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THE ROSONE LANDSLIDE (ORCO RIVER VALLEY, WESTERN ITALIAN ALPS): AN UPDATED MODEL

ABSTRACT: DELLE PIANE L., FONTAN D. & MANCARI G., *The Rosone landslide (Orco river valley, Western Italian Alps): an updated model*. (IT ISSN 0391-9838, 2010).

The Rosone landslide (Western Italian Alps) is a major sliding phenomenon affecting a metamorphic basement and periodically damaging the structures (tunnels and penstocks) of a nearby hydro-power plant. This paper presents the results of a recent study including field geology, seismic surveys and deep boreholes, investigating the poorly known deep structure of the sliding mass, as well as the geometry of the sliding surfaces. A synthetic comparison is made with another large landslide at Mt. Castello, showing some analogies with the Rosone landslide.

KEY WORDS: Rosone landslide, Gran Paradiso, Seismic surveys, Boreholes, Structural geology, Sackung.

RIASSUNTO: DELLE PIANE L., FONTAN D. & MANCARI G., *La frana di Rosone (Valle dell'Orco, Alpi occidentali italiane): un modello aggiornato*. (IT ISSN 0391-9838, 2010).

La frana di Rosone è uno dei più noti fenomeni gravitativi delle Alpi. Il fenomeno si sviluppa a carico di un basamento cristallino ed è causa del frequente danneggiamento delle strutture di un importante impianto idroelettrico, oltre che della passata delocalizzazione dell'abitato di Rosone. Questo contributo illustra i risultati di uno studio recente comprendente rilievi di terreno, prospezioni sismiche tomografiche e sondaggi profondi (fino a 300 m), il cui scopo è stato di investigare la struttura profonda del corpo in frana, fino ad oggi poco nota, e la geometria delle superfici di scivolamento. Viene presentato un breve confronto con un fenomeno analogo osservato nella stessa vallata, la frana del M. Castello, dove ricorrono condizioni strutturali predisponenti analoghe.

TERMINI CHIAVE: Frana di Rosone, Gran Paradiso, Prospezioni Sismiche, Sondaggi, Geologia strutturale, Sackung.

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We would like to thank the Company IRIDE S.p.A., owner of the hydroelectric power plants of the Valle dell'Orco, and Dr. Eng. Nicola Brizzo from the Company itself, for authorizing us to use the data derived from a feasibility study aiming to evaluate technical solutions to minimize the interference between the Rosone landslide and the existing hydroelectric installations.

INTRODUCTION

The so-called *Rosone landslide* is located in the Orco river valley (province of Turin, Italian Western Alps; fig. 1) and has been known since the beginning of the 20th century as an active phenomenon characterized by a slow yet constant evolution (Ramasco & *alii*, 1989; Forlati & *alii*, 1993; Luino & *alii*, 1993), repeatedly damaging some mountain villages and the Ceresole-Rosone hydro-power plant, presently owned by the City of Turin Electricity Board, IRIDE S.p.A. The penstocks and the diversion tunnel coming from the hydroelectric basin of Ceresole Reale have been suffering continuous deformations since the time of their completion, in 1929 (Bornati, 1930).

During the diversion tunnel construction, stability problems due to strong convergences in the underground charge tank area were caused by the presence of so-called «talcoschisti» (talc-schists) with very poor geomechanical characteristics, requiring the armouring of several tunnel sections (Bornati, 1930). The original diversion tunnel plan had to be successively abandoned for an inner and safer solution. Even today, continuous localized cracking of the concrete lining demands periodic maintenance. Deformations suffered by the penstocks along the landslide eastern margin made the adoption of adjustable bearings necessary, in order to maintain the penstocks alignment.

The Rosone landslide (fig. 2) is a typical but at the same time complex deep-seated gravitational sliding phenomenon affecting the pre-quaternary basement, made of granitic orthogneisses (fig. 3).

The basement is affected by a varying degree of disarticulation, with a gradual transition from an undisturbed to a fully disjointed rock mass, up to chaotic debris fields with large boulders and slabs of dislocated basement.

On the basis of its morphological characteristics, Ramasco & *alii* (1989) divided the sliding mass into three main sections (*Ronchi, Perebella, Bertodasco*) with different evolutional stages, from incipient to senescent. Instability at

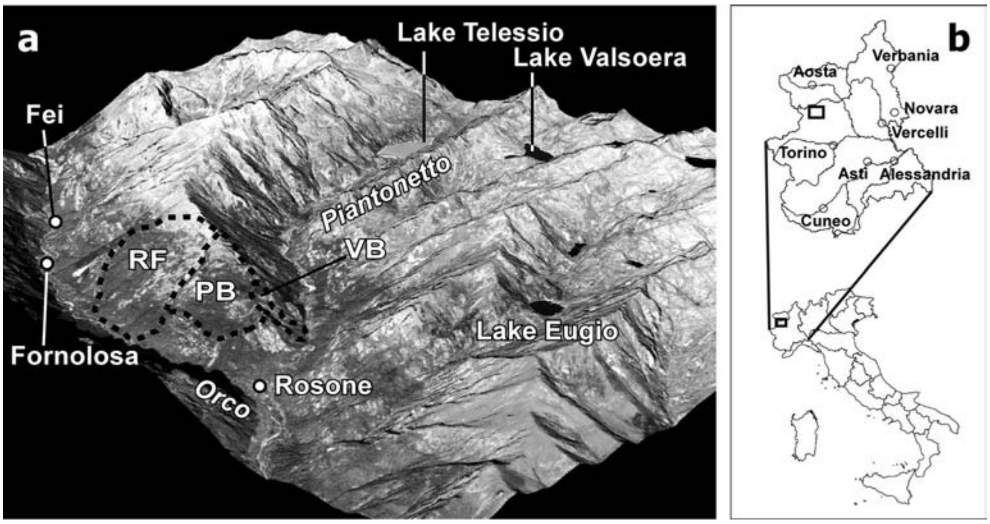

FIG. 1 - a: DTM of the Rosone area with indication of the landslide approximate boundaries (dotted line); b: geographic location.

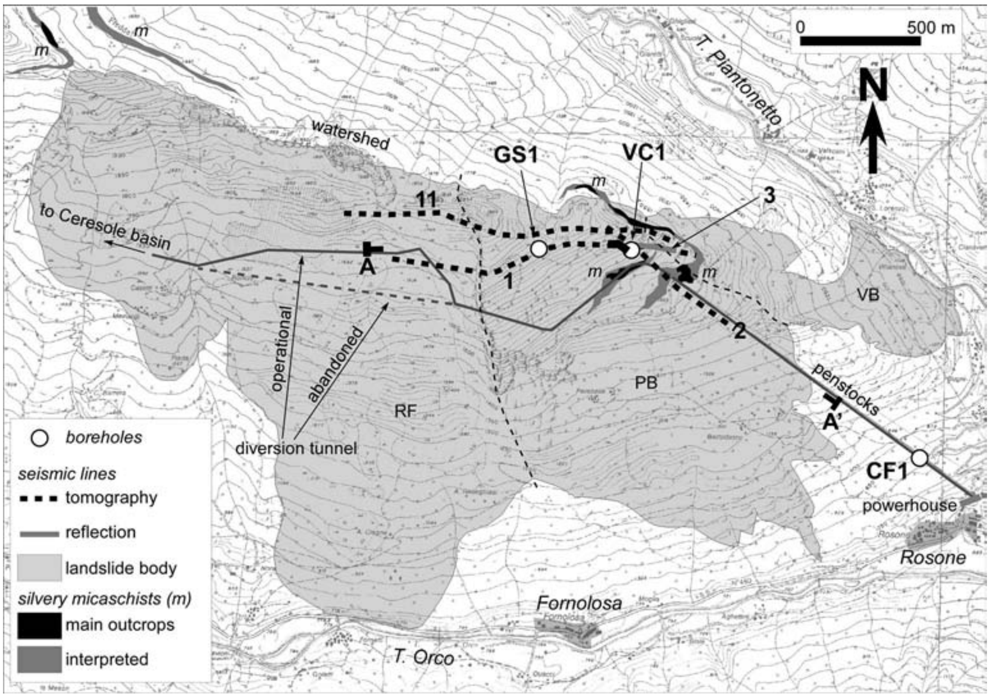

FIG. 2 - Synthetic map of the Rosone landslide area. The position of the IRIDE hydro-power plant and of the new investigations is indicated. RF: Ronchi-Fontane Fredde sector; PB: Perebella-Bertodasco sector; VB: Villanova-Buriat sector.

the landslide foot, suspended above the valley floor, originated in the past debris flows and rock falls, causing the old village of Rosone to be abandoned.

