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GEOLOGICAL STRUCTURES OF THE VAJONT LANDSLIDE

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ABSTRACT

The Vajont rockslide is not the largest rockslide in the Italian Alps, but it is a reference at a worldwide scale due to its complex behaviour and catastrophic effects in terms of economic losses and human casualties.

An essential aspect to be considered in any kind of approach to the Vajont landslide, whether hydrogeological, geomorphological or related to geomechanical modelling, is the highly three-dimensional character of the geological structures of the Monte Toc northern slope. The knowledge of the geometry and shape of the sliding surface as well as of minor structures, such as folds and steps, represents the starting point for any subsequent analysis and interpretation of the landslide.

In order to reach an in-depth evaluation of the structural setting, remote sensing analyses (LIDAR and photogrammetric DTMs) integrated by field data surveys were applied. Our results have clarified the structural relationships between major folds and faults affecting the Monte Toc slope and shown at various scales the primary importance of tectonic folds in controlling the kinematics of the 1963 event. Two pre-existing fold systems (ca. E-W and N-S trending), deforming the sliding surface, and associated minor structures (small scale faults and fractures) have most likely conditioned the sliding process. Particularly the concave shape of the sliding surface, reflecting a major syncline (Massalezza syncline), leads to the separation of the landslide into two distinct blocks with different kinematics.

Key words: *Vajont, rockslide, folds, interference pattern, flexural slip, thrusts*

INTRODUCTION

The Vajont landslide history represents a dramatic example of the incompleteness of the investigations carried out before the 1963 event on some relevant geological aspects. It was indeed a sequence of natural events and misconceived technical operations leading to the catastrophic landslide, an event for which the complex combination of the geological factors involved have not yet lead (50 years after the catastrophe) to an unambiguous and complete explanation of the phenomenon.

The Vaiont landslide occurred on the southern limb of the Erto syncline, which is dipping 30° to 50° towards the north-northeast and north, deeply reworking a former paleo-landslide covering the northern slope of the Monte Toc (Giudici & Semenza, 1960; Semenza, 2010). The sliding surface is localized within the middle-upper Jurassic Fonzaso formation, a sequence of thin-stratified limestones with thin (0.1-5 cm) intercalations of clays (Hendron & Patton, 1985).

A focal point to explain the kinematics of the landslide is the adoption of a reliable geological model that takes into account the highly three-dimensional character of the geological structures of the northern slope of Monte Toc. The knowledge of the geometry and shape of the sliding surface at large scale, minor structures such as folds and steps and the rock mass characterization of all the involved lithological units, represents the

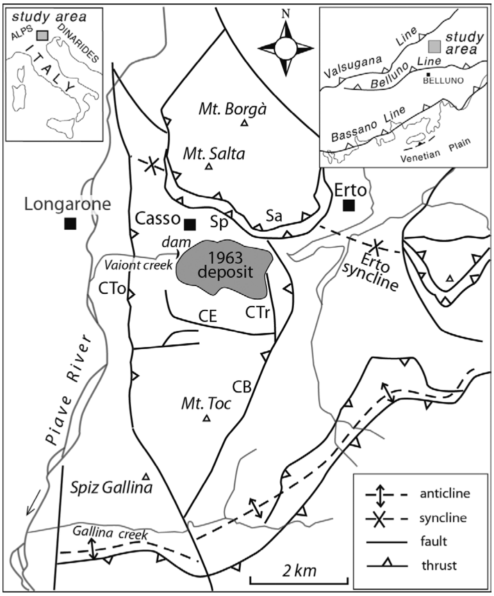

Fig. 1 - Structural sketch of the Vajont area (modified after Riva *et alii, 1990)*

starting point for any subsequent analyses and interpretation of the landslide.

Indeed many authors have illustrated the importance of considering the influence of structural features like faults and fractures on the development of large rock slope instabilities (Agliardi *et alii*, 2001; Ambrosi & Crosta, 2006; Brideau *et alii,* 2009; Jaboyedoff *et alii*, 2009). Massironi *et alii* (2003, 2011) and Di Luzio *et alii* (2004) have also demonstrated the importance of the interplay between the orientation of folds and faults with respect to the slope in controlling large gravitational mass movements.

