The Genesis of the Anomalous Sernio Fan, Valtellina, Northern Italy

E. De Finis, P. Gattinoni, L. Scesi

Abstract**—**Massive rock avalanches formed some of the largest landslide deposits on Earth and they represent one of the major geohazards in high-relief mountains. This paper interprets a very large sedimentary fan (the Sernio fan, Valtellina, Northern Italy), located 20 Km SW from Val Pola Rock avalanche (1987), as the deposit of a partial collapse of a Deep Seated Gravitational Slope Deformation (DSGSD), afterwards eroded and buried by debris flows. The proposed emplacement sequence has been reconstructed based on geomorphological, structural and mechanical evidences. The Sernio fan is actually considered anomalous with reference to the very high ratio between the fan area ($\approx 4.5km^2$) and the basin area ($\approx 3km^2$). The morphology of the fan area is characterised by steep slopes (dip $\approx 20\%$) and the fan apex is extended for 1.8 km inside the small catchment basin. This sedimentary fan was originated by a landslide that interested a part of a large deep-seated gravitational slope deformation, involving a wide area of about 55 km². The main controlling factor is tectonic and it is related to the proximity to regional fault systems and the consequent occurrence of fault weak rocks (GSI locally lower than 10 with compressive stress lower than 20MPa). Moreover, the fan deposit shows sedimentary evidences of recent debris flow events. The best current explanation of the Sernio fan involves an initial failure of some hundreds of Mm^3. The run-out was quite limited because of the morphology of Valtellina's valley floor, and the deposit filled the main valley forming a landslide dam, as confirmed by the lacustrine deposits detected upstream the fan. Nowadays the debris flow events represent the main hazard in the study area.

Keywords**—**Anomalous sedimentary fans, debris flow, deep seated gravitational slope deformation, Italy, rock avalanche.

I. Introduction

THIS paper deals with the Sernio basin-fan system (Figs. 1 and 2), which can be considered anomalous with reference to its geomorphological features. The main goal of the study is to reconstruct the emplacement sequence of the fan, pointing out the evidences that lead to consider this fan as the result of a rock avalanche. In particular, the failure mechanism and the subsequent dynamic processes are presented. Besides, implications for the residual hazard in the fan area are discussed, mainly in relation to the debris flow events. Actually, the development of sedimentary fans in Alpine areas is often affected by catastrophic processes associated with extreme flood or landslide events, causing serious hazard for people and infrastructures being on the fans. Hazard assessment in these areas depends on proper identification of the dominant sedimentary process. This last point has important implications for both hazard assessment and risk mitigation on fan areas. In most of alpine fans, the primary depositional processes are stream flows and debris flows [1]. Moreover, sedimentary fans in some alpine areas may still be influenced by paraglacial activity and landslide processes. A frequently used classification scheme of alluvial fans is based on statistical analyses of their morphometric parameters. Crosta and Frattini [1] use this classification for Alpine sedimentary fans and analyses fan gradient, fan area and catchment area of more than 200 fans in the Central Alps. These authors verify the negative correlation between fan gradient and catchment area as known from semi-arid and arid fan systems [2]. Within their diagram (Fig. 1) the Sernio fan plots far from the regression line between fan area and drainage area. The fan is then classified within the range of anomalous fans, and the exceptional accumulation of sediments was considered because of a single huge landslide event, probably occurred because of a prehistoric slope failure.