Since 1960, the eastern landslide margin (penstocks sector, fig. 2) has been the subject of several survey campaigns aiming to define the depth of the sliding mass and to monitor the movements; in this area, inclinometer-equipped boreholes show active movements down to a depth of 20-70 m, along a discrete sliding surface with an apparently planar shape, locally characterized by the presence of chloritic, non cohesive silt.

This sector is presently the most active one; instrumental data from an integrated monitoring system installed by IRIDE and by the Regione Piemonte, record continuous movements in the order of 21 mm/year; movements between 12 and 130 mm have been observed on the occasion of the October 2000 flood event alone (Amatruda & *alii*, 2004; Ramasco & Troisi, 2003). By interpreting the available data, Ramasco & *alii* (1989) supposed active movements down to a depth of 200-300 m in the slope sections far-off the penstocks.

In spite of the huge amount of data concerning the penstocks area, little information is available up to date on the higher part of the slope, i.e. on the main landslide body. A study campaign has been carried out in 2005-2006 on behalf of IRIDE S.p.A., aiming to define in detail the geological setting of the upper part of the landslide, where the diversion tunnel is presently located, as well as to evaluate the extension at depth of the interferences with the existing underground works.

Geological, structural, geomorphological and photogeological detailed surveys have been carried out, supported by deep boreholes, on-site and laboratory geomechanical tests and seismic surveys (deep tomography plus reflection seismic; fig. 6 and fig. 7). The obtained data allowed updating the reference geological model derived from previous studies, which include, in addition to the cited works, a large amount of unpublished data and reports retained in the IRIDE S.p.A. technical archives.

This contribution presents the results of this study campaign.

GEOLOGICAL SETTING

In order to better understand the causes and mechanisms influencing the landslide evolution, in the light of the new surveys, it is of some interest to recall some distinctive aspects of the regional geological setting in the studied area.

Lithostratigraphic setting

The Rosone landslide is located within the penninic Gran Paradiso Unit (GPU) cropping out, in the Orco valley, between the village of Locana to the E and the Nivolet pass to the W; it includes a pre-Triassic crystalline basement made of late-Carboniferous metagranites (the so-called «complesso degli ortogneiss occhiadini», about 280 My old) intruded into an amphibolite-facies basement (the present «complesso degli gneiss minuti») (Compagnoni & Prato, 1969; Compagnoni & *alii*, 1974; Vissers & Compagnoni, 1984; Dal Piaz, 1993). The augen gneisses locally preserve extensive relics of the original igneous textures (Callegari & *alii*, 1969).

In the Rosone area coarse-grained augen orthogneisses mainly crop out, with dominant quartz, centimetric K-feldspar porphyroclasts, plagioclase relics, red-brown biotite and phengitic white mica; the low-grade alpine metamorphic paragenesis is made of biotite-II, albite, white mica, epidote, ± allanite, chlorite, sericite; the original magmatic plagioclase is completely replaced by albite + sericite + saussurite aggregates (Baietto, 2002).

The low-grade Alpine main schistosity (Sp) coincides with the axial plane of large isoclinal to tight folds; an older schistosity (Sp-1) is preserved as a possible high pressure relic (SEA Consulting, 2000; Baietto, 2002; Momo, 2002). The K-feldspar defines a noticeable syn-Sp E-W trending stretching lineation with. Locally, mylonitic orthogneisses with tabular texture are found, reflecting the presence of syn- to post-Sp ductile shear zones.

THE "SILVERY MICASCIHSTS" (SM)

Within the GPU there is a characteristic association between orthogneisses and decimetric to decametric lenses of a) *silvery micaschists* (SM) with chloritoid + talc + quartz + phengite + Mg-chlorite ± glaucophane ± kyanite ± garnet and REE accessory minerals (Gabudiano Radulescu & *alii*, 2009), and b) Mg-chlorite schists with albite, quartz, white mica, biotite, epidote (MOMO, 2002). The gradual transition from the SM and the orthogneisses seems to indicate that the SM are directly derived from the encompassing granitic rocks (Compagnoni & Lombardo, 1974; Dal Piaz & Lombardo, 1986; Colombo, 1990).

These peculiar metasomatic rocks formed along high-pressure ductile shear zones, probably coeval with the eo-alpine metamorphic event. Metasomatism caused depletion in SiO_2, K_2O, CaO, Na_2O, Ba as well as enrichment in Al_2O_3, MgO, Ti, Zr, V, Sc (Colombo, 1990; Colombo & *alii*, 1994).

In the upper part of the Rosone landslide, metric levels of SM and of associated Mg-chlorite schists can be observed cropping out by the Perebella underground charge tank and west of it, beyond the watershed; the SM dip parallel to the main schistosity and to the slope facing the Orco river as well. They probably belong to a ductile shear zone cropping out discontinuously along both sides of the Orco valley (in particular, on the right side between the Cima di Deserta and the Lillet and Dres lakes; on the left side, between the M. Castello, the Alpe Loserai and the abandoned village of Chiapili). In our opinion this shear zone could subdivide the GPU in two tectonic sub-units: an upper, mainly mylonitic one and a lower, non-mylonitic one where the metagranites often have preserved magmatic textures.

The presence, within the SM of the Rosone area, of domains with a preserved Sp-1 foliation defined by Mg-chloritoid + garnet + rutile and by the talc-phengite-chlorite association, seems to confirm their origin in a high pressure metamorphic context (Momo, 2002).

Structural setting

The post-metamorphic structural evolution of the GPU had already been the subject of detailed analyses in the frame of a feasibility study for the renewal of the Orco valley hydroelectric plants (SEA Consulting, 2000).

The Rosone area is characterized by a structural association including a pervasive network of joint and regional faults with a polyphasic evolution (Perello & *alii*, 2004). On the field, two main subvertical joint sets can be observed: K1 (trending N-S to NNE-SSW) and K2 (trending E-W to ESE-WNW); a third set (KS) is parallel to the regional schistosity and to the silvery micaschists levels. K2 coincides with tension cracks and trenches allowing the rock mass dislocation by the watershed; K1 forms a lateral releasing system and KS is parallel to the main sliding vector (fig. 3).

The post-metamorphic structural evolution of the GPU probably had a decisive influence in determining the predisposing causes of instability. As a matter of fact, the landslide area lies by the SE termination of the so-called *Noaschetta fault*, a regional transpressive NW-SE fault, associated to a larger E-W strike-slip fault zone, which

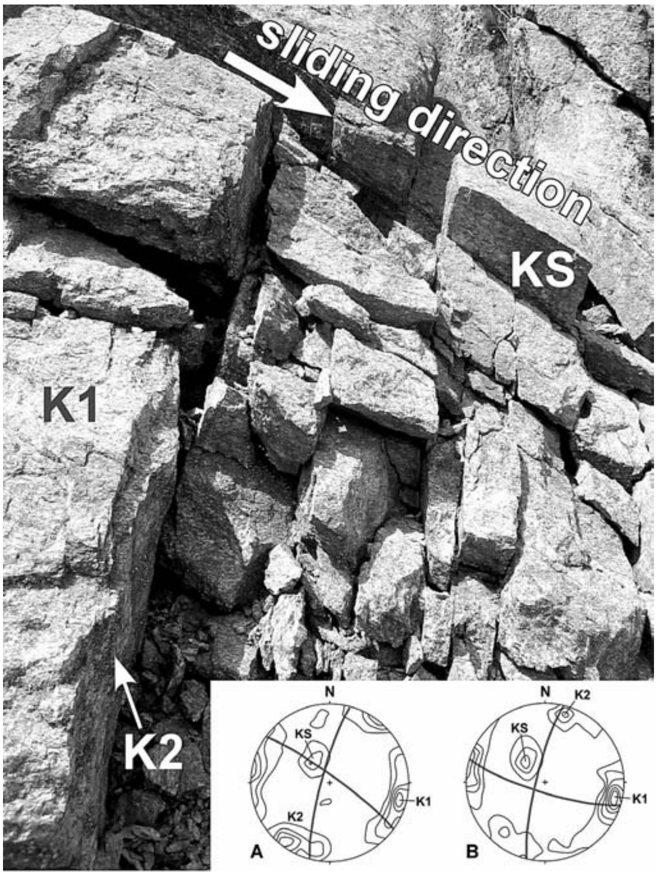

FIG. 3 - The typical structural association of joints in the Rosone orthogneiss; in the lower box: structural plots of the main discontinuity sets in the Rosone area. A: Noasca-Fornolosa sector (1127 data); B: Rosone-Eugio sector (911 data). Schmidt equal area projection, lower hemisphere, contour interval 1%.

seems to be a synthetic R-type shear (Perello & *alii*, 2004; fig. 4).