In this paper we show how the applied remote sensing techniques (analyses of LIDAR and photogrammetric DTMs) along with the geo-structural field investigation, allowed to characterize in detail the structure of key areas inside and outside the landslide and to clarify relevant aspects concerning the structural setting of the Vajont valley with particular regard to northern slope of Monte Toc. All of the identified faults and folds systems in the Vajont area reflect the regional tectonic pattern, here interpreted as the result of a superposition pattern of different deformation stages. Hence, the location and geometry of the Vajont rockslide are controlled by regional tectonic features. In particular, the interference between two fold systems strongly affects the Vajont sliding surface and is fundamental to evaluate the rockslide kinematics.

GEOLOGICAL FRAMEWORK

GEO-STRUCTURAL SETTING

The study area belongs to the eastern Southern Alps domain, which represents the Neogene-Present back-thrusted (S-vergent) part of the Alpine chain. The Vajont valley coincides with the core of an Alpine syncline (Erto syncline) with an E-W to WNW-ESE trending axis (Ferasin, 1965; Riva *et alii*, 1990) gently plunging towards the E (Broili, 1967) (Figs. 1, 2). The deformed rocks are Liassic to Eocene carbonates and marls (Semenza, 1965; Masetti, 1986). The Erto syncline lies on the hanging wall of a main structure of the Venetian Alps (Belluno thrust, Doglioni, 1992) and it is paired with the trailing limb of a main frontal asymmetric anticline located south of the study area. The shape of the Erto syncline is very asymmetric, because the northern limb is reversed and stretched, lying just at the foot of the Mt. Borgà and Spesse thrusts (Mt. Salta thrust in Riva *et alii*, 1990), two older thrusts passively transported on the back by the Belluno thrust. Therefore, the Erto syncline can be referred to as a recumbent fold with a gently dipping axial plane (Fleuty, 1964).

The sliding layered sequence was laterally constrained by a system of subvertical faults (Croda Bianca and Col Tramontin Lines to the east and west branch of the Col delle Erghene Line to the west), while the rockslide crown was constrained by E-W structures (Col delle Erghene Line; Riva *et alii*, 1990) (Figs. 1, 2).

STRUCTURAL CHARACTERIZATION

In order to define the relationships among tectonic setting, rockslide, and topography of the Vajont landslide, a morpho-structural investigation of the whole area has been performed. The analysis was carried out through the integration of traditional structural field investigations with remote sensing techniques. In particular, the remote sensing analysis was carried out on air-photos and DTMs derived from photogrammetry and recent LIDAR acquisitions, whereas the conventional structural field survey was aimed to describe and interpret brittle and folding deformations. The application of remote sensing techniques was particularly suitable to the Vajont case study due to the steep and inaccessible rock face at the head scarp and sliding surface.

The information collected in the field concerns dips and dip-directions of bedding planes, faults and fractures and trends and plunges of fold axes. Due to the openness of most of the fold hinges, the latter measurements have been mainly derived by fold limbs attitudes. All structural data were plotted stereographic projections (Fig. 3).

FOLDS

The shape of the Monte Toc northern slope is the direct expression of the back-limb of the Belluno anticline where it merges into the E-W to WNW-ESE oriented Erto syncline (Riva *et alii*, 1990; Broili, 1967; Hendron & Patton, 1985; Doglioni & Carminati, 2008; Genevois & Ghirotti, 2005). At the scale of the entire Monte Toc northern slope another major fold has been revealed by our field analysis, photogrammetric data (Wolter *et alii*, submitted) and LIDAR DTMs, that have highlighted an appreciable difference in the average attitude of the bed-