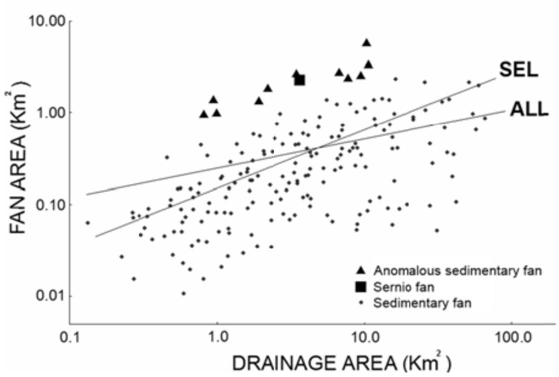

Fig. 1 The log-log plot of fan area versus drainage area (modified from [1]). ALL = regression line for the whole dataset; SEL= regression line for a selected dataset obtained by omitting anomalous fans

As it is evident, the Sernio fan is not the only one showing these features. Indeed great sedimentary fans, located at the mouth of small catchment basins surrounded by imposing scarps, have strongly contributed to model Alpine valley floors (e.g. Valtellina and Venosta valleys).

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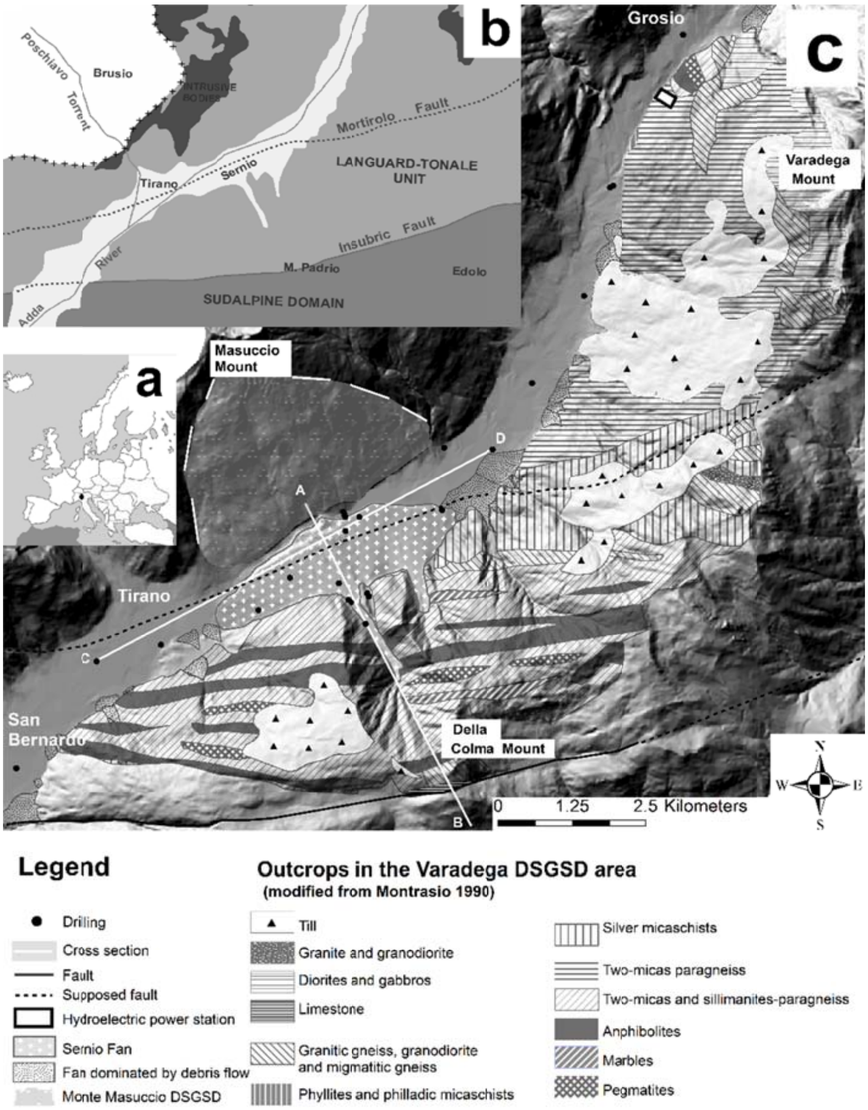

Fig. 2 (a) Geographic framework of the study area; (b) structural framework [6]; (c) Geological map of the Deep Seated Gravitational Slope Deformation in which the Sernio basin-fan system lies (lithologies from [8])