The sliding-affected slope would be located within the *step* between this fault and its probable SE prosecution, the so-called *Piano Reiner fault* (Perello & *alii*, 2004; fig. 4). Probably, the stress field associated to the deformation transfer between the two faults generated a swarm of minor faults which locally crop out on the field, significantly contributing to the rock mass weakening and favoring the later action of morphological factors, such as those of glacial origin.

From a kinematic point of view, K1 is consistent with the stress field that is supposed to be associated to the Noaschetta fault; a common age of these structural elements is testified by high-thermality mineralizations, composed by quartz, chlorite, albite, hematite, tourmaline, chalcopyrite and pyrite (Perello & *alii*, 2004).

Geomorphological outline

In the studied area there is a well-known and widespread evidence of complex sliding. The ridge between the

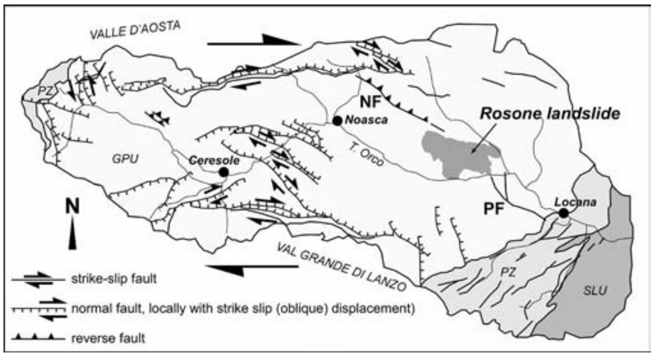

FIG. 4 - Structural sketch of the middle and upper Orco valley. The kinematics of the main fault systems suggest a possible dextral strike-slip regional stress field, with a late extensional reactivation. GPU: Gran Paradiso Unit; PZ: Piemonte Ophiolite Zone; SLU: Sesia-Lanzo Unit; NF: Noaschetta fault; PF: Piano Reiner fault (from Perello & alii, 2004, redrawn).

Orco and Piantonetto valleys is characterized by large trenches and sackungs resulting from the emersion of major cracks within the slope. Along the eastern landslide margin, especially above the penstocks, the basement outcrops are modeled by glacial erosion and form *roches moutonnées* where deep and up to 1 m-open cracks can be observed.

On the other hand, the western landslide margin is poorly defined, being characterized by widespread remodeling and by a detrital cover which masks any possible cropping out of fissures and sliding surfaces.

The main sliding body coincides with a vast debris expanse, originated by the complete dislocation of the basement rock. By the ridge area the basement is nearly undisturbed, while large downwards-settled and partially dismantled basement slabs are found within the main sliding mass; among these, is a long, 50 to 90 m high vertical rock wall in the central landslide sector.

The superficial portion of the slope shows evidence of composite secondary instability processes such as creeping and flow along nearly-circular surfaces and concave niches, involving the detrital cover and possibly part of the underlying dislocated basement, for a depth of about 30-40 m.

NEW SURVEYS IN THE ROSONE AREA

The 2005-2006 study campaign involved the carrying out of:

1) three deep continuous core-logging boreholes (fig. 5);
2) deviation, temperature and electric conductivity logs;
3) borehole hydro-fracturing and permeability tests;
4) geomechanical laboratory tests;
5) digital borehole cores high-resolution scanning;
6) deep seismic tomographies and reflection profiles exceeding a length of 3880 m (fig. 6 and fig. 7).

Boreholes

Three wire-line boreholes (fig. 5) have been carried out by the Italian firm NewGeoTecn S.r.l., using two drilling

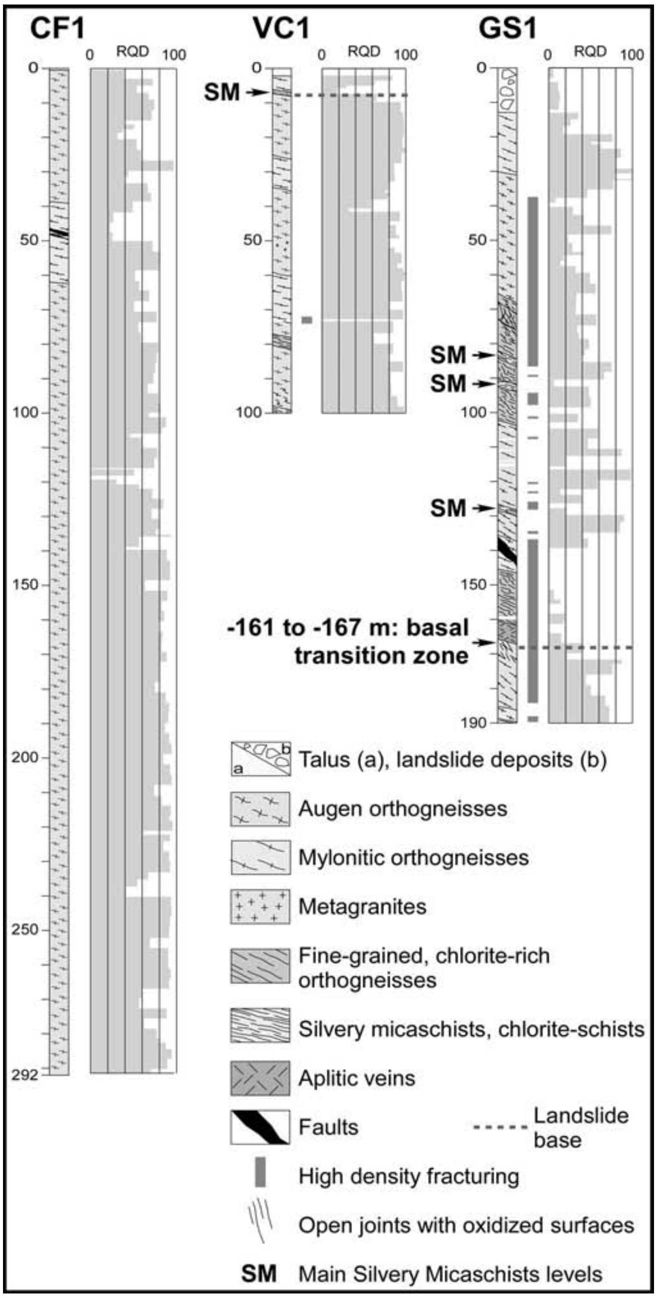

FIG. 5 - Synthetic borehole & RQD logs. Notice the discontinuous RQD in GS1, high RQD values above -163 m being related to competent rock slabs within the landslide. VC1 starts within the landslide and rapidly reaches a fairly sound basement, even though open fractures are recorded. CF1 is located outside the zone affected by movements.

rigs equipped for deep drilling and transported on site by helicopter (Boart Longyear L44; Puntel PX 410 AL).

The GS1 (alt. 1700 m, L = 190 m) and VC1 (alt. 1600 m, L = 100 m) vertical boreholes have been positioned within the landslide, above the existing diversion tunnel plan; the CF1 borehole (alt. 900 m, L = 292 m, inclination 40°) has been drilled below the supposed emergence of the main sliding zone, close to the existing penstocks.