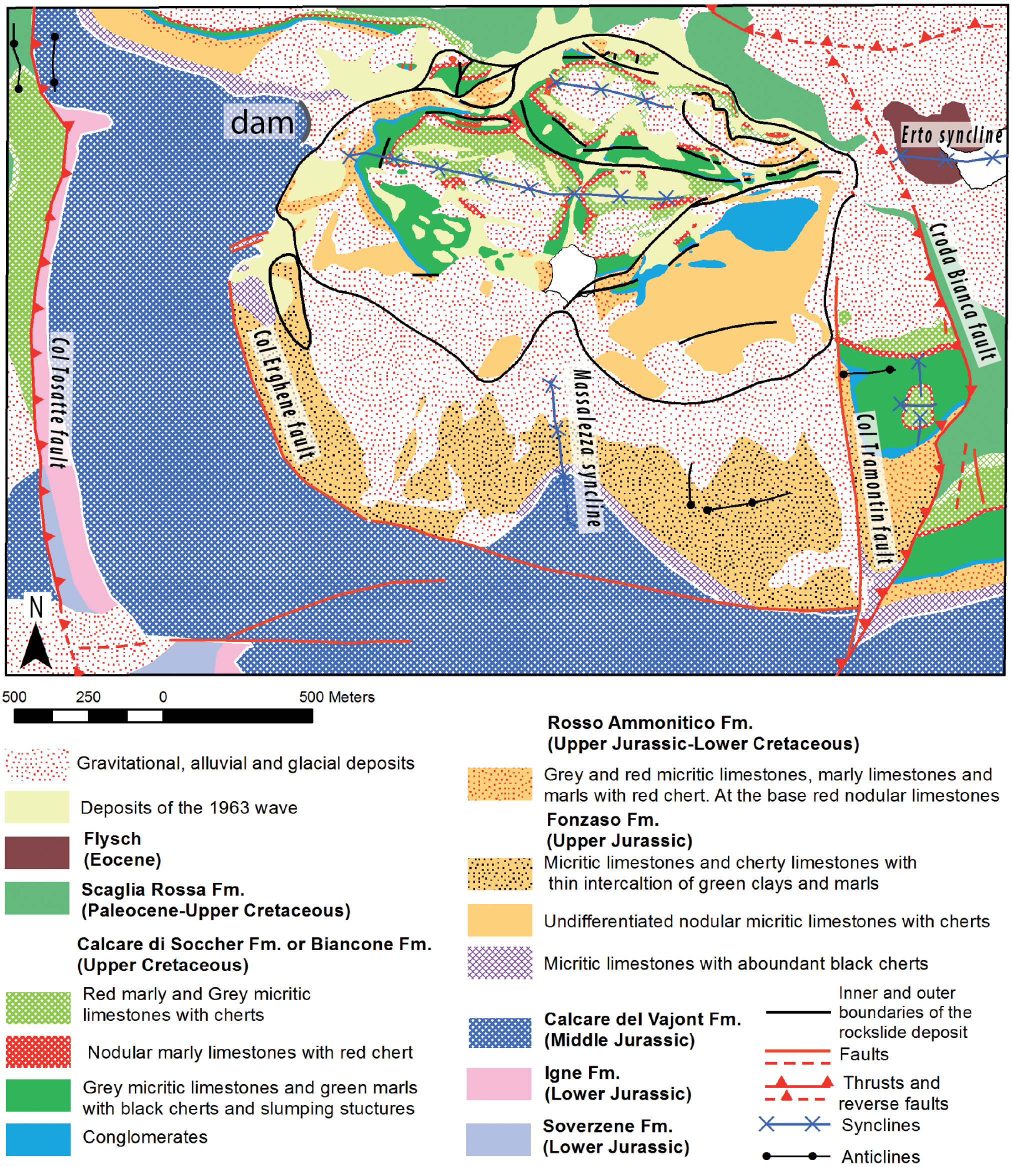

Fig. 2 - Geological map modified after Rossi & Semenza (1965) and Riva et alii (1990). Stratigraphic sequence redrawn after Rossi & Semenza (1965) and Paronuzzi & Bolla (2012)

planes at the eastern and western parts of the sliding surface (Fig. 3). Indeed strata have an average dip of 45° and dip direction N 340° in the eastern side, 35°/N360° in the middle and 35°/N020° in the western sides delineating an open syncline with a hinge in correspondence to the Massalezza Stream. This fold, from here on named Massalezza syncline, accounts for the overall concave shape of the sliding surface and the different average attitudes of the strata on the sliding surface already pointed out also by Semenza (2010) and Paronuzzi & Bolla (2012). The structural complications related to the interference between the parasitic minor folds of the Erto and Massalezza synclines are responsible of the undulation and folding of the sliding surface which was generally attributed to gravitational processes (e.g. Hendron & Patton, 1985; Paronuzzi & Bolla, 2012) or even neglected. Only Broili (1967) recognized the tectonic origin of these features, although he did not provide any structural explanation of them.