These fans often blocked the main valley floor, as landslide dams, then a silting process in the lake-basins upstream the fan happened. The outcome is a profile of the valley floor characterized by a series of morphological steps for several tens of meters in high perpendicularly to the main direction of the valley. Indeed the Sernio sedimentary fan created a step of 80 meters along the Valtellina's valley floor. In addition, the neighbouring sedimentary fans of Ponte in Valtellina and Migiondo show morphological steps along the valley floor of 50 m and 100 m respectively. Former authors speculate about the genesis of this type of fan. With regard to the Venosta Valley (Northern Italy), Jarman [3] suggests that the genesis of the Malser Haide fan, considered the greatest sedimentary fan in the Alps with a surface above 16 km², is due to a catastrophic landslide (among the five greatest landslides in the Alps). Guglielmin and Orombelli [4] interpret the Migiondo fan (Valtellina, Northern Italy) as the deposition of rock avalanches and debris flows connected with deep-seated gravitational deformations. In different geo-climatic contexts, other studies show the formation of new small basins because of large landslides. In particular Blair [5] points out that the fan of Nord Long John (Owens Valley, California) was caused by a big rock avalanche, responsible for the first sediments of the fan, that has left a great spoon-shaped scar in the fore part, forming a new small basin. Subsequent debris flow events along the basin buried the primary deposits of the rock avalanche.

As well known, rock avalanches can be triggered off by a number of different factors such as earthquakes, volcanic eruptions, heavy and long-duration rainfall, rapid snowmelt or a combination of these. The identification of the cause of a prehistoric event is therefore difficult; however, the analysis of the local and regional setting, as well as the analysis of the morphological and sediment logical structure of the deposits, can provide some insights about the emplacement dynamics. In the present study, the Sernio basin-fan system was reinterpreted as the result of a rock avalanche, eroded and buried by subsequent debris flows. At this aim, both the source area and the fan deposit were characterized based on the available subsurface data and detailed in situ surveys. In addition to geological and geomorphological surveys, ground investigations including 27 drillings, 70 geo-mechanical surveys, 147 Point Load Tests were carried out.

II. The Study Area

The Sernio basin-fan system (Fig. 3) is located in a large Alpine valley (Valtellina) which is situated in the central Alps of northern Italy (Fig. 2 (a)). Valtellina is an east-west-trending valley superimposed on the Insubric Line (named Tonale Line in Valtellina): an intercontinental subvertical plane of subduction, with a slight dips northwards. This Valley represents the upper drainage basin of the Adda River. Before, during and after the last deglaciation the valley was filled with fluvio-glacial, alluvial, lacustrine and landslide deposits.

From the geological-structural point of view, the study area is rather complex (Fig. 2 (b)). Two important sub parallel faults cross it: the Insubric Line, south, and the Mortirolo Line, north.

Fig. 3 Panoramic image of the large Sernio fan (in front), with its small catchment basin; the black line is the scarp nonlinear data to a higher dimensional feature space

Vertical movements and phenomena of right trans current characterize the kinematics of the Insubric Line. Because of this tectonic setting, the study area is composed of two main structural domains: the Sudalpine and the Austroalpine, the one separated from the other by the Insubric Line [6]. More in detail the Sernio basin is located just to the north of the Insubric Line bringing about a wide presence of fault rocks; therefore only the Languard-Tonale tectono-metamorphic unit (TMU) of the Austroalpine domain [7] outcrops, with the following lithologies: two micas and sillimanites-paragneiss; granitic gneiss, granodiorite and migmatitic gneiss; anphibolites, marbles and pegmatites (Fig. 2 (c)) [8].

From the morphological point of view, the study area is located within a DSGSD (Deep Seated Gravitational Slope Deformation) zone (Fig. 2 (c)) interesting an area of about 55 km², which extends from the Orobic crest (from Monte Vara dega at 2,639 m a.s.l., to the Monte della Colma at 2,142 m a.s.l.), reaching the Valtellina valley floor.

