pian del Toc) in correspondence to the alluvial thalweg. In fact, the rigid motion of the overlying rock mass determined the thickening of the shear zone materials and its accumulation within the former valley cut.

Owing to the interposition of the thick shear zone, the lower rupture surface is distinguishable from the upper one. Both failure surfaces are typically stepped, showing marked flat segments alternating with steeper parts (Fig. 10). The steps determined the breakage of single strata or of some layered assemblages, whereas less inclined segments coincided with the stratification joints. The stepped-shape of the basal failure surface is clearly visible on the detachment plane where multiple steps occurred as small rock scarps parallel to the direction of the strata. Both rupture surfaces are also characterized by a marked transverse (N–S direction) step morphology causing the progressive rising of the detachment plane from west to east (Fig. 5). For this reason, the rock mass units involved in the failure on the eastern extremity are younger (*b*, *c*, and *d* units) than the failed rock layers in the central and in the western part (*ma*, *a′*, and *a″* units). A similar stepped pattern in two directions of the rupture surface has been observed on a wide range of scales in other rock slope failures such as the Hope Slide (Brideau et al., 2009), and the Palliser rockslide (Sturzenegger and Stead, 2012).

The upper rigid 'slab,' made up of several distinct rock units (the top of the *a″* unit and the entire sequence formed by the overlying *b*–*c*–*d*–*e*–*f* units), is subdivided into three main rock mass units, each placed one on top of the other. Going from the bottom valley

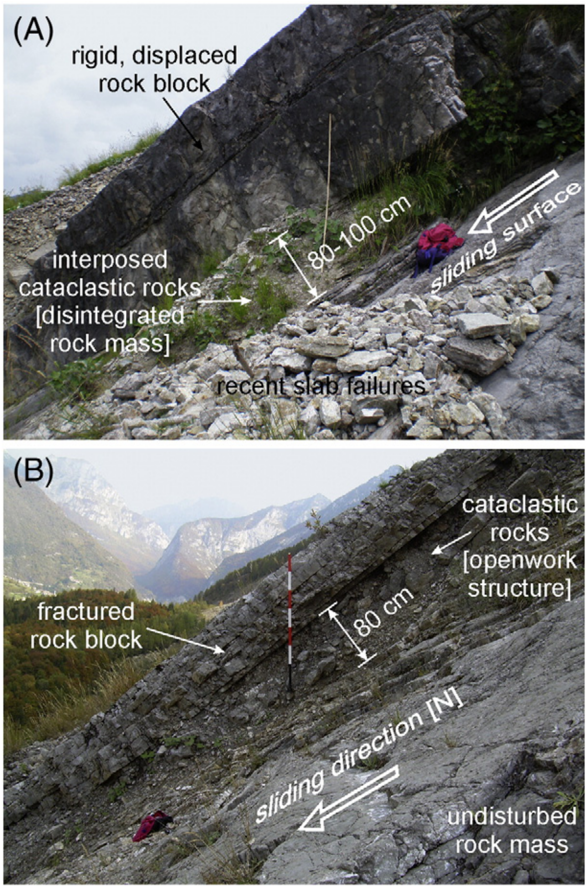

Fig. 15. Characteristic features of the remnants of the basal shear zone above the 1963 detachment surface. (A)–(B) Displaced, stratified rock blocks overlying a metric bed of limestone angular debris: several centimeters of cataclastic rocks separated them from the bedrock (Fonzaso Fm.), which appears to be unfolded and poorly fractured.

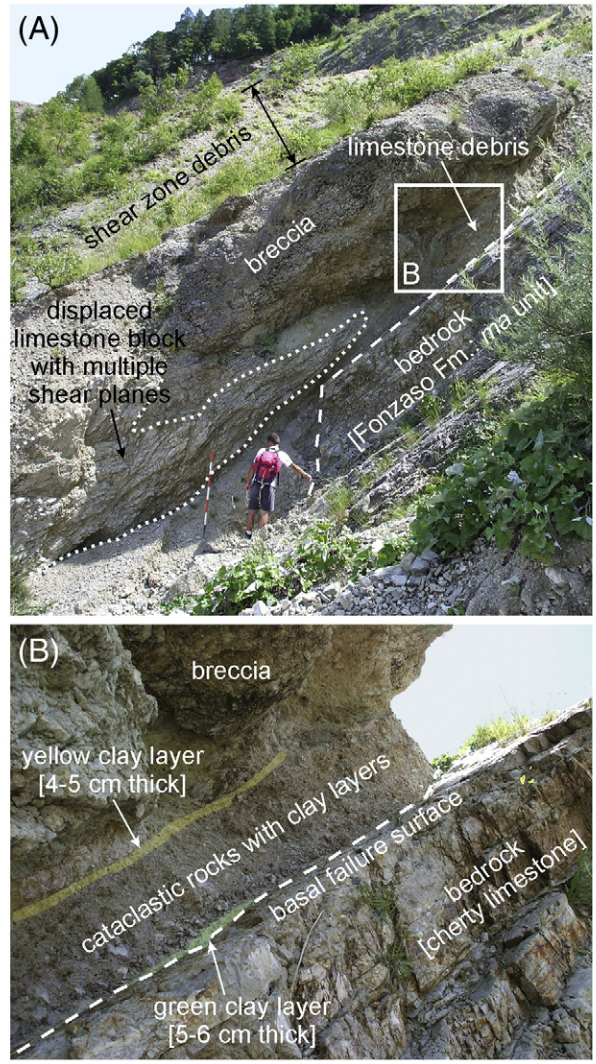

Fig. 16. (A) Main outcrop of the basal shear zone in the eastern part of the detachment surface showing the occurrence of very different materials (limestone debris, clay lenses, limestone blocks, and breccias); (B) detail of thin clay layers (Ca-montmorillonitic clays) involved in the basal rupture.

to the upper slope, these large individual rock blocks were the: 'Pian del Toc' block, 'Pian della Pozza' block, and 'Massalezza' lobe (western and eastern halves) (Figs. 23 and 24). The two lower blocks were characterized by wide terraced slope areas, with near horizontal or gently dipping ground surfaces utilized before the 1963 catastrophe as pasture (Fig. 3). The lower unit (Pian del Toc block) was a rock terrace extending from the 740- to 790-m contour lines, whereas the upper terraced area (Pian della Pozza block) was considerably wider and was characterized by ground elevations ranging from 835 to 870 m. At the southwestern border of the Pian della Pozza Terrace, an elongated depression was present, occupied by a small pool (term corresponding to the Italian word 'pozza'). The depression was erroneously interpreted in the past as a karstic sinkhole. The anomalous rock terraces, located at the northern toe of the Mt. Toc slope, were the most characteristic geomorphological feature of the prehistoric rockslide, indicating the lower accumulation zone of the prehistoric slide mass (Fig. 3). These terraced belts were also sometimes interpreted as fluvial terraces.

At the NW edge of the Pian del Toc block, the limestone stratified sequence was characterized by stratification dipping gently (15–22°) toward the ENE with lower inclination angles at the front where the rigid rock mass rested on the palaeo valley bottom. The northern rock wall of the Pian del Toc Terrace also showed a progressive decrease in the strata inclination from west to east, passing to near horizontal layers or to strata dipping westward as visible at the eastern edge (Fig. 10). All this data supports the en masse sliding model of the Pian del Toc block into a palaeo Vajont Valley cut that was rather large and whose width can be estimated at about 400–450 m at the front (Figs. 23 and 24). The general strata attitude of the block reflects the progressive settling of the rigid rock mass into the preexisting valley morphology as a consequence of the sliding motion characterized by a marked rotation toward the NE. At the eastern extremity, the

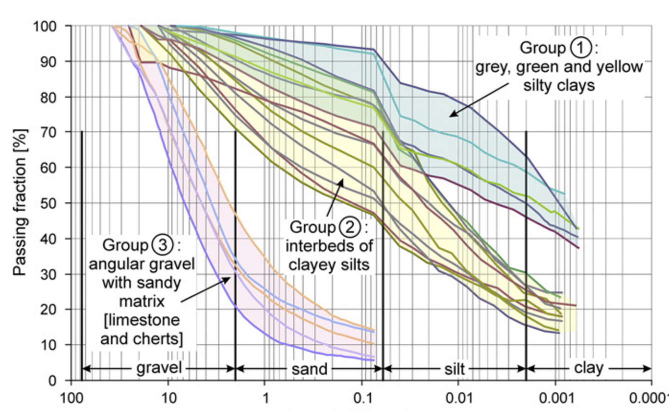

Fig. 17. Grain size distribution curves of various loose materials forming the basal shear zone. Samples include clay with different colors (Group 1), clayey silts (Group 2), and angular gravel (Group 3).