The folds that can be easily recognized, even from a great distance (Fig. 4), on the entire sliding surface consist in a series of E-W to WNW-ESE structural terraces (sensu Twiss & Moore, 1992, Fig. 11.13) and monoclines (see also Broili, 1967 and Hendron & Patton, 1985), and of frequent N-S to NNW striking undulations (axes average trend/plunge: N010°/40°), often controlling gulley incisions, particularly in the western lobe of the sliding surface (see also Hendron & Patton, 1985). The E-W to WNW-ESE folds affecting the Fonzaso beds frequently display flexural slip processes generating meso-scale flat-ramp thrusts verging toward the south (Fig. 4). This kinematics, developing in contrast to the local gravitational gradient, unambiguously demonstrates the tectonic origin of these folds, ruling out other interpretations that would explain their nucleation uniquely as a consequence of the shear stresses at the base of the sliding mass (either the paleo-landslide or the 1963 event; see for example Carloni & Mazzanti, 1964 a, b and Paronuzzi & Bolla, 2012).

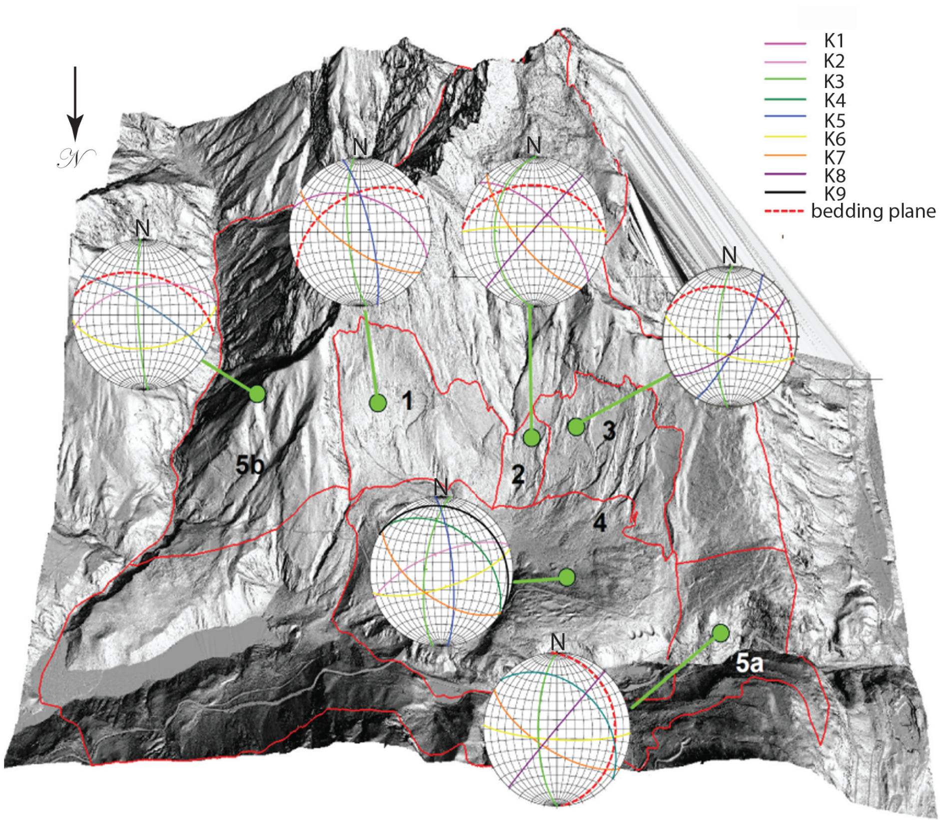

Fig. 3 - Stereo-plots (equal-angle, lower-hemisphere) showing the average attitudes of strata and joints in the different domains (1 to 5) of the Vajont landslide and surroundings