In the present climatic conditions, this sackung is moving toward the north of some mm/year at least in the eastern zone, as it is confirmed by interferometric data [9] and by the monitoring data of the penstock of a hydroelectric plant (Fig. 2 (c)). These monitors have indeed recorded the deformations of the penstock, connected with a movement of the slope regarding both the quaternary deposits and the bedrock [10].

Very closed to the Sernio fan, another DSGSD is present: the DSGSD of Mt. Masuccio (Fig. 2 (c)), which probably affects the Sernio fan evolution along its northern part.

III. Characterization of the Source Zone

The catchment basin which insists on the Sernio fan, called Valchiosa, covers a very small area of about 3 km² and extends from an altitude of about 1,100 m a.s.l. up to 2,142 m a.s.l. (Monte della Colma). Moreover, the hydrographic catchment presents a large and steep scarp that bounds the upper basin. This zone shows the arcuate bowl shape (Figs. 3 and 4), typical of the source area of a rock avalanche.

The head of the scarp is about 2,140 m a.s.l. and its base around 1,830 m a.s.l.. The length of the head scarp is 2.8 km. The Valchiosa basin is bounded by side-scarps (Fig. 4) having a length of about 7,850 m and it results neither very ramified nor carved. Within the basin, no evidence of glacial erosion can be detected and glacial deposits are present only above the scarp zone, which enables to consider the Valchiosa basin as a recent basin.

Along the head, there are morphological evidences typical of DSGSD: dividing of crests, trenches, counter slopes (Fig. 5 (c)), lowered blocks (Fig. 5 (b)). These blocks locally originate one cave arising from stress release. Furthermore, there is a series of main terraces, dislocated in smaller terraces. At present, the area surrounding the Valchiosa basin, characterized also by hummocky areas (Fig. 5 (a)), is prone to scarp retreat, with relating great detrition that originated several events of debris flow.

It was made an attempt, in this study, to reconstruct the pre-failure paleo-topography of the source zone in order to estimate the likely volume of debris involved in the collapse. Actually, by "best-guessing" the former contour lines and comparing them to the current situation it is possible to estimate the volume of lost rocks. Although the errors due to the use of this technique could be high, this estimate suggests that the landslide body contained a volume of up to 1,000 Mm³. The lithologies, outcropping in the source area, are granitic gneiss, granodiorite, migmatitic gneiss, two micas and sillimanites-paragneiss, with intercalations of amphibolite, marble and pegmatite. The geomechanical surveys carried out along the slopes of the source area (Fig. 4) showed schistosity mainly dipping towards South and an average dip above 50°, which in some cases reaches 90°. Smaller faults along the schistosity are in great numbers, even if they are differently oriented along the whole catchment.

The geostructural surveys show that the rock masses are characterized by a high degree of both fracturing and alteration. Actually an average value of Geological Strenght Index (GSI) equal to 32 ±16 was obtained (Figs. 6 (b)), with the lowest values equal to 5 especially in the northern area of the Valchiosa catchment, corresponding to the area with the most altered rocks (Figs. 4 and 5 (d)). Three samples were collected in order to characterize the mechanical strength of the intact rock. At this aim, Point Load Tests were carried out both perpendicular and parallel to the schistosity. Fig. 6 (a) shows the compressive strength values perpendicular to the schistosity (that are in greater number) pointing out that the highest frequency values are for the classes between 75 and 300 MPa. The values of compressive strength parallel to the schistosity are approximately halved. The average values of compressive strength perpendicular to the schistosity is 200 ±134 MPa and the average parallel to the schistosity is 106 ±72 MPa. These values indicate a fairly quality of the rock. Sclerometric tests also pointed out a very high ratio between uniaxial compressive strength perpendicular to the schistosity and apparent compressive strength, exceeding four times the unity, which indicates the considerable alteration of the outcropping rock masses, as confirmed by the GSI classification (Fig. 6 (b)).