BOREHOLE CF1

The borehole CF1 (fig. 5) investigated the inner part of the slope to assess the feasibility of a new underground penstock hypothesis. It has been drilled through coarse-grained augen gneisses and isotrope metagranites, locally grading to sheared, fine-grained gneisses, with Sp dip of about 30-40° to the SE.

The borehole didn't cross any significant tectonic structure or sliding plane, allowing to exclude instability to extend towards the lower part of the slope. The RQD values are in the range 40-60% in the first 40 m, are less than 20% between –40 and –50 m and vary between 60-100% from –50 to –292 m; an RQD fall from about –118 to –121 m is related to a moderate pressure water inflow (about 0.6 bar) causing groundwater to rise up to the surface with a constant flow of about 0.1-0.2 l/s. RQD values testify a good rock mass except some localized zones with open joints within the first 120 m.

The temperature variations are not significant: 12,6° C by the surface, 14,7° C at the bottom, with a sudden rise (from 12,9 to 14,1°C) between –104 and –118 m. Similarly, the electrical conductivity log carried out on December 4, 2005, didn't point out any particularity, with a trend from 86 ms/cm (surface) to 110 ms/cm (bottom), correlated to the temperature variations.

BOREHOLE GS1

The borehole GS1 (fig. 5) is the most important as it crosses the whole landslide body in its maximum thickness zone.

The borehole logged an heterogeneous rock mass, with partly or fully dismantled basement slabs, voids, friction-crushed rock zones, faults, SM levels and related clayey alteration products.

A nearly vertical fault zone with associated gouge and cataclastic breccias was encountered between –138 and –142 m; the fault is sub-parallel to the numerous fissures and trenches, trending E-W to ESE-WNW, visible by the ridge in the «Costa delle Fontane Fredde» sector.

Voids and wide-open joints are found up to –166.4 m; up to this depth, the recovery was discontinuous, often absent and accompanied by instability of the borehole walls. The RQD varies from 0 to a maximum of 50-60%.

The disturbed basement preserves some structural coherence, as pointed out by the constant Sp attitude (20°-40° towards the SE), attesting a prevalence of planar, schistosity-parallel sliding.

The main SM and chlorite-schists levels, characterized by weak geomechanical parameters, have been encountered between –83,0 and –85,0 m and between –90,6 and –93,0 m. However, as the recovery is very low, one cannot exclude that some altered, soft chlorite-schists have been crushed and washed out during drilling and that therefore they have been missed.

The rock mass is locally crushed by sliding-related friction, with strong grain reduction and concentration of chloritic or muscovitic silt along centimetric to metric sliding planes.

Below –166,4 m the GS1 crosses a less and less fractured rock mass whose RQD progressively rises up to 80%.

The groundwater absence reveals a highly permeable and drained rock mass even in the less fractured part, below the sliding base. Quantitative permeability data are lacking, owing to the impossibility of carrying out hydraulic borehole tests due to the constant fluid loss.

All along the borehole joints with diffuse oxidation are found, suggesting cyclic groundwater flow both in the landslide and in the undisturbed basement as well, up to -192 m at least. Morphological, seismic and core drilling data allow us to exclude, anyway, the presence of significant movements below -166.4 m.

BOREHOLE VC1

The borehole VC1 (fig. 5) has been carried out above the existing Perebella underground charge tank, to investigate the rock mass conditions where a new underground storage and charge tank could be planned.

The borehole met the undisturbed basement at –2 m, as one could easily foresee based on the presence of rock outcrops in the drilling site immediate surroundings. The borehole logged coarse-grained augen gneisses with mylonitic levels; between –6.4 e –6.9 m a SM horizon was found with aplitic lenses; no SM horizons have been found beyond this point. The Sp constantly dips 30° to the SE.

The rock mass is always poorly fractured, the RQD index varying from 20-60% in the first 10 m to 60-100% between –10 m and the borehole bottom (–100 m), highlighting a rock mass with fair to good geomechanical features; some open joints are found between –72 and –76 m, possibly being the cause of the continuous drilling fluid (water) loss observed both during drilling and the subsequent, unsuccessful attempt to carry out permeability tests.

The investigated basement is undisturbed, as no sliding surfaces referable to gravitational sliding have been found; nevertheless, active sliding in the sector immediately W of the drilling site caused the partial basement dislocation and, locally, the formation of voids. The cyclic groundwater flow in the rock mass is testified by joints with frequent oxidation traces, up to –74,0 m.

Borehole tests

PERMEABILITY TESTS

The only borehole where permeability tests could be carried out successfully is CF1; Lugeon tests pointed out a rock mass with very low permeability, as it is shown in tab. 1. No on-site data are available concerning the landslide body.

HYDRO-FRACTURING TESTS

To evaluate the stress state at different depths, some hydro-fracturing tests have been carried out in borehole CF1. The test interpretation (tab. 2) highlights a N150°E-directed maximum horizontal stress, which is consistent with a topographic effect enhanced by the steepness of the mountain side. No tectonic effects can be supposed on the basis of the obtained information.

TABLE 1 - Results of rock mass permeability tests in borehole CF1

Borehole #	Rock type	Depth (m from g.l.)	Test type	k [m/s]
CF1-Test 1	Gneiss	271-276	Lugeon	1.37 E-09
CF1-Test 2	Gneiss	280-285	Lugeon	5.08 E-09
CF1-Test 3	Gneiss	287-292	Lugeon	1.07 E-09

TABLE 2 - Results of hydrofracturing tests in borehole CF1

Depth (m from g.l.)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)
200	9.43	3.39	3.88
215	9.2	3.63	4.18
230	8.97	3.86	4.47
245	8.74	4.09	4.76
260	8.51	4.32	5.05
275	8.28	4.55	5.34
290	8.05	4.78	5.63
305	7.83	5.01	5.92
320	7.60	5.24	6.22
335	7.37	5.47	6.51
350	7.15	5.70	6.80

σ_H: maximum horizontal stress (mean value)
σ_h: minimum horizontal stress (mean value)
σ_v: vertical stress (mean value)

Geophysics

The seismic surveys carried out in the upper part of the landslide («Perebella» and «Fontane Fredde» sectors; fig. 6, fig. 7 and tab. 3) have been executed by PROGEO S.r.l., Forlì (I) and include three deep tomographies (cross-sections n. 1, 2 and 11) and a high-resolution reflection profile (cross-section n. 3).

Tomography n. 1 (fig. 6) is parallel to the watershed and runs between about 1350 and 1750 m passing by boreholes GS1 and VC1; n. 2 (fig. 7) follows the penstocks axis between about 1050 and 1650 m; n. 11 (fig. 6) runs parallel to n. 1 and north of it, towards the watershed; a reflection profile (n. 3) has been carried out along the same alignment of tomography n. 1, east of the intersection between the latter and tomography n. 2.

TABLE 3 - Geometric features of the seismic profiles

sector	nr.	type	L	geophones	
				nr.	spacing
Perebella/	1	tomography	1430 m	144	10 m
Fontane	2	tomography	710 m	72	10 m
Fredde	3	HR reflection	195 m	196	1 m
	11	tomography	1550 m	156	10 m