The most striking E-W structural terrace (Fig.4 a) runs through the eastern lobe, where detrital talus rests at the middle of the slope. The photogrammetric analysis and field survey have shown that there the strata change their dip from 45° in the upper part, to 30° at the terrace and 50° in the lower flank. As well as the meso-scale structures with a similar asymmetry, also this structural terrace is likely the product of a hidden south-verging flat-ramp-flat thrust induced by flexural processes (Fig. 4 b, c, d). Indeed, the terrace is the uphill boundary of an evident step on the sliding surface where a stratigraphic jump is recorded. This suggests a gravitational reactivation of the pre-existent flat-ramp-flat thrust system (Fig. 5). To the west the E-W structural terrace interferes with a N-S trending antiform plunging to the north with a dip angle of about 40°. This represents a spectacular large scale example of a refolded fold which, in our opinion, is responsible of a major N-S trending step separating the western lobe of the sliding surface from the eastern one east of the Massalezza stream (Fig. 4 a).

According to the usual parasitic folding behavior, the N-S fold system increases its frequency approaching to the hinge zone of Massalezza syncline and similarly the E-W to WNW-ESE monoclinal folds increase at the base of the slope close to the Erto syncline hinge.

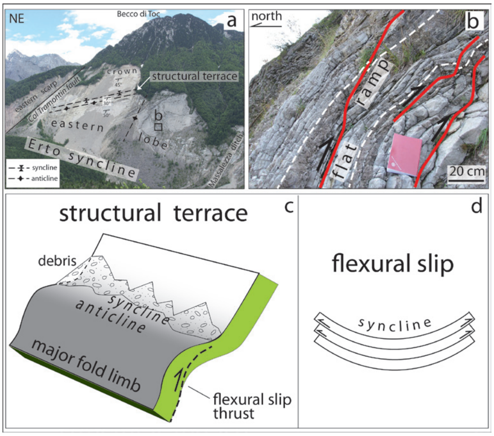

Fig. 4 - a) Eastern lobe of the Vajont sliding surface showing a structural terrace with a syncline-anticline couple; b) close view of the Fonzaso Fm. layers showing flexural slip thrusts with ramp-flat geometries and associated folds with a southern vergence (anti-gravitational); c) interpretation of the structural terrace of the Vajont eastern lobe; d) flexural slip mechanism operating within a syncline

Hence, the meso-scale structural pattern is dominated by superposed folding in the lower-central area of the

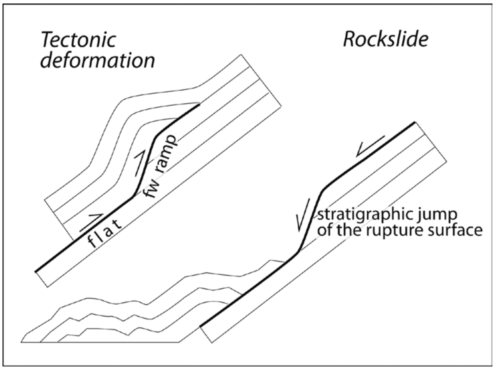

Fig. 5 - Sketch showing the development of a structural terrace by tectonic deformation and the subsequent inversion of the displacement along the thrust surface by gravitational sliding. Fw ramp: footwall ramp