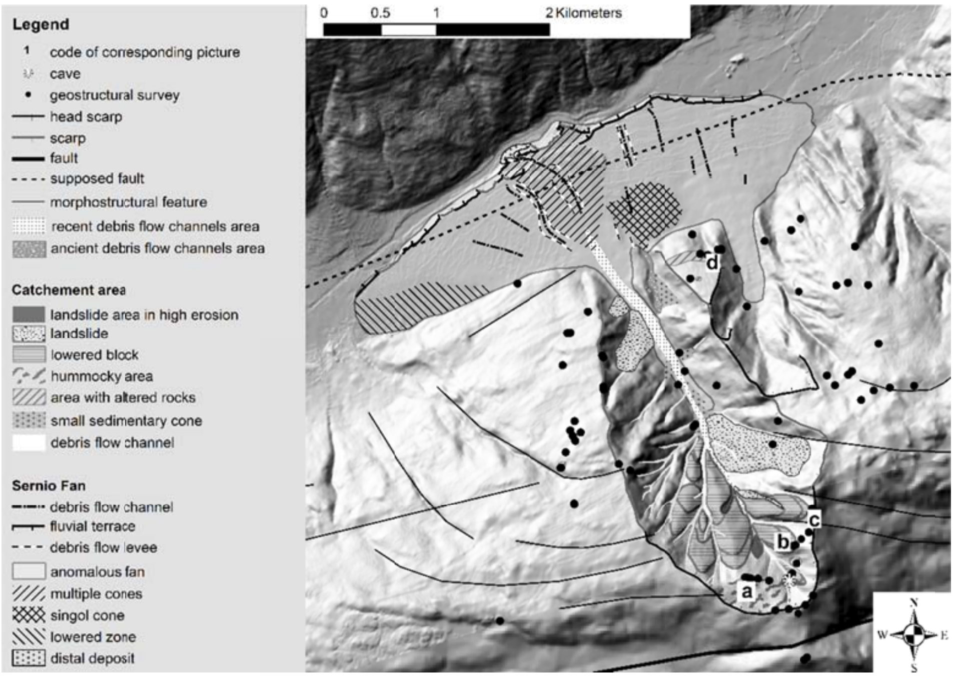

Fig. 4 Geomorphological map of Sernio fan-basin system

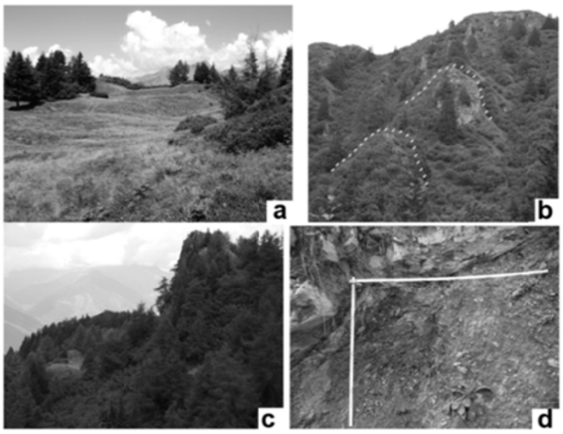

Fig. 5 (a) Hummocky area; (b) lowered blocks (identified by the yellow dotted lines); (c) detail of the main scarp area; (d) altered rocks in a fault zone

IV. Characterization of the Fan Deposit

The Sernio fan is particularly large with respect to Alpine standards having a surface of about 4.5 km² and an average slope of about 20%. The main stream, flowing in the main debris flow channel (Fig. 4), is characterized by a flow nearly equal to 0. This recent incision is located on the distal part of the cone surface, with direction SSE/NNW, and it enters in the Adda River at approximately 460 m a.s.l.. A peculiarity of this sedimentary fan is observed in Fig. 2 (c) that shows how its apex enters for about 1.8 km within the basin maintaining a smooth profile. The five drillings in the apical zone give no information about the substratum, they reach the maximum depth of 20 m. The altitude of the valley floor of Valtellina ranges from 420 m a.s.l. downstream of the Sernio fan to 500 just upstream the fan: therefore, the difference in altitude is 80 m approximately (see cross section CD in Fig. 7). The profile of the Alpine valley floor generally has a trend sub-horizontal downstream and upstream of the cone.