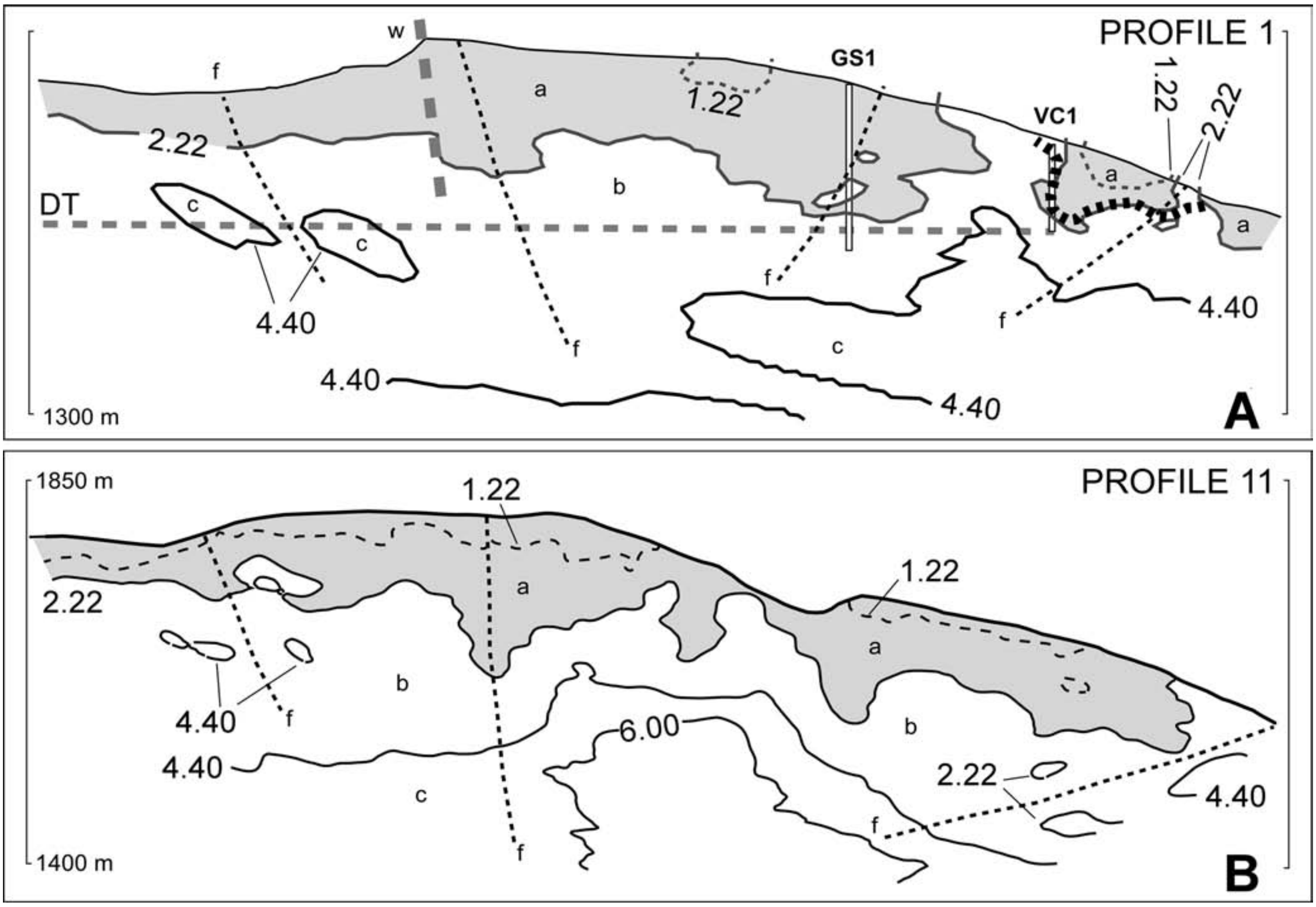

FIG. 6 - Cross sections along Vp seismic tomographies nr. 1 (A) and 11 (B). a: landslide; b: fractured rock mass; c: sound rock mass with massive layers (possible fold hinges or texture changes); w: surface limit between the western senescent sector and the eastern active sector; f: fault or fracturing zones (hypothetical). The black dotted line by borehole VC1 is the limit of the fractured zone as defined by the seismic reflection profile nr. 3. The apparently chaotic trend of the 2.22 km/s interface could be due to the presence of sub-vertical steps between fractured (low Vp) and less fractured (high Vp) rock, nearly parallel to the profiles plane, i.e. belonging to the K2 set (see fig. 3).

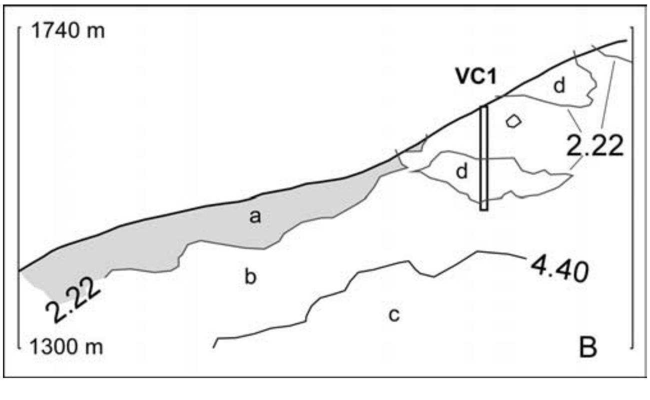

FIG. 7 - A: seismic tomography nr. 2 (Vp, km/s); B: simplified interpretative cross section. a: landslide; b: fractured rock mass; c: sound rock mass; d: low-Vp basement (lithological and/or textural changes).

The explosive-generated seismic impulses have been recorded by a 72-channels device with a 96-output selector, allowing to shift simultaneously the active channels without moving every time the recorder, provided that an adequate number of geophones is available.

The tomographic technique divides the volume crossed by seismic waves into a grid of small cells (1 m), allowing to evaluate very small variations in the P- and S-waves velocity distribution. Both the *velocity* (V, km/s) and *attenuation* (a, m/dB) parameters were analyzed; the former is used to evaluate the compactness of the investigated rock mass, the latter expresses the energy adsorption caused by inter-granular friction and fluid overpressure mechanisms, thus giving information about the fracturing density and, when expressed as ap/as, on the saturation degree as well.

TOMOGRAPHIC CROSS-SECTION N. 1

In this cross-section (fig. 6), the whole ridge area is characterized by very low Vp and a values, even at depth; a zone with Vp <2,22 km/s extends up to –160 m by borehole GS1; the correlation with the borehole stratigraphy allows to identify with good precision such limit as coinciding with the possible basal interface between the sliding mass and the undisturbed basement.

The attenuation parameter, which is particularly fracturing-sensitive, is low to very low (a < 10 m/dB) in the first 100-150 m from the surface in the central part of the section.

The rock mass fracturing geometry seems to be dominantly sub-vertical, in agreement with field data (K1 and K2 sets).

Tomographic cross-section n. 2

In the surroundings of borehole VC, the cross-section n. 2 (fig. 7) points out the presence of horizons with different P-wave velocity (due to alternating good and poor rock mass parameters), but with a fairly homogeneous attenuation. On the basis of field geological and structural data and of the VC1 stratigraphy, this seems to be most probably due to lithological variations (e.g.: repetition of augen gneiss and fine-grained sheared gneisses) rather than to a difference in the fracturing and dislocation degree.

The thickness of the fractured basement (a < 10.6 m/dB) is in the order of 50-60 m; some sectors with a <2.31 m/dB seem to be characterized by open joints. Slightly above the existing underground charge tank, the surface, or zone, that we interpreted as the base of the Rosone landslide presents a concave, niche-like shape; it extends downwards with irregular and step-like morphology, at a depth ranging between 20 and 40 m (Vp = 2,22 km/s isoline).

Tomographic cross-section n. 11

Cross-section n. 11 (fig. 6) coincides approximately with the Orco/Piantonetto watershed and scans therefore the upper part of the landslide.

The results are consistent with the geological model issued from other data: the possible landslide/rock interface (Vp = 2.22 km/s isoline) rises gradually towards the mountain ridge, by keeping itself parallel to the slope, in agreement with the morphological field observations.

The 2,22 km/s surface is very irregular in the E-W direction, which is most likely due to the presence of structural discontinuities influencing the morphology of the landslide base; the very fractured basement (Vp < 2.22 km/s) reaches a depth of as much as –160 m; the mean thickness of the Vp < 2.22 km/s zone is of about 100 m.

Within the landslide body some higher-Vp compact nuclei are found, possibly representing relatively undeformed, downwards shifted basement slabs.

High-resolution (HR) reflection cross-section n. 3

The HR cross-section n. 3 is superposed to tomography n. 1 from the borehole VC1 eastwards and shows a sequence of laterally persistent reflectors dipping towards the Orco valley; in the borehole vicinities a zone of higher noise could be related to higher fracturing. The lateral shifting of some reflectors, with a small central attenuated zone, could be interpreted as small fault planes or as open joints possibly dipping about 70° towards the ridge zone.

The superficial part of the cross-section doesn't show any reflector; by superposing this zone to the seismic tomography n. 2 we observed that it is characterized by low velocity and attenuation parameters, indicating a high fracturing degree.