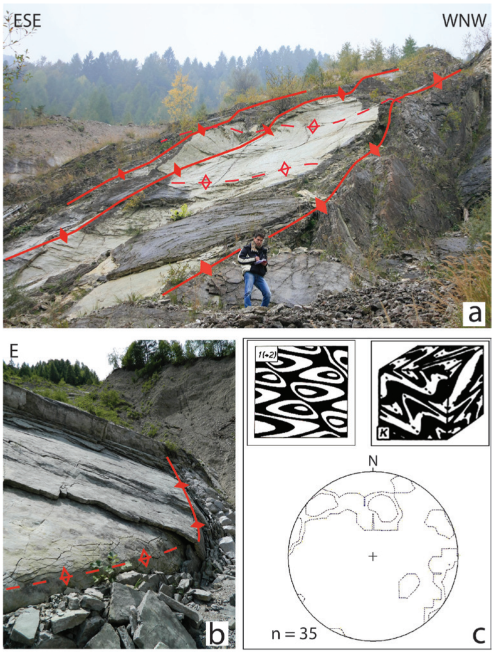

Fig. 6 - a) Meso-scale refolded folds in the sliding surface of domain 2; b) Meso-scale refolded folds in the sliding surface of domain 3 (continuous line = hinges of the Massalezza syncline fold set; dashed line = hinge of The Erto syncline fold set); c) Top: Interference pattern after Ramsey *(1967) (left) and* Thiessen & Miens *(1980) obtained by considering the average axes trends and axial planes of the Massalezza syncline and Erto syncline sets. Bottom: Contour plot (equal-area lower-hemisphere) of the fold axes on the sliding surface*

sliding surface where both the parasitic folds of the Massalezza and Erto synclines increase (Fig. 6a, b). The interference among folds is also testified by the local dispersion of fold axes revealed by the structural measurements acquired in the field (Fig. 6c). Refolding processes becomes particularly relevant at the base of the Massalezza stream. Despite the considerable dispersion of the data, two dominant axial trends are well recognizable: E-W to WNW-ESE and N-S to NNW, perfectly consistent with the two major folds (i.e. Massalezza and Erto synclines). Considering the representative orientations and geometries of the two fold sets and taking into account the tilting process due to the Belluno ramp on the N-S to NNW-SSE folds plunges, we have derived the interference pattern according to the Ramsey (1967) and Thiessen & Miens (1980) classifications obtaining type 1-2 and type K interference patterns , respectively (Fig 6c). This means "domes and basins" to "crescents and mushrooms" type refolded folds deforming the sliding surface at the meso-scale (Fig. 6c). These structures gave rise to the observed fold axes dispersion which have led several authors (e.g. Broili, 1967; Paronuzzi & Bolla, 2012) to the misleading interpretation of a coexistence of many fold sets, being actually two (N-S to NNW-SSE and E-W to WNW-ESE).

The significant wideness of the two major synclines as well as the north dipping orientation of the Massalezza one exclude any gravitational genesis. The north dipping folds and undulations must be unrelated to any gravitational phenomena on the north facing Monte Toc slope by definition, whereas the considerable scale of several E-W to WNW-ESE monocline folds and the anti-gravitational vergence associate to several of them similarly rule out a direct relation with gravitational sliding processes. The strict consistency between the meso-scale folds with the two major synclines and the resulting interference structures confirm the tectonic origin of many plicative deformations of the area. Hence, most of the meso-scale folding, affecting in particular the weakest and clay-rich horizons of the succession (Fonzaso formation), is no doubt due to the regional tectonic deformations and therefore preexisted any sliding event. Some E-W to WNW-ESE folds are reworked by gravitational sliding (Fig. 5), but the recent suggestion that all the meso-scale folds should represent remnants of a ductile deformation along a supposed thick shear zone at the base of the paleo-landslide (Paronuzzi & Bolla, 2012) does not find an adequate support from the field evidence.

Looking at the pre-1963 geological map by Rossi & Semenza (1965), it appears clear that the accumulation of the paleo-landslide is deformed onto two open synclines E-W oriented and with a core made up of the upper members of the Calcare del Soccher unit and separated by a narrower anticline. This setting does not change much in the nowadays framework as testified by the post-1963 geological map of Rossi & Semenza (1965) (Fig. 2). It is most probable that the southern syncline finds its eastern prosecution onto the small syncline enclosed between the Col di Tramontin and Croda Bianca faults (Fig. 2). If this is the case, the related axial trace is a good marker to obtain a rough estimate of displacement of the upper portion of the paleo-landslide that, in agreement with Paronuzzi & Bolla (2012), but with different motivations, could be estimated at about 500 m.

The N-S to NNW folds as well as the E-W to WNW-ESE ones, are detectable in both the paleolandslide and 1963 gravitational accumulations (Fig. 1). In particular, meridian folds have been revealed by undulation of some geological limits in the pre-1963 geological map of Rossi & Semenza (1965), historical photographs (R64-36, R63-15, R63-11 in Masè *et alii*, 2004), meso-strucutural data (Broili, 1967 and this work) and on recent geophysical surveys (Francese *et alii*, 2013).