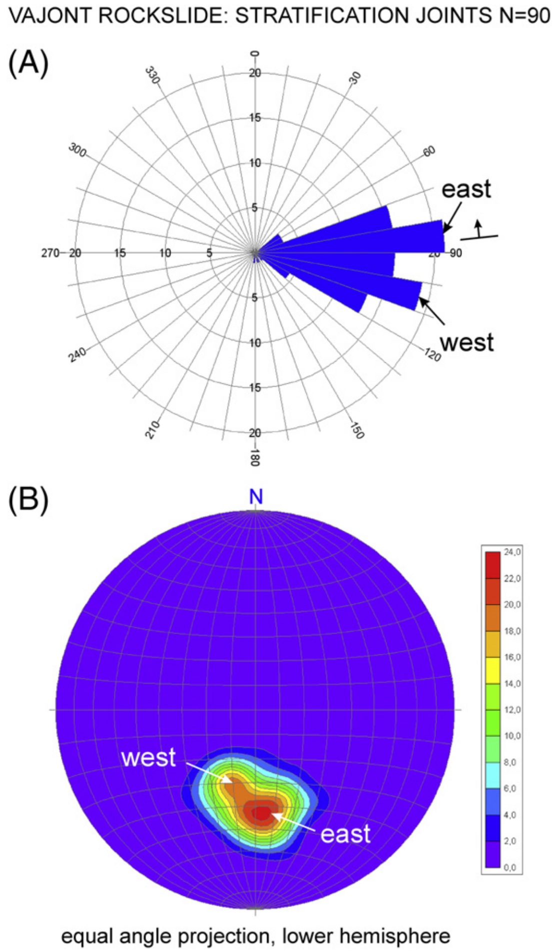

Fig. 18. (A) Rose diagram and (B) contoured pole plot (Wulff stereonet) of stratification joints measured on the detachment surface of the 1963 Vajont rockslide. The diverse stratification attitude, differentiating the eastern sector from the western part, is clearly recognizable determining a rock wedge geometry.

Pian del Toc block stopped on the opposite valley side partially superimposing it, and this constituted an important mechanical constraint for future reactivations (Fig. 23).

A relict of the original front of the large rockslide formed the so-called 'Castelletto' relief, a very characteristic, strongly fractured rock mass with many columnar blocks evidently lowered and tilted toward the Vajont Valley floor (Figs. 23, 24A). The Castelletto relief represented the main remnant of the distal part of the prehistoric rockslide, and its rear face was directly in contact with the adjacent Pian del Toc block. The Castelletto block impacted against the opposite slope of the palaeo Vajont Valley, partially rising above it as demonstrated by some strata attitude dipping toward the SSW, i.e., in the opposite direction compared to the main sliding direction of the prehistoric rockslide.

The Castelletto and the Pian del Toc units were crossed by multiple sets of near-parallel fractures having a marked linear trend ranging from E–W (80–100°) to a NW–SE direction (120–140°). Fracture planes appeared on the field as steeply dipping joints (70–90°) toward the N or NE and exhibited a long persistence. Some of these fractures created very characteristic surface trenches, 1–3 m deep, clearly visible at the western edge of the Pian del Toc unit (Fig. 11). Pervasive vertical fracturing was the principal preparing factor of the antecedent rockfalls triggered at the front (1960 rockslides) and of the progressive toppling involving the Castelletto relief. Heavily vertical splitting was mainly caused by the frontal impact against the opposite steep rock walls (right valley side); for this reason, the frequency and intensity were higher on the outer blocks (Castelletto and Pian del Toc blocks) than on the rear blocks. The progressive deepening of the Vajont Valley, after the occurrence of the prehistoric rockslide, induced the tilting and the marked toppling of the strongly fractured rock masses resting on the loose material of the thick shear zone. In particular, this phenomenon involved the rock masses located at the front of the prehistoric rockslide (Castelletto relief) (Fig. 24A) and was the dominating process characterizing the mechanical behavior of the related steep rock faces (Müller, 1964).

The internal structure of the intermediate block or Pian della Pozza block is reconstructed with greater difficulty owing to the less favorable conditions of the field expositions. However, some important field evidence, before and after the 1963 collapse, can be recognized. The intermediate block rose above the preceding one (Pian del Toc block) giving diffuse small folding in the contact area (Figs. 11, 23, and 24). At the front, owing to the superimposition mechanism, the stratification attitude was clearly dipping upslope (toward the south) as already noted by Rossi and Semenza (1965) at the northwestern border of the Pian della Pozza (unstable rock scarp involved in the rockfall triggered in early November 1960). The block superimposition caused a consequent thickening of the upper rigid rock slab caused by the repetition of the involved stratigraphical sequence. The motion on the underlying block was enabled by the presence of heavily fractured rocks at the base related to the shear zone and was accompanied by widespread fracturing of the rock mass (both shear and tension cracks). The characteristic en masse motion mode was also favored by the presence of a thick strong conglomerate layer (*b* unit: 2–10 m thick) located in proximity to the base of the mobilized rock sequence. The stratigraphical sequence characterizing both failed blocks (Pian del Toc and Pian della Pozza units) was very similar and included the whole succession from the top of the *a*″ unit up to the *f* unit. In the geological map drawn immediately after the 1963 disaster (Rossi and Semenza, 1965), the contact between these two blocks was characterized by a main fault trace having a near E–W trend (90–110°) and effectively reproducing the ancient block superimposition.

The upper block or Massalezza lobe was formed exclusively by *a*′ and *a*″ units, which were strongly deformed and fractured (Figs. 23 and 24). This probably reflects the existence of an important weakness zone located in correspondence to the reddish-green marls characterizing the bottom of the *a*″ unit. In fact, most deformation and fracturing processes are concentrated in two zones (Fig. 20): the lower or basal zone at the top of the *ma* unit with many thin layers of high plasticity clays, and the upper zone at the bottom of the *a*″ unit where heavily stratified marls (very often 1–5 cm thick) are predominant. The Massalezza lobe superimposed itself on the preceding block (Pian della Pozza unit) similarly to the distal rock masses.

7. Multistage failure and rockslide reactivations

On the whole, the structure of the prehistoric Vajont rockslide was characterized by three separate superimposed units emphasizing a typical staged sliding process well differentiated chronologically. The first failure created the Castelletto and Pian del Toc blocks (length of about 450–500 m) that moved rapidly together downslope, impacting against the opposite valley side and partially rising up onto it (eastern extremity). The initial rockslide filled the palaeo Vajont Valley with a considerable thickness (200–250 m, considering the maximum value) and caused the burial of the preexisting alluvial deposits (5–15 m thick, most likely). The sliding motion of the overlying rigid rock mass occurred on the thick shear zone and was characterized by a marked rotation of the failed slab toward the NNE.

Immediately after the first failure, or a short time after (seconds or minutes, very probably), the second main slope rupture took place mobilizing the Pian della Pozza block (length of about 550–600 m) that slid down, superimposed itself and stopped on the 'back' of the previously fallen block. Caused by the different geometrical constraints,