Geophysical data interpretation

The tomographies highlighted the presence of major geophysical horizons, corresponding to Vp = 1,22 - 2,20 - 4,40 km/s, and a = 2,31 - 10,6 - 19,8 m/dB; such horizons coincide most probably to main variations in the physical state of the rock mass, therefore they can be interpreted as major interfaces within the landslide and at its base.

According to our interpretation, supported by the GS1 borehole stratigraphy, the main boundary between the landslide and the underlying undisturbed basement can be placed at the Vp = 2,22 km/s interface. Only for Vp > 4,00 km/s the rock mass can be considered sound enough to be treated as an homogeneous geophysical medium, whereas for Vp < 4,00 km/s it appears, from a geophysical point of view, «blurred» and fractured.

The matching of the tomographic isoline at Vp = 2,22 km/s with the lower limit of the very fractured rock mass in the reflection profile n. 3 (dashed line by the VC1 borehole in fig. 6) further supports this interpretation. In this section the landslide/basement boundary has a step-like morphology, which is probably due to the presence of sub-vertical joints coinciding with the main observed joint sets (K1, K2).

We think that the Vp = 2,22 km/s zone corresponds to a transition zone at least a few meters thick, rather than to a discrete interface referable to a single basal sliding surface, as is suggested by the GS1 borehole as well. In facts, the borehole highlighted a gradual but marked decrease in the fracturing degree below –160 m, but not any clearly identifiable basal sliding surface (and no basal SM as well).

At higher velocity and attenuation values (4.40 km/s < Vp < 6,00 km/s; a > 9.8 m/dB) several seismic structures with a mean attitude towards the E or the SE can be observed within the undisturbed basement; they are probably referable to nuclei of extremely compact rock, nearly parallel to the regional schistosity and possibly corresponding to large isoclinal (or sheath) fold hinges.

The low-Vp zones in the right part of cross-sections n. 1 and 2 are referable to lithological changes (coarse-grained augen gneisses and fine-grained sheared facies) rather than to the presence of a dismembered rock mass, as it is demonstrated by the VC1 borehole stratigraphy. This unexpected convergence in the seismic response from mediums with a very different geological meaning highlights the need for precise field borehole data, in order to properly calibrate the geophysical interpretation.

Geophysical features possibly referable to faults or major open fractures don't have, in general, a clear surface expression, owing to the low outcrop percentage. It must be observed anyway that the seismic cross-sections n. 1 and 11 run nearly parallel to all major structures (fractures, trenches, uphill facing scarps) observed in the field in the watershed sector, i.e. E-W to ESE-WNW; this could give way to misleading interpretations if not kept into account.

Geotechnical laboratory tests

In order to obtain a more complete picture of the characteristics of the pre-quaternary basement inside and outside the landslide, some geomechanical laboratory tests on 15 gneiss and micaschist samples extracted from the borehole cores have been performed (tab. 4), namely:
– volume unit weight determination;
– uniaxial compression strength with axial deformation control;
– indirect Brazilian-type resistance to tensile stress;
– Cerchar abrasiveness.

TABLE 4 - Laboratory tests results

Borehole #/ sample #	Rock type	Depth (m from g.l.)	γ (kN/m³)	ν (-)	C_o (MPa)	T_o (MPa)	E_t (GPa)	CAI
CF1/1	Gneiss	302.0-302.4	25.35	0.28	123.29	7.4	50.15	5.94
CF1/2	Gneiss	314.0-314.4	26.06	0.30	134.89	9.63	59.29	4.31
CF1/3	Gneiss	322.5-322.9	25.83	0.25	86.23	8.56	47.78	5.38
CF1/4	Gneiss	334.8-335.2	27.31	0.28	103.53	8.48	48.77	5.13
CF1/5	Gneiss	338.0-338.4	25.49	0.33	139.13	8.49	54.94	5.44
VC1/1	Micaschist	31.0-31.3	25.97	0.22	133.31	14.39	48.00	5.75
VC1/2	Gneiss	85.3-85.6	25.96	0.26	154.92	9.71	45.25	5.06
VC1/3	Gneiss	92.0-92.2	26.16	0.15	92.85	8.73	37.18	5.75
VC1/4	Gneiss	95.7-96.0	25.93	0.30	80.49	5.88	36.50	4.81
VC1/5	Gneiss	99.7-100.0	26.21	0.22	115.13	9.27	33.34	4.31
GS1/1	Gneiss	88.3-88.9	26.00	0.29	86.36	5.28	37.25	5.31
GS1/2b-GS1/2c	Micaschist	83.1-83.5	26.15	0.24	14.69	2.89	14.57	3.5
GS1/3a-GS1/3b	Gneiss	138.0-138.1	25.32	0.12	29.41	4.86	10.32	5.38
GS1/4b-GS1/4c	Gneiss	82.2-82.5	26.20	0.19	64.35	10.39	22.60	4.75
GS1/5	Micaschist	183.1-183.9	25.81	0.13	84.75	12.13	27.14	4.81

Legend:
γ: unit weight — T_o: tensile strength
ν: Poisson coefficient — E_t: tangent elastic modulus
C_o: uniaxial compressive strength — CAI: Cerchar Abrasiveness Index

It can be observed that all values derived from the tests in the micaschists show a wide range of variation; among the three tested micaschist samples, only GS1/2b.2c shows very poor parameters; this is due to the difficulty of obtaining sound and coherent samples, large enough for testing purposes, from the most altered micaschist levels; these could not be properly logged, also owing to the strong disturbance unexpectedly caused by drilling and coring.

Anyway, uniaxial compressive strength values lower than 0,15 GPa have been measured, which could further decrease in the altered micaschists horizons. Some particularly altered gneisses within the landslide show C_o values less than 30 MPa (e.g. sample nr. GS1 3a/3b).

The Cerchar test allows classifying the rock abrasiveness as a function of the Cerchar Abrasiveness Index (CAI), as shown in table 5. The tested samples, having a mean CAI = 5.0, can be in most cases classified as extremely abrasive lithotypes, owing to the high quartz content, typical of the orthogneisses and metagranites.

TABLE 5 - Cerchar abrasiveness indexes

CAI	Description
<0.3	non-abrasive/soft rock
0.3-0.5	slightly abrasive rock
0.5-1.0	moderately abrasive rock
1.0-2.0	abrasive rock
2.0-4.0	very abrasive rock
4.0-6.0	extremely abrasive rock
6.0-7.0	quartzitic rock

Summing up, the laboratory tests could define some of the main basic geomechanical characteristics of the intact to poorly fractured rock mass, both within the landslide and outside of it. It must be remembered that these values refer to *intact rock* (i.e. at the scale of the tested sample), rather than *whole rock*, parameters. The relatively high number of determinations assures a discrete statistical representativeness. On the other hand, we missed the possibility to properly characterize the geomechanical behavior of the weakest lithotypes, i.e. the *SM* and associated chlorite-schists, owing to the strong crushing suffered during drilling. Appropriate hand sampling of outcropping micaschists will be needed for further testing.

GEOLOGICAL REFERENCE MODEL

The results of this study allowed us to add some important elements to the generally accepted geological reference model of the Rosone landslide, in particular concerning the inner structure of the uppermost part of the slope, characterized by typical sackung landforms.

As regards the geomorphological setting of the active slope, a difference is confirmed between its western and eastern sectors; the former is characterized by a mature evolutional stage, highlighted by senescent landforms and by a significantly reduced thickness, as it has been shown by the seismic profiles; the latter is the most active and is characterized by a complex morphology, even at depth; in all cases, we point out that cracks of minor importance develop in the lining of the diversion tunnel section lying below the western landslide sector as well.

The boundary between the two sectors can be assumed to coincide with a vertical rock wall which extends along the maximum slope W of the abandoned mountain village of Perebella, forming the western boundary of a huge, settled slab. By supposing an originally homogeneous thickness of the downwards-sliding mass, the present rock wall height can give an indication of the volume removed by recent gravitative processes in the western sector, which is in the order of 100÷150 **x** 10^6 m^3.