The coincidence between the fold trends on the slid mass with the ones of the sliding surface supports the tectonic nucleation of most of the folding in the area as well as the "en-mass" displacement of the paleolandslide and 1963 gravitational events

FAULTS

The structural analysis of brittle deformations has been focussed along the two major fault systems enclosing the Monte Toc slope: the Col delle Tosatte fault and the Croda Bianca-Col Tramontin system. The Col delle Tosatte fault lies on the Piave valley left slope cropping out in the Vajont gorge downstream of the dam and is classically interpreted as an high angle normal fault bounding the eastern margin of what has been supposed a graben and named after Longarone (Semenza, 1960; Riva *et alii*, 1990). By contrast, our field observations, historical photographs (A-11 and A-25 in Masé *et alii*, 2004) and new kinematic data have unambiguously revealed that the Tosatte fault is actually dipping toward the east and is a westward-directed reverse fault. This fault is associated to a ramp anticline deforming the Liassic Igne formation, at present overlying the Cretaceous Soccher sequences (Fig. 7). At the Col delle Tosatte fault footwall a minor splay has been also found; it is associated to a ramp anticline in the hanging wall and an asymmetric syncline in its footwall, both involving the Soccher sequence and Scaglia Rossa formation (Fig. 7). Possibly, the frontal part of this secondary ramp anticline was previously misinterpreted as the morphological evidence of a normal fault dipping toward the Piave valley (Riva *et alii*, 1990).

Both the Col Tramontin and Croda Bianca faults are traditionally reported as vertical in the geological sections (Besio & Semenza in Riva *et alii*, 1990) and much more attention has been always paid to the former one, because it bounds to the east the 1963 Vajont landslide mass (Semenza, 2010; Paronuzzi & Bolla, 2012). However, as already pointed out by Paronuzzi & Bolla, 2012) (2012), the steep Col Tramontin fault is only a subsidiary element of the much more relevant Croda Bianca fault which, on the other hand, clearly dips towards the west as can be easily recognized in the Rossi & Semenza (1965) and Besio and Semenza geological maps (in Riva *et alii*, 1990). The subordinate relevance of the Col di Tramontin fault with respect to the Croda Bianca one is evidenced by its limited extension in the same maps, an by the absence of any displacement in the Vajont Gorge as it was mapped in the pre-1963 landslide map by Rossi & Semenza (1965). Field investigations and 3D geological reconstructions suggest a reverse kinematics of the Croda Bianca fault associated to steep or folded strata beds at its footwall and open folds at its hanging-wall. Therefore the Col Tramontin fault can be interpreted as a high angle hanging-wall splay of the Croda Bianca reverse fault, later reactivated as the eastern boundary of the Vajont landslide.

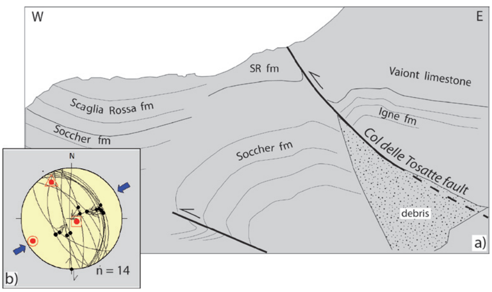

Fig. 7 - a) Structural sketch of the right side of the Vajont gorge downstream of the dam; b) stereoplot (equal-angle lower-hemisphere) and stress inversion (circle: σ1; triangle: σ2; square: σ3; red arrows: maximum horizontal compressional axis, WinTENSOR by Delvaux & Sperner, 2003) derived from kinematic data of meso-faults associated to the Tosatte line

In summary, the slope interested by the rockslide, i.e. the southern limb of the Erto syncline, is enclosed between two downward converging faults with a highly reverse component of displacement (Croda Bianca-Col Tramontin system to the east and Col delle Tosatte fault to the west). The deformation along these two conjugate fault systems plus the reverse activity along the Belluno flat-ramp-flat thrust accounts for the two main fold systems, showing a characteristic interference pattern, recorded on the sliding surface.