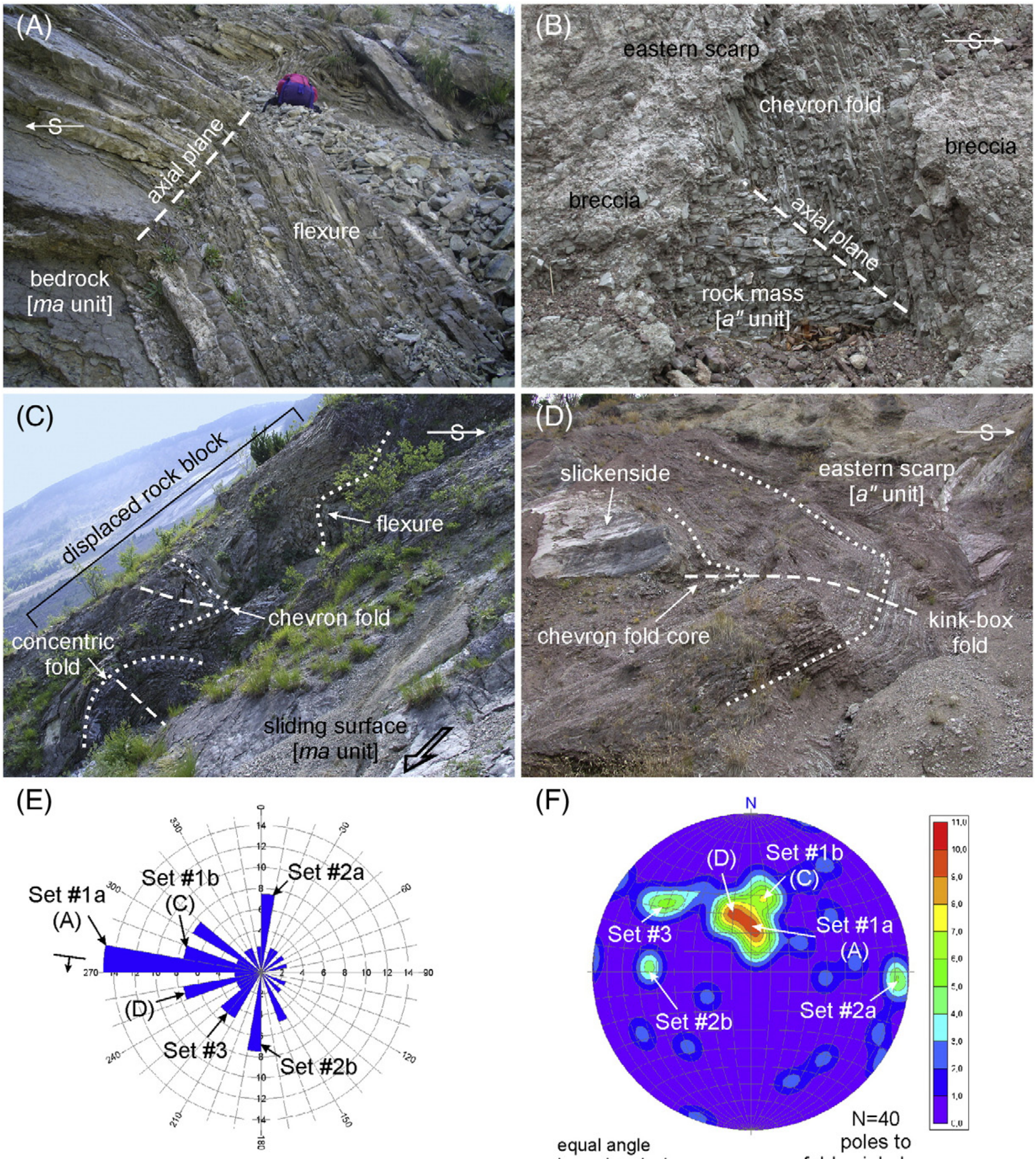

Fig. 19. Various types of metric-sized folds (amplitude: 1–3 m) associated with the shear zone of the Mt. Toc rockslide. (A) Flexure involving the top of the bedrock; (B) chevron fold affecting a thin-layered limestone sequence in proximity of the eastern rockslide boundary; (C) structures with multiple folding at the base of the shear zone; and (D) kink-box fold involving various thin layers (1–5 cm) of reddish-colored marl and cherty limestone. (E) Rose diagram and (F) contoured pole plot (Wulff stereonet) of fold axial planes measured on the 1963 detachment surface.

the sliding motion of the second block was prevailingly directed toward the north, and the rotation was less marked. The stopping condition was substantially controlled by the preceding block and the superimposition resulted in a typical overthrust-like structure. The superimposition of the two main rigid blocks was possible thanks to the mechanical characteristics of the cataclastic rocks and associated debris-clay assemblage related to the formation of the bottom shear zone. These blocks (Castelletto, Pian del Toc, and Pian della Pozza) constituted the overlying rigid rock masses mobilized by the prehistoric rockslide and represented the most significant displaced rock volume.

As a consequence of the first and the second main failure, in the upper part of the Mt. Toc slope, the underlying shear zone surfaced for a length of about 450–500 m, starting from the tectonic contact — the Col delle Erghene Fault — which acted as a preexistent geologic release. In this way, a thickness of about 30–40 m of heavily fractured and deformed rock masses (a' and a'' units, prevailingly) was suddenly revealed, and these materials were later involved in repeated slope instability phenomena owing to their weak geotechnical properties. Loose materials and some 'rock mass shavings' forming the bottom shear zone were destabilized, creating distinct superimposed slide accumulations. These multiple slide deposits accumulated on the lower slope and partially overlapped the rear of the Pian della Pozza block (Figs. 23 and 24).

A considerable remobilization of the material created from the shear zone occurred at the eastern border of the prehistoric slide

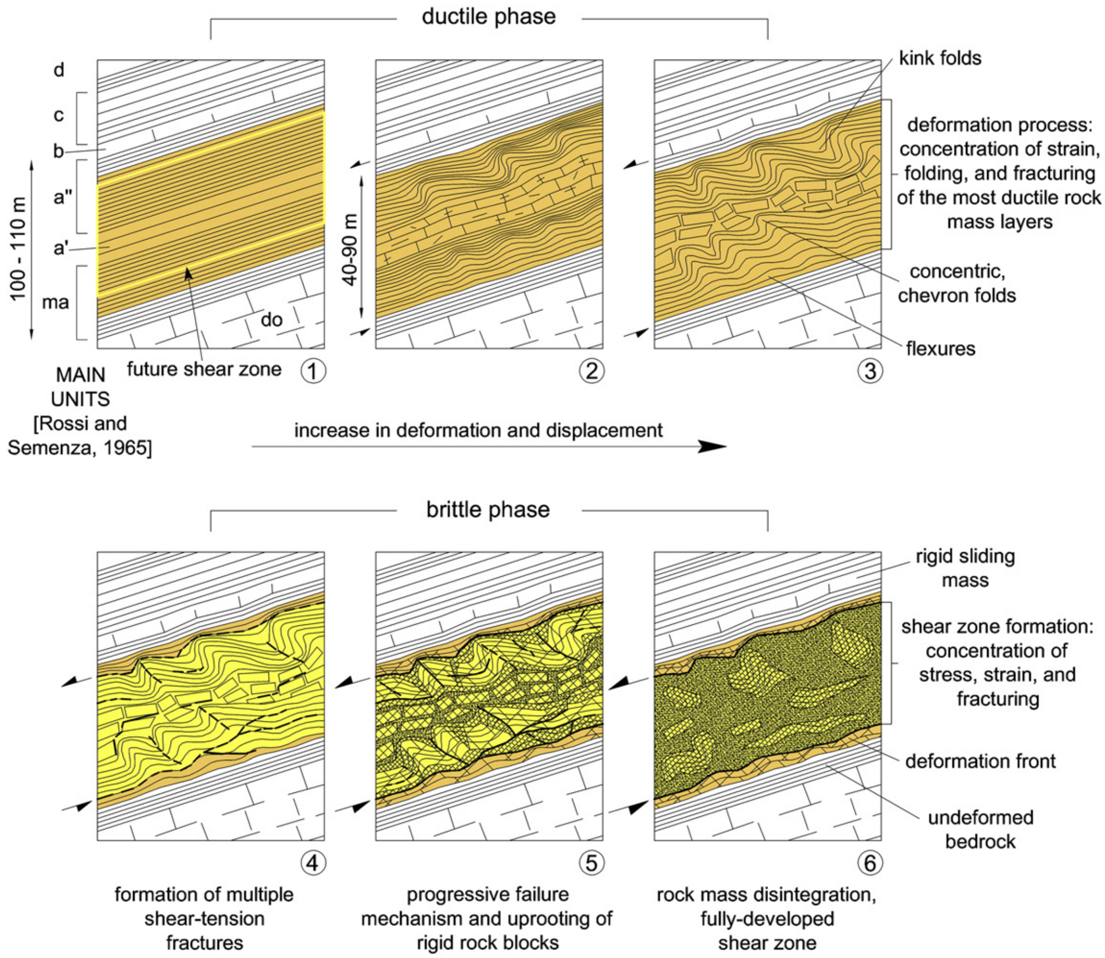

Fig. 20. Diagram reproducing the hypothetical evolution characterizing the progressive formation of the shear zone: ductile behavior prevails during the first stages, whereas brittle processes predominate during last phases preceding the rupture. Previously formed folds are then fractured and sheared off by final sliding movement.

mass after the main failure: strongly fractured rocks chaotically arranged (*a*″ unit: Biancone Formation) slid down from the Massalezza unit superimposing on the eastern half of the Pian del Toc block and resting on top of the formerly displaced rock mass (*f* unit, Biancone Formation). The remobilized material formed a sheet surface cover (about 25–30 m thick) characterized by strong rock mass damage (heavily fracturing, folding, contorted lenses of finer materials, etc.) as visible on the eastern rock scarp limiting the Pian del Toc Terrace (Fig. 12). Remobilized materials — essentially made up of thin-layered, red-colored marly limestone and cherty limestone — gave a large surface cover extending from the 700- to about the 820-m contour lines. This anomalous superimposition was noted during initial field surveys but was interpreted as an 'eastern spreading' of the prehistoric rockslide material that expanded eastward, separating from the main slide mass (Semenza, 2001, 2010). In reality the remobilized material, created by the basal shear processes, simply superimposed itself on the rigid Pian del Toc block and never passed over the eastern border of the ancient detachment surface (Fig. 23). The eastern remobilization exhibited considerable mobility as the shear zone material stopped at a certain distance from the source area. This was probably favored by the presence in the eastern area of more inclined stratification joints (40–50°) compared to the strata dip of the western part (35°).