As regards the slope facing the Piantonetto valley, E of the existing penstocks, a large rockfall lying on the opposite slope and originating from the watershed above the underground charge tank, appears to develop in continuity with the Rosone landslide. We named this sector *Villanova/Buriat*: the *Villanova rockfall* (fig. 8) originates from an area with a morphologically ill-defined ridge; there is little evidence of the detachment zone, located by a zone of smooth troughs separated by rounded ridges. The accumulation reaching the Piantonetto valley floor has been modeled to form two distinct mixed (detrital-alluvial) fans which apparently lie over the Piantonetto stream alluvial deposits. On the basis of the remodeling degree, the evolutionary stage of this rockfall is mature in the right part and senescent in the left part. The *Buriat rockfall* seems to be of rock avalanche-type, even if in the detachment zone some clue of possible planar sliding exists. It is bounded by a rocky niche about 20-30 m high; the rockfall covers the valley floor alluvial deposits.

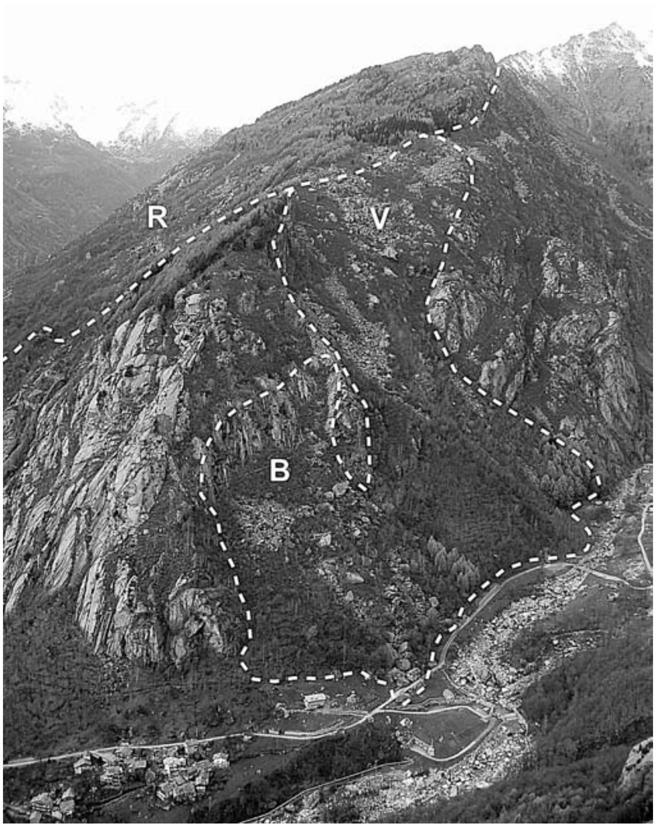

FIG. 8 - Aerial view of the Villanova (V) and Buriat (B) landslides; in the background the active eastern sector of the Rosone landslide (R) is visible.

The relationships between these two rockfalls and the main Rosone landslide are unclear but their age seems to be comparable and they originate from the same ridge area. Most probably, the gravitational sliding of the Orco-facing slope caused a marked instability on the opposite, much steeper slope as well.

The steep, exaration-related morphology and the ridge destabilization caused by the onset of movements along the Orco stream side could have favored the instability even in the absence of other predisposing structural elements.

Geometry of the base of the sliding mass

The interpretation of the results of the 2005-2006 survey campaign as well as the morpho-structural setting of the watershed, characterized by sackungs and uphill-facing scarps, suggest that the active (eastern) portion of the Rosone landslide is settling along more than one sliding surfaces, sub-parallel to the regional schistosity and locally coinciding with metric horizons of micaschists. Most of these surfaces trend are characterized by dominantly planar sliding; the most superficial ones are characterized by a more irregular shape and by complex movements (e.g.: rotational sliding, creep) partly related to the surface remodelling of the settling mass.

It is not possible to precisely define a discrete boundary between the sliding mass and the stable basement; a transition zone of a few meters at least has to be supposed instead, which can be identified with the geophysical horizon at Vp = 2,22 km/s, and coincides with a pronounced but gradual decrease in the rock mass fracturing density and the progressive disappearing of voids, oxidized open joints and friction-crushed levels. The transition zone can be possibly associated to *SM* or to chlorite-schists, which are anyway a discontinuous structural feature.

This gradual transition observed in the upper and central part of the settling mass clearly differentiates it from the eastern landslide margin (i.e. the penstocks zone), where the available borehole and inclinometric data seem to point out a single, discrete sliding horizon lying at a depth ranging from 20 and 71 m from the surface (Forlati & *alii*, 1993; Amatruda & *alii*, 2004).

The base of the landslide lies therefore, in the studied sector, at a depth of 160-170 m from the surface, rapidly deepening west of the penstocks; this sudden deepening occurs just a few meters W of the borehole VC1 (underground charge tank zone), as pointed out by the seismic cross-sections. Nevertheless, on the basis of the seismic surveys, the mean thickness of the sliding mass is in the order of 100-120 m, even if significant variations occur; this leads us to suppose an overall sliding-affected volume of about 190÷230x10^6 m^3.

The landslide/basement transition zone is marked out by nearly vertical steps, both parallel and perpendicular to the slope, which most probably can be put into correlation with the K1 and K2 joint sets. Westwards, the base of the landslide gradually reaches the topographic surface with a more regular trend, without any significant step.

At the foot of the chaotic landslide-generated debris accumulations no clear emersion of sliding surfaces and dislocation planes are observed and probably they are masked by the detrital cover. This basal zone is affected by secondary gravitational processes (creeping, small soil slips, debris flows and rockfalls) caused by the progressive dismantling of the debris accumulation, suspended above the Orco valley floor.

The metric levels of *SM* cropping out by the underground charge tank probably correspond to a local emersion of the basal transition (sliding) zone, because in this area the undisturbed basement outcrops are widespread. By extrapolating the structural position of these horizons it is possible to suppose that the base of the sliding runs under the detrital cover parallel to the slope, intersecting the valley floor between the villages of Fornetti and Fei, E of the village of Rosone. The absence of outcrops along the slope and at its base leads to some uncertainty, nevertheless such an hypothesis is consistent with the observed presence, on the right side of the Orco valley, of a *SM* zone extended at the scale of the GPU and recognized between the northern side of the Cima di Deserta and the Lillet lakes (SEA Consulting, 2000).

Groundwater

The boreholes carried out in the sliding mass (GS1) or at its eastern margin (VC1) pointed out the complete absence of groundwater, in addition showing a constant drilling fluid (water) loss.

The joint salbands oxidization, mainly related to the alteration of Fe-carbonates and sulphides, highlights the fact that the rock mass is cyclically affected by groundwater circulation.

The absence of a saturated zone at the base of the sliding mass indicates that the groundwater table is normally located within the underlying less fractured basement; the settling mass is therefore drained during most of the year, which in ordinary conditions is a stability favoring factor.

The permeability of the sliding mass is extremely high and the permeability contrast with the underlying undisturbed rock permeability is significant; when heavy rains occur, the undisturbed basement rapidly saturates, causing the water table to rise up to the base of the landslide (transition zone); there, the weak horizons (crushed rock and altered schists) are progressively saturated as well. The concomitant infiltration of water from the surface can follow intermediate local circuits set along shallower weakness horizons, thus favoring the onset of differential sliding velocities.

The modification of the ordinary hydrogeological equilibrium and the rising up of the basement-hosted water table are the main instability-triggering factor, as demonstrated by a close correlation between intense rainfalls and an acceleration of movements (Amatruda & alii, 2004; Binet & *alii*, 2006).

Predisposing causes

Many different features have been suggested in time to be the predisposing factors to sliding: i) the repetition of zones with very different alteration and fracturing conditions, ii) the high relief energy, the stress release related to the glacier retreat (Ramasco & *alii*, 1989), iii) the presence of silty material at the landslide/basement interface and iv) the supposed but, until today, not directly confirmed, presence of sliding planes along to the chlorite-schists levels (Forlati & *alii*, 1993; Luino & *alii*, 1993).

On the basis of the recent survey campaign, it is clear that the complex geometry of the sliding mass results from the interaction of structural, geomechanical and geometrical predisposing factors.

The main structural factors are:

a) the presence of slope-parallel weak horizons, represented by high pressure mylonites (the *SM*) and their retrograde products (the chlorite schists) and by the regional schistosity as well;
b) the post-metamorphic structural evolution, placing the Rosone area within the stress field associated to a regional strike-slip fault system (Perello & *alii*, 2004).