JOINTS AND FRACTURES

On the basis of the structural framework recognized in the Vajont area, the area was divided into five main structural domains (Fig. 3). Domains 1 and 3, which are respectively the eastern and western flanks of the Massalezza syncline and correspond to the two lobes of the sliding surface, are characterised by relatively undulated bedding planes with some steps and discontinuities. Domain 2, located near the centre of the sliding surface, where the slope is carved by the Massalezza gully, is the most complex since it is located where the fold hinge of the Massalezza syncline interferes with the Erto syncline. Domain 4 includes the deposit area and Domain 5 is constituted by the surroundings not affected by the 1963 event. In turn Domain 5 has been subdivided into 5a and 5b. Domain 5a is characterized by bedding planes dipping to the East, reflecting the eastward plunge of the Erto syncline. Domain 5b is finally the one affected by the Croda Bianca and Col Tramontin faults.

In the whole study area, 9 discontinuity sets (both joints and fractures), have been recognized based on their orientation (Fig. 3). The domains in the bedrock are generally characterized by 4 or 5 systems (Fig. 3). Among these the steep N-S striking ones (K3 and/or K5) are common to all the domains and are related either to the folding process responsible of the N-S striking folds or to fracturing accompanying the major N-S fault systems (Croda-Bianca, Col di Tramontin and Col delle Tosatte faults). The conjugate NW-SE systems (K1 or K4 and K7) as well as the E-W striking ones (K6 and secondarily K1) are extremely recurrent and primarily related to fractures and joints associated to the folds with the same trends (compare figures 2 and 5) and faults governing the flexural slip, most of which probably reactivated by the gravitational phenomena (in particular the northward dipping ones). It is noteworthy that the more intensively folded domain 2 is also the one with the higher number of joint sets. In the domain 4 are still recognizable all the major sets of the other domains (plus several others related to the gravitational phenomena), proving once again the "en-mass" sliding behavior of both the paleolandslide and the 1963 events.

DISCUSSION AND CONCLUSIONS

The structural investigation has revealed that the Monte Toc northern slope, structurally located at the back-limb of the asymmetric Belluno anticline (southern flank of the Erto syncline), is enclosed between two N-S to NNW-SSE striking and downward converging reverse fault systems (Croda Bianca-Col Tramontin system and Col delle Tosatte fault). This peculiar structural setting has led to the N-S trending Massalezza syncline, which accounts for the two distinct lobes of the Vajont landslide (eastern and western) and is associated to a series of poly-harmonic folds. These folds interfere with similar meso- to large-scale folds related to the Erto-syncline and striking E-W to WNW-ESE. Despite some gravitational reactivation, many of these folds are associated at various scales to south-vergent anti-gravitational flat-ramp-flat thrust systems generated by flexural slip processes. Both E-W and N-S folds are still visible at various scales also on the slid mass. Most of the joints and fractures revealed by the structural analysis on the whole area seem strictly related to the folding and faulting processes accompanying the formations of the Massalezza and Erto synclines. The structural analysis has governed the 3D geological reconstruction of the Vajont landslide (see Bistacchi *et alii*, 2013) that, once populated with the geomechanical data, will constitute the base of 2D and 3D geomechanical models (e.g. Castellanza *et alii*, 2013; Hungr, 2013). The structural setting summarized above lead to the following major consequences for the Monte Toc slope evolution.

1) The Massalezza syncline and related concave shape of the sliding surface played a major role in the evolution of the 1963 Vajont landslide, favouring the collapse of the two lobes (eastern and western) that followed two slightly different and northward converging sliding paths.

2) Most of the folds recorded on the sliding surface pre-existed the landslide events and may have affected the gravitational processes in different concurrent modes:

a) as meso-scale roughness/waviness, unevenly distributed on the sliding surface (since the fold frequency and interference patterns increase toward the lower Massalezza ditch);
b) through reactivation of the fold-associated flat-ramp-flat thrusts that are primary elements favouring the interconnectivity between the clay rich layers and seams as well as stratigraphic jumps of the sliding surface within the Fonzaso beds;
c) controlling the distribution of the joint sets characterizing the in situ rock mass.

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