The slope instability processes affecting the upper part of the prehistoric detachment zone probably occurred soon after the main rupture, but some reactivations could also have been triggered a long time after the prehistoric rockslide. All these repeated slope failures, directly related to the prehistoric rockslide or caused by successive independent episodes, contributed to the formation of a very thick cover (up to 100–110 m) of loose materials on the upper slope dominating the prehistoric Vajont rockslide mass (Fig. 24). Unfortunately, this was a determining factor for the unsuccessful recognition of the upper boundary of the prehistoric rockslide during the first geological surveys (Giudici and Semenza, 1960). However, both the southern and the eastern limits of the prehistoric rockslide were still visible at that time caused by the marked rock scarps left on the slope by the prehistoric failure. At present, instability phenomena continue to affect the upper part of the slope causing the detachment of isolated relict parts of the shear zone materials, as demonstrated by some recent surface debris slides (25–26 April 2009).

This mechanical behavior characterized by typical multistage and retrogressive failure processes, progressively involving the upper part of the slope, was confirmed by the 9 October 1963 catastrophic collapse. In this circumstance, two separate masses (the so-called 'eastern and western lobes') slid from the upper slope at a certain time (secondary failure) after the penetration of the main rock mass into the Vajont reservoir (primary failure). The secondary mobilized masses slid from the upper slope preserving the original forest and partially covering the formerly collapsed block (Castelletto–Pian del Toc–Pian della Pozza composite block), which was completely washed out as a consequence of the waves induced by the rapid descent of the failed mass into the reservoir (Fig. 25).

The occurrence of such a multistage failure phenomenon is not rare in rockslides because the sudden rupture determines a drastic variation in the slope geometry, inducing considerable changes in the stress state and finally causing the successive failure of the upper destabilized slope. Primary and secondary failures can be

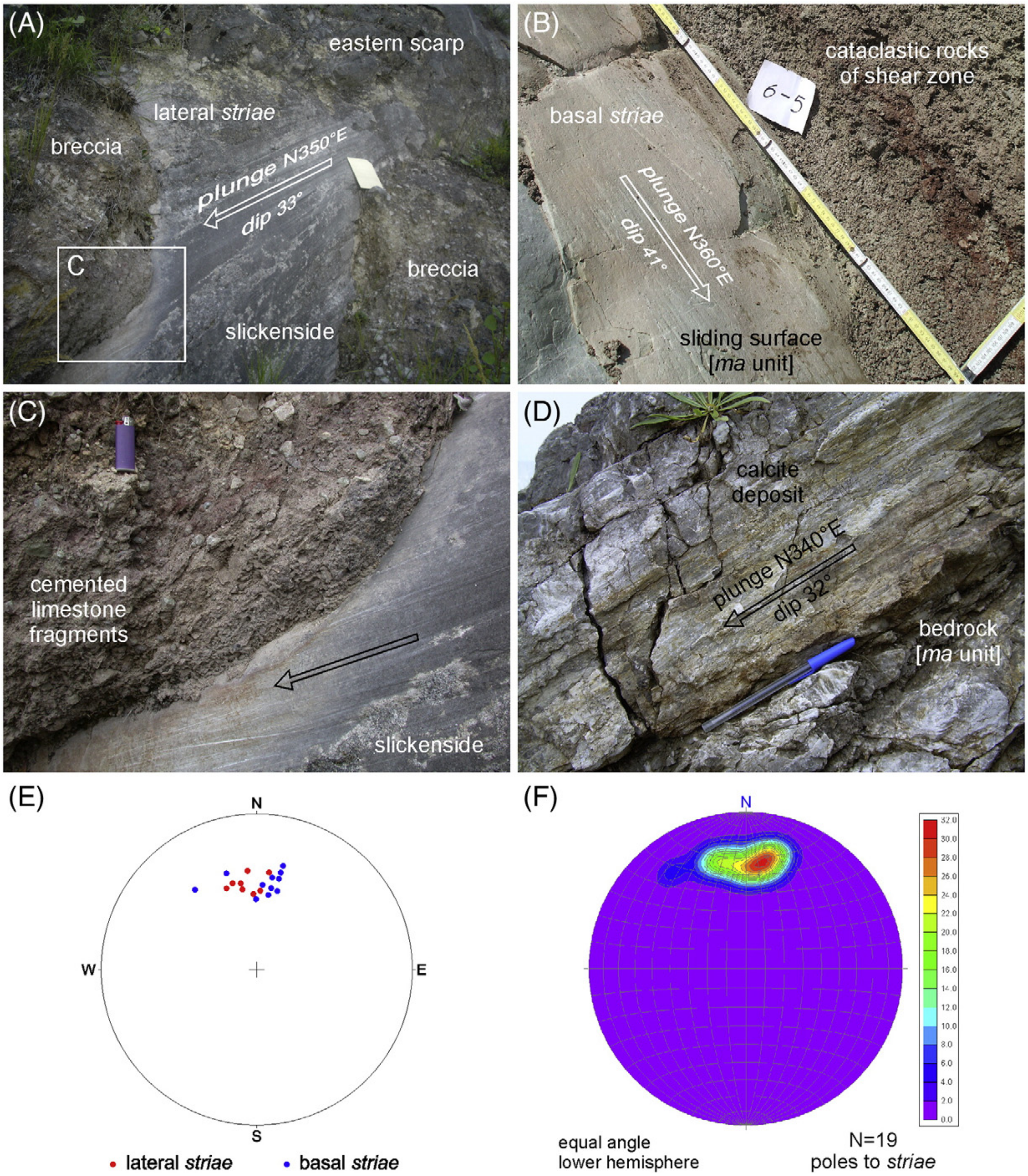

Fig. 21. Sliding-induced *striae* occurring both on the lateral eastern rupture surface (A, C) and on the basal detachment surface (B, D). (A) and (C) Linked photographs of a lateral, striated shear plane formed within calcareous breccia; (B) a striated sliding plane on a stratification joint (Fonzaso Fm.); and (D) *striae* on a lateral fracture in the basal rupture surface. (E) Stereoplot and (F) contoured pole plot (Wulff stereonet) of measured *striae* (dip range: 21–41°) caused by sliding processes related to the prehistoric Mt. Toc rockslide.

separated by variable timespans. This slope evolution, also recorded for small-sized rockslides, characterizes frequently large slope ruptures caused by the very strong variations induced in the slope geometry. However, the peculiarity of the prehistoric Vajont slide was the multistage failure mechanism associated with the en masse block motion that allowed the preservation of the entire rock mass structure (Fig. 25). This anomalous mechanical behavior was induced by the formation of the very thick shear zone.

After the occurrence of the prehistoric rockslide, the landscape of the Vajont Valley changed drastically: about 2 km of the preexisting alluvial cut were completely filled and the flow of the ancient Vajont Stream was dammed. In the following thousands of years (1000–5000), the Vajont Stream excavated a new alluvial bed, eroding the front of the failed mass just at the contact with the ancient opposite valley side. The fluvial erosion determined the formation of a younger Vajont Valley, 50–100 m wide, shifted northward compared to the older, wider (400–450 m) stream bed. Within this palaeo valley, characterized by a thalweg ranging from 580 m (Colle Isolato site, immediately westward of the Vajont Dam) to about 610 m (Ponte di Casso site), the heavily fractured rock mass constituting the Colle Isolato relief slid from the south toward the north (Figs. 23 and 24B). This outcrop, described in great detail by Semenza (Giudici and Semenza, 1960), was the starting point for the identification of the prehistoric Mt. Toc rockslide (Semenza, 2001, 2010). The superimposition of a strongly deformed and fractured rock mass (80–100 m, thick) on loose alluvial deposits was considered the main geological evidence of a catastrophic en