The main geomechanical factors are related to the degradation of the rock parameters, which is due to different causes:

c) the retrograde metamorphism of the *SM* and of the mylonitic orthogneisses, with development of chlorite-rich schists;
d) the friction-related alteration of the mica-rich levels and of the orthogneisses, generating secondary fine-grained products (uncohesive crush breccias with sub-centimetric rock fragments, chlorite-rich silt).

The morphological factors are related to the local topography determined by the intersection between the two glacial valleys of the Orco and Piantonetto streams, as well as by the presence of very steep slopes of glacial origin; the sometimes invoked stress release related to the glaciers retreat plays in our opinion a minor role with respect to the above mentioned factors, for two reasons: i) the glaciers may have disappeared in different times and with different modalities in the two adjacent valleys and ii) the nearby mountain slopes which underwent the same morphological evolution, yet in the absence of structural predisposing factors, are stable.

THE MONTE CASTELLO LANDSLIDE

We could find that the occurrence of an association of structural and morphological factors similar to that characterizing the Rosone landslide is at the origin of another large phenomenon, the M. Castello landslide, situated on the left side of the Orco valley, above the village of Noasca (fig. 9). It is an active and complex landslide involving both the pre-quaternary basement in the ridge area and the glacial deposits of the lower part of the slope. Its geo-

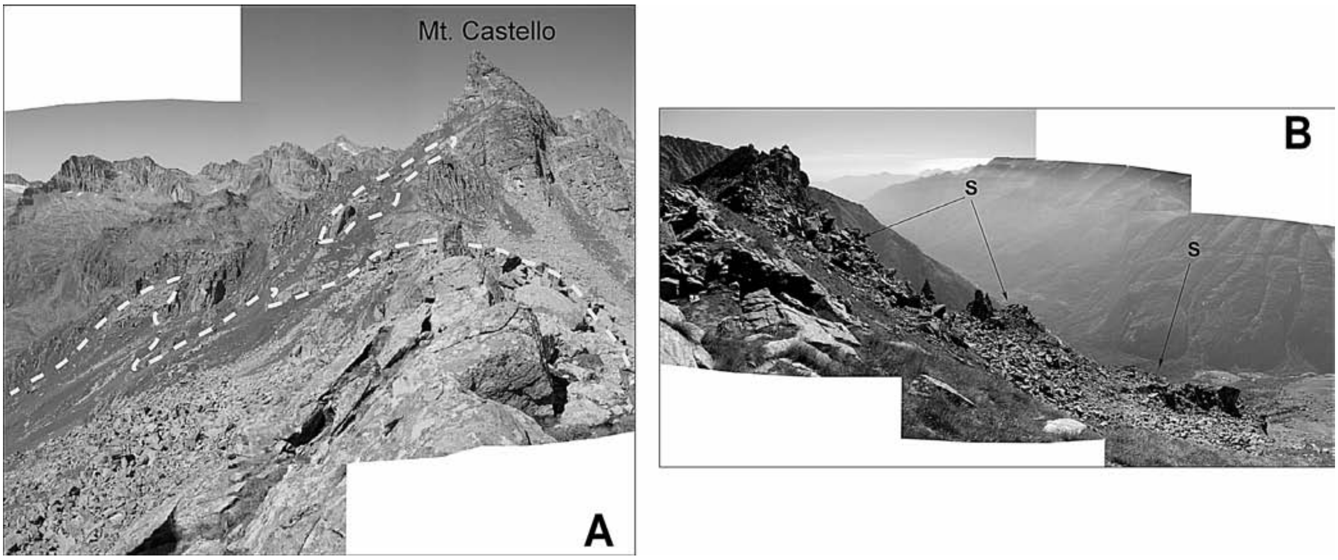

FIG. 9 - Compared to the Rosone landslide, the Monte Castello landslide is a more evolved phenomenon; the sliding mechanism in its upper part is analogous: slope-parallel silvery micaschists crop out in the ridge zone triggering instability. A: the upper, partly eroded landslide body (white contour). B: large slabs of relatively undeformed basement (s) probably gliding over silvery micaschists levels.

morphological setting is significantly different compared to the Rosone area, where a long ridge located between two large valleys of glacial origin is affected by gravitational processes; in this case, the sliding develops along a regular slope, facing a lateral valley of the Orco stream basin.

In the detachment zone a dismembered basement crops out, made of GPU coarse-grained augen orthogneisses; sackung, trenches and troughs trend parallel to the ridge line, being related to the same joint sets observed in the Rosone area (K1, K2); some basal sliding surfaces have been observed in the field to coincide with metric levels of slope-parallel silvery micaschists.

The higher part of the sliding mass is characterized by large boulders and basement slabs shifted by planar sliding, a feature similar to the Rosone crest zone but in a more mature stage; an incipient instability still persists, as suggested by toppling and tilting of numerous rock pillars.

In the intermediate and lower part of the slope, a more regular slope is made of a remodeled chaotic diamicton, referable to an ancient landslide deposit, under which the basement locally crops out. On the right side of this ancient landslide, between about 1700 and 1800 m, an accumulation of large rockfall-derived boulders lies on a flat area of *roches moutonnées*, suggesting that the instability was active at the time of the Ciamousseretto glacier retreat; such boulders could be the remnants of a large rockfall which might have reached the surface of the retreating glacier.

At the base of the slope, the landslide accumulation has probably obstructed, in the past, the Orco stream course: a chaotic deposit with cyclopic boulders lying on the opposite (right) valley side is clearly visible from the road going from Noasca to Ceresole; the accumulation climbs up the right valley flank up to about 1160 m. The damming of the stream course probably originated a small lake upstream, by the place presently called «Pian» («The Plain»); specific stratigraphic data are not available, nevertheless it seems plausible that in this point lacustrine sediments accumulated for some time, as it is suggested by the flat morphology of the area; such deposits are probably covered by recent alluvial deposits of the Orco stream.

Later on, the stream would have eroded the natural dam forming the morphological step by which are the hairpin bends of the road above Noasca. Mega-boulders from the landslide accumulation are distributed along the Orco stream bed, down to the village.

The intermediate to lower part of the landslide accumulation lies over a thin discontinuous layer of fine-grained, mainly saturated lodgment till, which crops out locally; this contributes to destabilize the landslide base, as happened during the October 2000 flood, when a 400 m long tension fracture flanked by two side fractures opened into the slope between about 1700 and 1900, involving an area of about 60.000 m^2 and a volume between 300.000 and 600.000 m^3.

CONCLUSION

The Rosone and M. Castello landslide are complex phenomena displaying on the one hand some senescent characters and on the other hand clear clues of diffused or localized activity.

The two landslides share, at least partially, common genetic factors and evolutional mechanisms; the detachment mechanism in the ridge area is in both cases of sackung/gravitational sliding-type, triggered by planar sliding along schistosity-parallel weakness horizons partly coinciding with talc-white mica and chlorite schists.

The upper part of the Rosone landslide is probably still active, as testified by cracks in the hydroelectric diversion tunnel lining; the upper part of the M. Castello landslide could be active as well, as it is locally characterized by juvenile landforms; instrumental GPS data and a more detailed study would be recommended, anyway, to confirm this. The intermediate portion of the M. Castello landslide, lying above the village of Noasca, is certainly active, as demonstrated by the movements related to the October 2000 flood; here, basement-seated planar sliding is no more the prevailing mechanism; rather, a saturation-dependent loss of cohesion within the debris cover lying on the slope and in the underlying lodgement till as well, can most probably be the dominant mechanism. There are no clues of the presence of saturated glacial till at the base of the Rosone landslide.

The analysis of the Rosone landslide shows how the inherited structural setting can generate predisposing conditions for the onset of gravitational sliding. The occurrence of a structural setting similar to that observed in the Rosone area can generate predisposing conditions for the onset of analogous phenomena, whenever structural and morphological factors interact in a similar manner. It is our opinion that, in the described situations, the weight of the structural factors is greater than that related to the commonly cited geomorphological factors which, alone, could not be sufficient to determine particularly critical instability conditions.

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