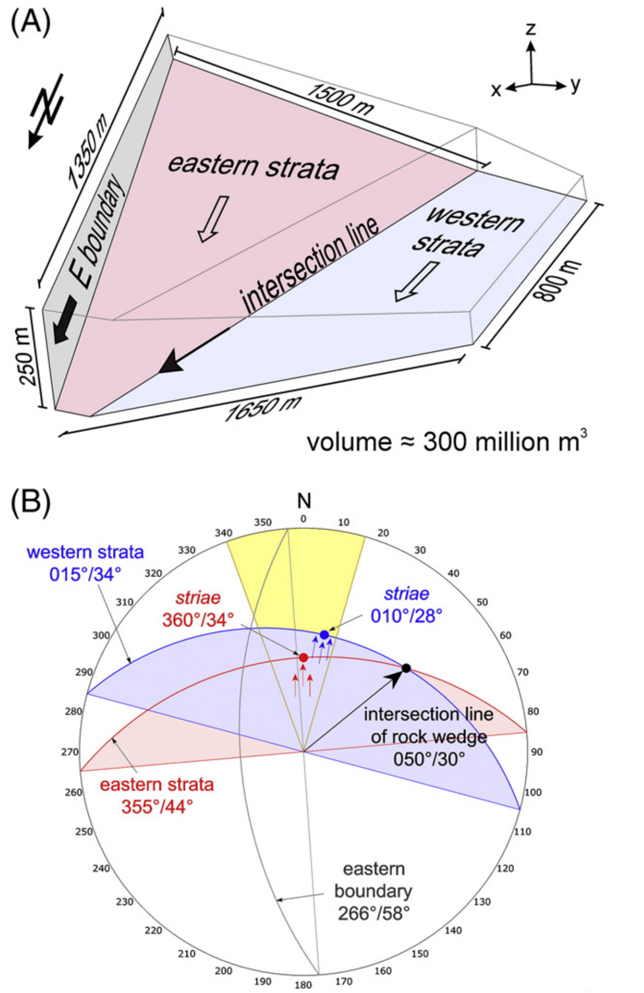

Fig. 22. (A) Three-dimensional representation of the prehistoric rock wedge characterizing the toe of the northern slope of Mt. Toc. (B) Stereonet (Wulff, lower hemisphere) showing the orientation of the three main planes (eastern and western stratification, eastern CTF boundary) controlling the kinematics of the prehistoric rockslide. The yellow sector emphasizes the azimuth of measured striae caused by the prehistoric rock wedge movement.

masse motion occurring in the past that had determined the complete filling of a palaeo Vajont Valley.

The traditional interpretation postulated by Semenza, and put forward again in his last work (Semenza, 2001, 2010), considered this evidently failed rock mass as a residual part of the prehistoric rockslide event. Nevertheless, various geometrical, geological, geomorphological, and mechanical features indicate different stopping conditions for this displaced rock mass, which are not consistent with the mechanical context of the prehistoric Mt. Toc rockslide. The main differences are the following (Figs. 23 and 24B):

- the displaced rock mass of Colle Isolato rested on the underlying alluvial deposits at an elevation of about 590–595 m, considerably lower than the corresponding bottom surface characterizing the opposite Pian del Toc block (625–630 m);
- the failed rock mass covered a deposit of stream bed gravels; these alluvial sediments were never identified at the base of the ancient displaced rigid blocks where loose materials are formed exclusively by cataclastic rocks;
- the general widely distributed disposition of the failed mass (relicts), which stopped against the opposite ancient valley side, strongly differed from other eastern blocks located at the front (see the Castelletto relief); and
- the stratigraphical sequence and the presence of a main fault trace are in line with the characteristics of the contact zone between the Pian del Toc and Pian della Pozza blocks, occurring on the opposite valley side (left or southern side).

On the basis of this evidence, the Colle Isolato failed rock mass and the other adjacent relicts can be adequately interpreted as residual masses displaced by a later reactivation, occurring some thousands of years ago and involving the northwestern border of the Pian della Pozza Terrace. During this slide episode, a great block belonging to the prehistoric rockslide mass slid down toward the north and filled the younger Vajont Valley (Fig. 24B). The damming effects on the preexisting valley were less drastic compared to those caused by the prehistoric Mt. Toc slope failure owing to the smaller size of the failed masses. However, the sudden blocking induced a local course modification in correspondence with the Ponte del Colomber site followed by a progressive deepening of the Vajont thalweg. This process determined the last valley morphology, with a typical gorge cross section, that was the site for the hydraulic procedures involved in the execution of the Vajont reservoir.

8. Discussion and conclusion

The comprehensive research described in this paper has made the detailed reconstruction of the prehistoric Mt. Toc rockslide possible for the first time, describing its main geometrical, geological, and mechanical features. However, the true age of the prehistoric primary failure has still to be ascertained, and also some important later reactivations (as the Colle Isolato landslide event and the related relict masses) cannot be considered adequately characterized from a chronological viewpoint.

In the past, the ancient Vajont rockslide was very often defined as a 'prehistoric' event (Semenza, 1965; Hendron and Patton, 1985; Müller, 1987). More recently, the term 'palaeoslide' has also been used to indicate the ancient slope rupture (Semenza, 2001, 2010). First, more specific dating was carried out by Semenza (1965) who considered the ancient Mt. Toc rockslide as post-glacial. Analogously, Hendron and Patton (1985) dated the ancient slope failure to post-glacial times (Holocene); whereas Semenza in his last book (2001, 2010) hypothesized the beginning of the complex slope deformation processes after the last glacial maximum (LGM), i.e., at the end of the Pleistocene period. All these dating proposals ranged essentially from late Pleistocene to early Holocene (corresponding time interval: about 15000–5000 Y BP), but no more precise time attributions were advanced and absolute dating methods were never utilized either. The 'prehistoric' adjective very often used in the past was actually taken from archaeology and late Pleistocene–early Holocene dating effectively corresponds to prehistoric times.

The proposed dating of the ancient Vajont rockslide was essentially based on geomorphological considerations, and the main geological evidence used for this chronological attribution was the narrow gorge excavated by the Vajont Stream at the front of the landslide mass. Another geological indication often taken into consideration was the presence of an older very narrow epigenetic gorge located in proximity to the Vajont Dam, completely filled by loose sediments (Ponte del Colomber site). These two gorges, with their characteristic very narrow cross section, were attributed to the post-glacial vertical erosion; and for this reason their infilling was dated to a hypothetical post-glacial landslide event.

The precise dating of the prehistoric Mt. Toc rockslide is out of the scope of this paper; nevertheless, some preliminary observations can be made. The rock blocks mobilized en masse by the prehistoric landslide (the Pian del Toc and Pian della Pozza blocks) were covered by limited Quaternary deposits having a moderate thickness (1–10 m, in most cases) (Fig. 24). The Quaternary deposits were mainly made by limestone angular gravel deposited by small stream fans that

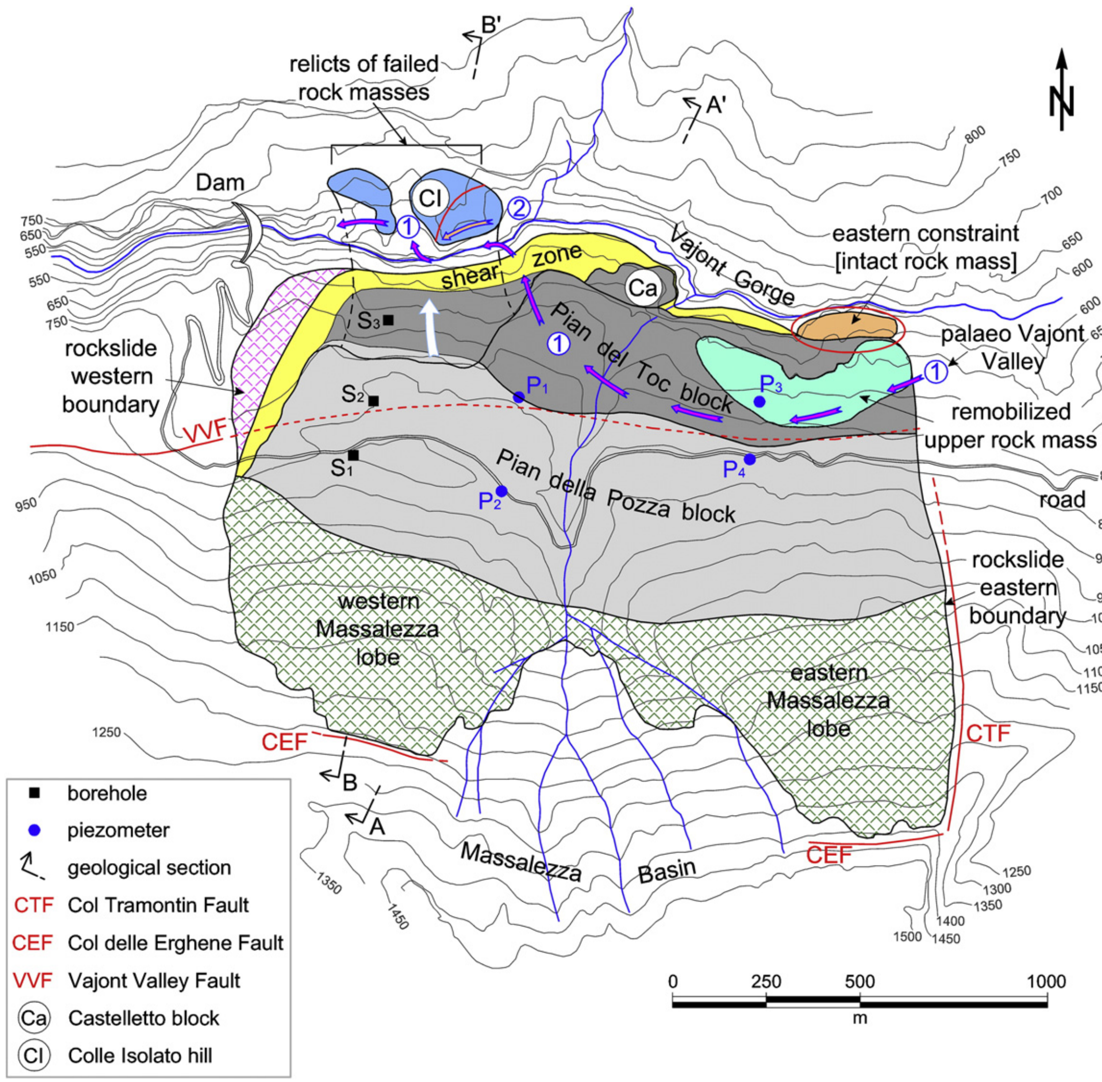

Fig. 23. Schematic map of the Vajont area illustrating the typical multiblock structure of the prehistoric Mt. Toc rockslide, as visible before 9 October 1963. The prehistoric rock mass structure was characterized by distinct rock blocks partially superimposed. The front of the prehistoric rockslide (Castelletto and Pian del Toc blocks) filled a palaeo Vajont Valley, burying some alluvial deposits.

flowed from the upper slope remobilizing the coarse material of the shear zone. Some of these small-sized fans exhibited poor cemented gravel or conglomerate layers as visible at the eastern border of the Pian del Toc Terrace. A characteristic sequence of fine sediments (laminated silts and clays: 1–1.5 m thick) accumulated into the small ground depression located at the top of the Pian della Pozza Terrace as evidenced by the field surveys carried out soon after the 1963 catastrophe. Fine sediments covered an underlying accumulation of angular limestone gravels (2–3 m thick) resting on the cretaceous stratified rock mass (*e* unit).

Particular attention must be paid to the fact that the surface Quaternary deposits may also be older than the first catastrophic slope failure owing to the characteristic rigid en masse motion. Quaternary cover can effectively be transported in a passive manner on top of the failed rock mass and subsequently displaced together with the underlying block. Such behavior occurred most evidently during the 9 October 1963 disastrous event when most Quaternary cover was passively displaced on top of the failed rock mass and thus can still be observed today. As a consequence, large en masse rockslides can be covered by glacial Pleistocene deposits (often LGM morainic deposits or erratic boulders), but this is not decisive geological evidence for the true age of the ancient landslide, as erroneously believed in the past (Abele, 1974, 1997). However, all geological data and geomorphological evidence is effectively consistent with a late Pleistocene–early Holocene dating, and this time interval most probably includes the true age of the prehistoric Vajont rockslide.

The postulated age of the prehistoric Vajont rockslide in the time window from about 15 000 to 5000 Y BP is effectively rather wide. However, it is interesting to note here (although in a preliminary way) the similarity to many other large rockslides that occurred in the European alpine territory and that have recently been dated (for example the Flims, Köfels, and Kander Valley rockslides). This recent research on large alpine rockslides, based on absolute dating methodologies, has showed an elevated concentration of catastrophic slope failures in a restricted period corresponding to the early Holocene and ranging about from 11 500 to 8500 cal. Y BP. This increased occurrence of large rockslides in the European Alps during the early Holocene coincided with a maximum of summer insolation related to mid-Boreal climatic conditions. The increase in the summer temperatures destabilized permafrost-affected slopes, having a considerable negative effect on slope stability, as does increased precipitation (Corsini et al., 2001; Deplazes et al., 2007).

Apart from the chronological considerations, this study has made the detailed reconstruction of the entire structure of the prehistoric Vajont rockslide possible for the first time, describing the complex geometry and the very characteristic superimposition of distinct rigid

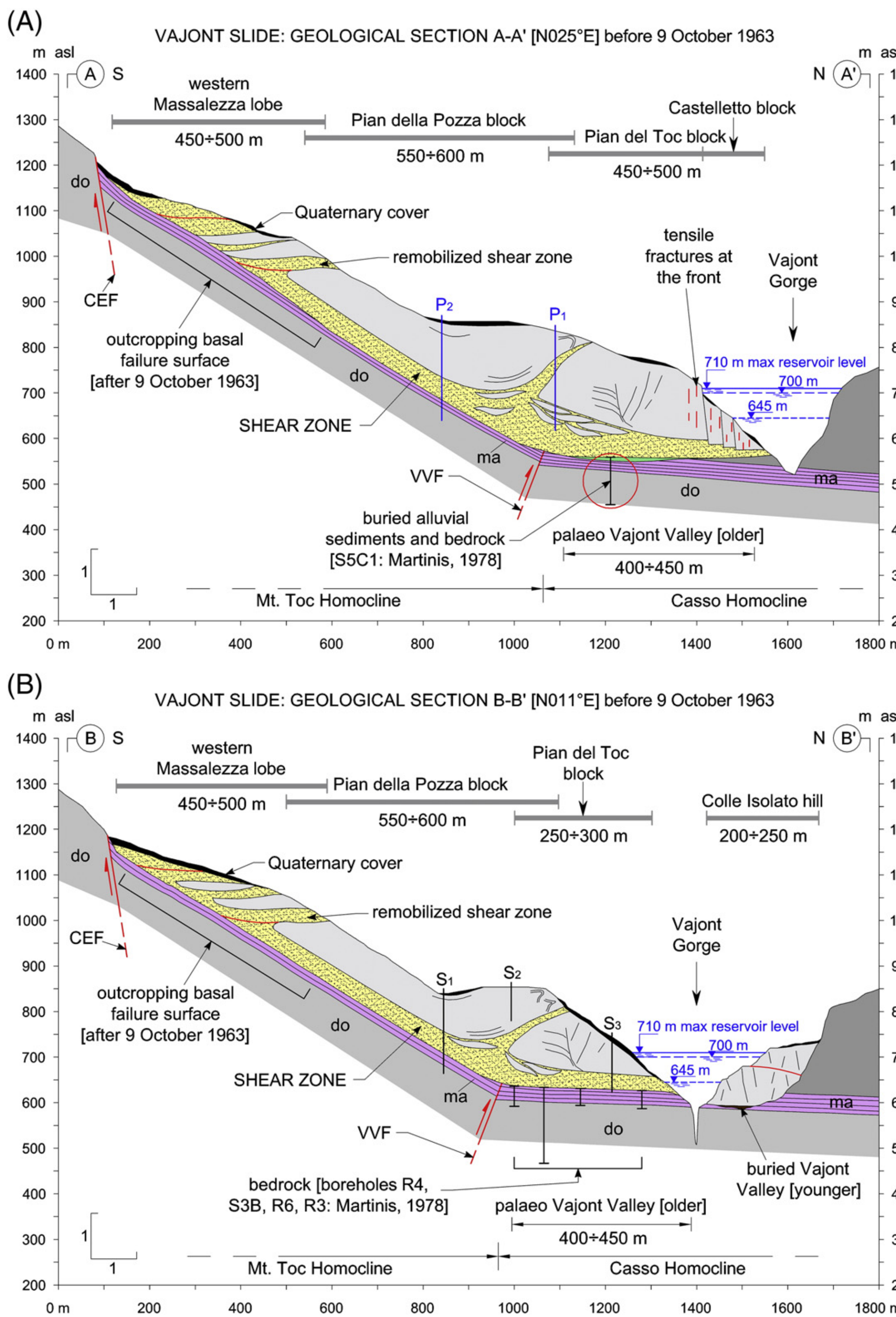

Fig. 24. Geological cross sections of the Mt. Toc palaeoslide before 9 October 1963, according to the new interpretation presented in this work: (A) Castelletto section; and (B) Colle Isolato section. For their location see Fig. 23.

blocks on a very thick shear zone (Figs. 23 and 24). The prehistoric Vajont rockslide was characterized by a multistage failure with a marked retrogressive evolution (Fig. 26), i.e., the first rupture (Pian del Toc block) rapidly destabilized the upper slope, mobilizing a second rock mass block (Pian della Pozza block) that, in turn, determined the multiple rupture of the revealed shear zone material (Massalezza lobe). The whole multistaged failure process was very rapid even if the exact timing of the different phases is not known. At the end of the multistage retrogressive failure, the slope morphology of the northern toe of Mt. Toc had drastically changed and the failed rock mass had settled into the preexisting Vajont Valley assuming the unusual chair-like geometry (Fig. 26).

Unfortunately, the prehistoric Vajont rockslide, although recognized early on by Giudici and Semenza (1960), was not adequately

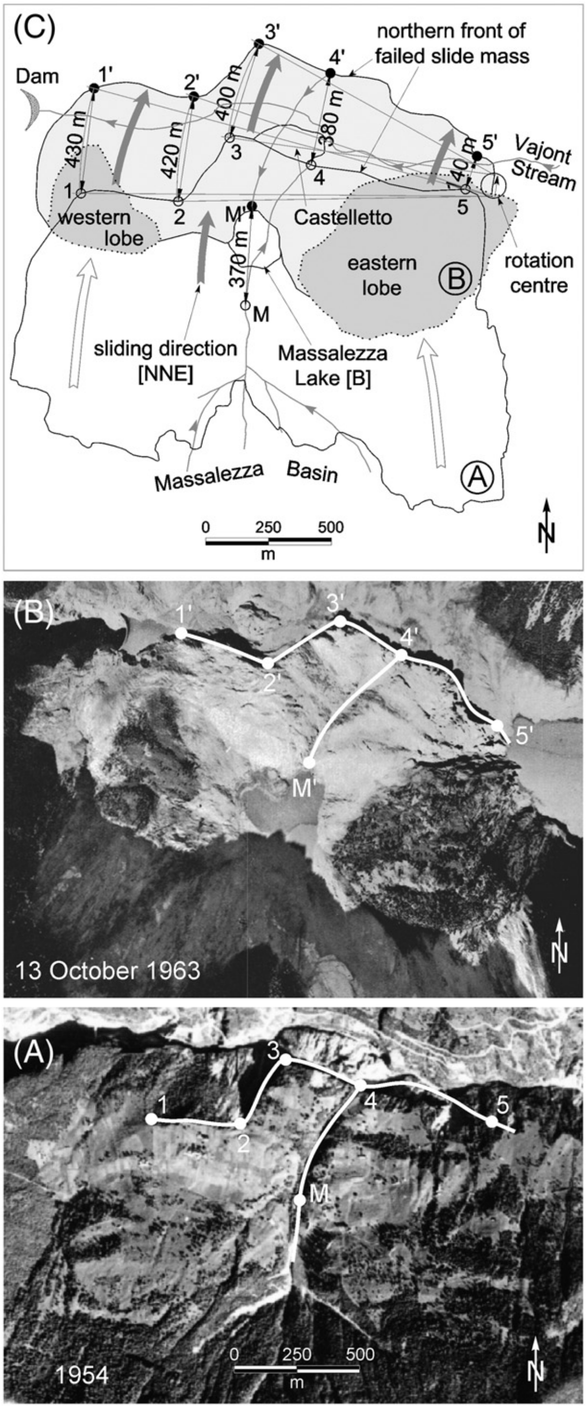

Fig. 25. Field evidence of the rigid en masse sliding (contemporary rotation and translation) caused by the 9 October 1963 catastrophic failure. Characteristic points and landforms of the mobilized rock mass are compared before (A) and after (B: modified from Selli and Trevisan, 1964) the 1963 rockslide to emphasize the type of movement and the magnitude of horizontal surface displacements (C). The mobilized rockslide mass exhibits a marked rototranslation toward the NNE, and the surface displacements range from 140 m (E) to nearby 450 m (W).

analyzed and characterized from geometrical and mechanical viewpoints. As a consequence, because of its effective geological complexity and because of the poor knowledge of rock mechanics at that time, the prehistoric Mt. Toc slope rupture was often denied (Müller, 1964; Selli and Trevisan, 1964; Broili, 1967; Müller, 1968) or misinterpreted (Giudici and Semenza, 1960; Semenza, 1965, 2001, 2010). The misunderstanding or even the nonacceptance of the hypothesized prehistoric landslide led to a completely wrong interpretation of the slope response during the filling-drawdown cycles of the Vajont reservoir, finally resulting in the catastrophic 9 October 1963 collapse.

Before this research, the most detailed reconstruction of the prehistoric Vajont rockslide was summarized by the three geological cross sections drawn by Rossi and Semenza for the comprehensive work of Hendron and Patton (1985). These geological sections included, for the first time, some internal discontinuities superimposing different units or blocks within the prehistoric rockslide mass. However, reported internal folding does not correspond to the effective field evidence visible before 1963, and the thickness of some stratigraphical units (in particular a' and a'') do not agree with the values observed in the *in situ* succession (Casso sequence). The geological sections constructed for this work (Fig. 24) solve this stratigraphical problem simply by considering the preexisting buried valley geometry, the filling effects from mobilization of the shear zone debris, and the multistaged failure mechanism.

The most important result from the described research plan on the 1963 Vajont rockslide is, without doubt, the identification of the very thick shear zone (40–50 m) located at the bottom of the prehistoric Mt. Toc landslide (Fig. 6). Strongly deformed and fractured rock masses were described soon after the 1963 landslide-induced disaster but were erroneously interpreted as 'mylonitic' or 'cataclastic' rocks caused by primary faulting processes (Giudici and Semenza, 1960; Semenza, 1965, 2001, 2011); whereas folding at first was essentially attributed to gravity tectonics (Carloni and Mazzanti, 1964). Cataclastites and fractured rocks were also recently interpreted as belonging to a fault gouge, and the basal rupture surface of the Vajont rockslide was considered as an exhumed fault plane (Mantovani and Vita-Finzi, 2003). Surface deposits of angular limestone gravel with lenses of high plasticity clays (montmorillonitic clays, in prevalence), related to the ancient bottom shear zone, widely outcrop at present on the giant detachment surface. Despite considerable geological evidence, emphasized by the outcrop exposed in the Massalezza Gully and photographed by Semenza (July 29, 1960), the thick shear zone was only recognized for the first time very recently (Paronuzzi, 2009b; Paronuzzi and Bolla, in press); and no previous author has made reference to it.

The recognition of the bottom shear zone is critical for the geotechnical and the hydrogeological modeling of the Mt. Toc slope. In fact, all former geotechnical models and the related slope stability back-analyses considered the 1963 Vajont rockslide essentially as a first-time failure (Müller, 1964; Selli and Trevisan, 1964; Broili, 1967; Müller, 1968), and the influence of a previous rupture surface was neglected. At the same time, the basal rupture surface was generally assumed as being characterized by a contact of the rock-on-rock type or even a rock-clay-rock contact. No reference was ever made to the occurrence of angular gravel materials at the basal failure plane of the 1963 landslide and the conventional geotechnical analyses considered limestone (rock) and/or clay (soil) as the exclusive materials involved in the rupture (Hendron and Patton, 1985). On the contrary, the exposed geological data clearly demonstrate that the 9 October 1963 disastrous slide involved the base of a preexisting, very thick shear zone made up of a chaotic assemblage of rock mass blocks, angular gravel (limestone and cherts), and thin clay lenses.

Owing to the considerable size of the bottom detachment surface (about 2 km^2) and to the unusual thickness of the shear zone, very different materials failed during the 1963 collapse. The basal rupture that occurred on 9 October 1963 involved localized intact rock (cherty limestone and marly limestone) and abundant loose soils, including coarse- (angular gravel) and fine-grained soils (clays and silty clays) of the bottom shear zone. All conventional slope stability back-analyses carried out in the past on the 1963 Vajont rockslide used, as a rule, a very simplified calculation scheme hypothesizing the presence of a single material type at the basal failure. This simplification does not correspond to reality, particularly in the case of the Vajont rockslide; and this aspect has to be kept in mind when one examines the back-calculated strength parameters (Φ) obtained by means of the traditional limit equilibrium approach. Typical back-calculated values of the friction angle Φ_m, obtained for the 1963 Vajont rockslide, ranged essentially from 17° to 28° (Müller, 1968), but these are average values referring to the entire slip surface and can differ considerably from the true shear strength properties of the materials effectively involved in the failure (intact rocks and soils). The strength parameters of these very heterogeneous materials are evidently highly variable, and the back-calculated values only reflect an average value computed assuming constant geotechnical properties along the whole rupture surface (which had a total length of about 1400–1600 m). This explains the marked difference between the friction angles measured by means of different shear tests on various Vajont clay samples ($\Phi_c = 6$–16°, Hendron and Patton, 1985) and the typical back-calculated mean values ($\Phi_m = 17$–28°, Müller, 1968).

The discovery of the thick shear zone located at the base of the prehistoric Mt. Toc landslide makes it possible to explain two very controversial aspects of the 9 October 1963 collapse: the elevated permeability of the Mt. Toc toe submerged by the reservoir and the catastrophic, unexpected, en masse motion. The very high permeability of the toe reflects the occurrence of the unusually thick debris gouge (40–50 m, on average), mostly made up of angular limestone gravel with abundant voids and often with an open-work structure. These loose materials are effectively characterized by an elevated hydraulic conductivity, with k values ranging essentially from 1×10^{-3} to 1×10^{-4} m/s. This range, based on geotechnical considerations, is very much in line with the value of $k = 1.2 \times 10^{-4}$ m/s back-calculated by Müller (1968) for the last slope behavior preceding the final 1963 rupture. No progressive fracturing of the rock mass is required to explain the high permeability of the submerged slope as formerly hypothesized by Müller (1968): the slope seepage induced by the reservoir filling mainly involved the coarse-grained materials formed by the prehistoric shear processes and by the related strong rock mass damage.

The en masse motion of the 9 October 1963 catastrophic slide (Fig. 25) was considered by most technicians as an 'unforeseeable' event, and its particular rockslide dynamics were never fully understood. Effectively, rockslides in most cases disaggregate immediately after failure and during motion, forming characteristic boulder and debris rockslide accumulations. The unusual evolution of the prehistoric Vajont rockslide was caused by the formation of the underlying, very

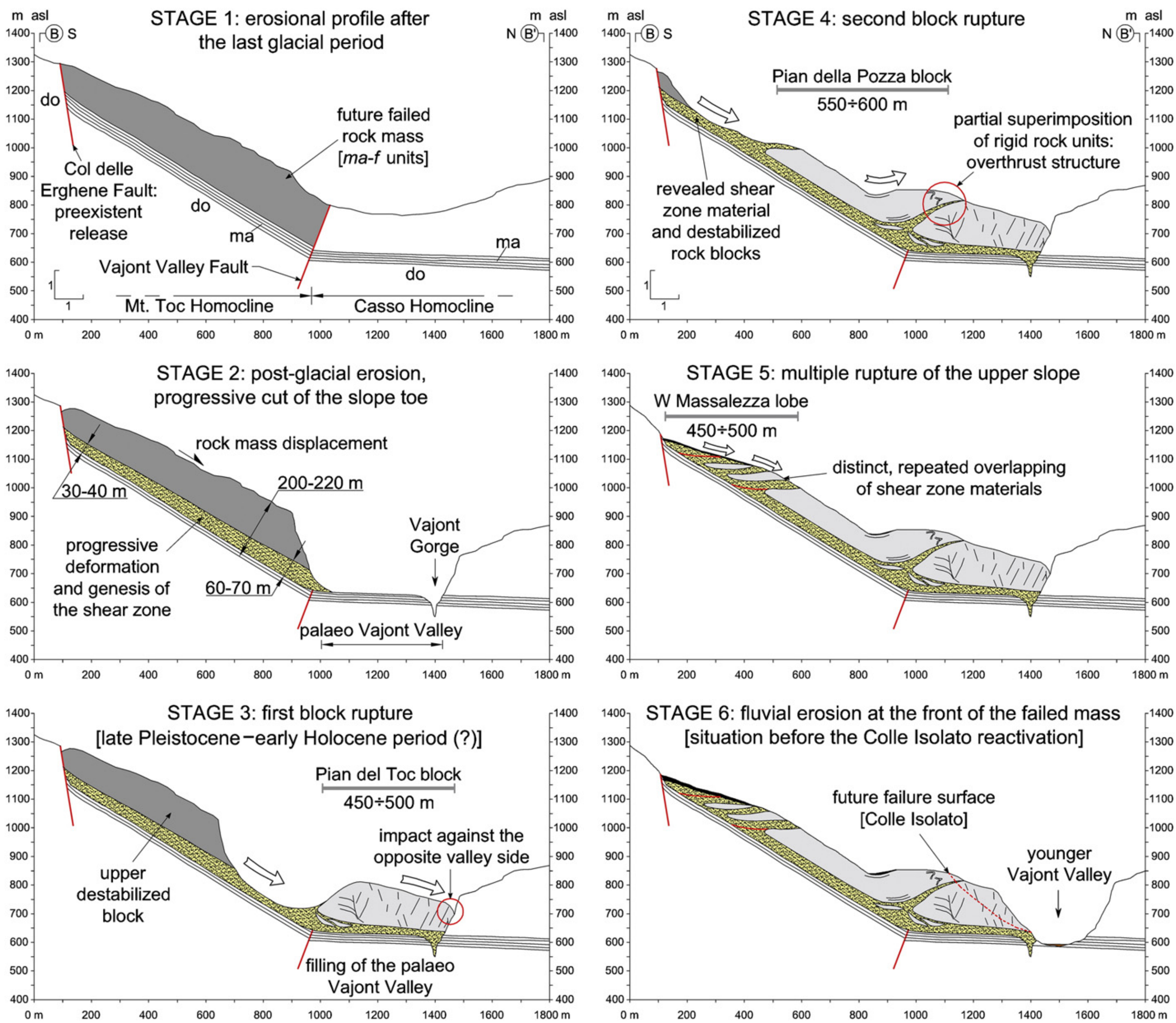

Fig. 26. Geological cross sections reproducing the hypothesized multistage and retrogressive failure process that characterized the prehistoric Mt. Toc rockslide (geological section B–B′).

thick, shear zone, on which distinct rigid rock masses slid as a consequence of a typical retrogressive multistaged failure. Upper rock masses moved downslope as a whole, sliding on the thick debris 'bearing' that allowed the preservation of the primary structures such as stratification and other sedimentological features (slumpings). The en masse motion of the prehistoric Mt. Toc slope failure was evidenced by several significant outcrops, but probably rock mechanics knowledge was at that time inadequate to correctly reconstruct the prehistoric landslide, from a geometric and from a kinematic point of view.

The kinematic reconstruction of the prehistoric Mt. Toc slope failure has helped us to solve another complicated and very debated question: the apparent discrepancy between the invoked progressive failure mechanism and the existence of the ancient rupture surface. This argument was advanced by Müller (1968) to confute the hypothesis of the prehistoric landslide. The main difficulty in explaining this apparent contradiction lies in the inadequate understanding of the prehistoric rockslide mass and especially of its three-dimensional geometry and related kinematics. The prehistoric rockslide mass was formed by three distinct blocks, and the distal block (Castelletto–Pian del Toc block) settled into the palaeo valley burying the old stream sediments and resting on the opposite side at the eastern extremity. Owing to the newly assumed geometry, the frontal block was stuck on the opposite valley side, partially rising up onto it. In this way the mobilized rigid slab was blocked at the eastern extremity (Fig. 10); and the basal contact with the stable, irregular-shaped bedrock worked as a mechanical constraint (Figs. 23 and 25). Future mobilization of the failed rigid mass, induced by the progressive stream excavation at the landslide front, required the rupture of this localized restraint. For this reason, during the critical phases of decreasing slope stability, which preceded the 1963 collapse, the prehistoric rockslide mass progressively slid on the ancient shear zone; but the progressive failure also occurred involving the northeastern constraint. The mechanism of the progressive failure of the intact rock became particularly important during the last period when rock mass damage considerably increased until the ultimate resisting part — formed by *in situ* rock mass (*c*, *d*, and *e* units, Biancone Formation) — suddenly failed. The particular location of the mechanical constraint at the northeastern edge of the prehistoric rockslide mass also caused the marked rotation of the unstable slope toward the NE, before (1960–1963 precursory slope movements) and during the last 9 October 1963 catastrophic sliding motion (Fig. 25).

The 1963 Vajont rockslide represents a very significant example of how a complex geological situation, if not adequately analyzed and reconstructed, can lead to dangerous misinterpretations determining the implementation of very rough or even erroneous engineering–geological models. At the same time, this famous dramatic landslide case history remains a cultural milestone for all geoscientists and engineers because it reminds us that no realistic geotechnical and hydrogeological modeling can be carried out without a detailed geological reconstruction of the slope structure, as determined by past natural events. This slope 'structure' in certain cases can be very complicated, as shown by the 1963 Vajont rockslide; but accurate fieldwork and modern technology can be fundamental in solving such a very intriguing 'geological puzzle.'

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