The volume of the cone was calculated as the difference between the DTM of the present Alpine valley floor (with Sernio fan) and the DTM of a hypothetical Alpine valley floor (before the edification of the Sernio fan). The height of the present valley floor of Tirano (420 m a.s.l.) was considered as the bed-surface of the cone. According to this hypothesis, the maximum thickness of the deposits is greater than 170 m (Fig.

7) and the cone is formed approximately by 525 Mm³ volume of debris. This is just an estimate: in fact in this area no survey is available to supply information about the real depth of the bedrock below the present Valtellina valley floor and therefore about the thickness of the quaternary deposits along this valley floor.

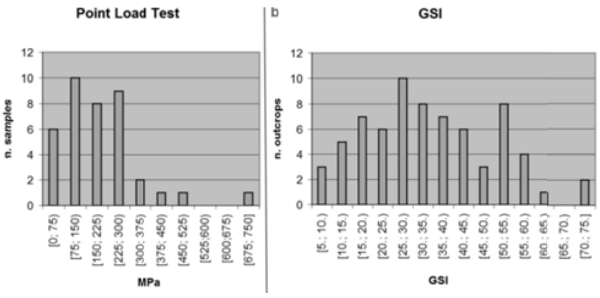

Fig. 6 Distribution of: (a) compressive strength perpendicular to the schistosity, (b) Geological Strength Index in each outcrop (Fig. 4)

One representative datum in neighbouring areas is represented by a reflection seismic profile located at a distance of 10 km west of Sernio [11]-[12]-[13]. It points out the presence of bedrock at about 180 m below sea level and 550 m below the present topographic surface.

Along the medial and distal zone of the fan the only available data are 5 drillings that reach a maximum depth of 70 m and do not intercept the bedrock, while the drillings downstream the fan show alluvial deposits up to 50 m depth.

On the other hand, the surveys upstream of the Sernio-cone detected silt-clay-deposits on the Quaternary Sequence, and they allowed reconstructing the presence of ancient lakes. Previous studies [14] show indeed three silt-clay levels located approximately at the following altitudes: a) 491 m a.s.l.; b) 499 m a.s.l.; c) 511 m a.s.l. respectively. Drillings beyond 5 km west of the artificial barrage do not show significant fine levels.

Therefore, it is possible to infer that the Sernio fan interrupted the course of the Adda River forming a barrage on the valley floor. Afterwards, the silting process of the lake-basin contributed to create the new profile of the valley floor. Subsequent smaller landslides might have blocked again the main water-course, as the valley floor is almost entirely occupied by this kind of sedimentary fan. This is what happened in front of the Sernio fan for example owing to the collapse of the foot of Masuccio in 1807 [15].

Afterwards the Adda River incised the Sernio fan deposit along a zone 100 to 250 m wide. So at present the distal part of the Sernio fan presents a deep (up to 80 m depth) and extensive (3.6 km) scarp (Figs. 3 and 7), particularly affected by slope instabilities.

Photographic and photogrammetric surveys were carried out along the whole scarp, by an Unmanned Aerial Vehicle (UAV) too, allowing detecting a very significant sedimentary structure, which is constituted by a channel of debris flow entirely filled with subsequent events. Besides the analysis of DTM pointed out that the genesis of the most superficial and distal zone of the fan is due to the repeated events of debris flow. Every new debris flow formed new deposits and has also partly eroded and demolished former deposits.

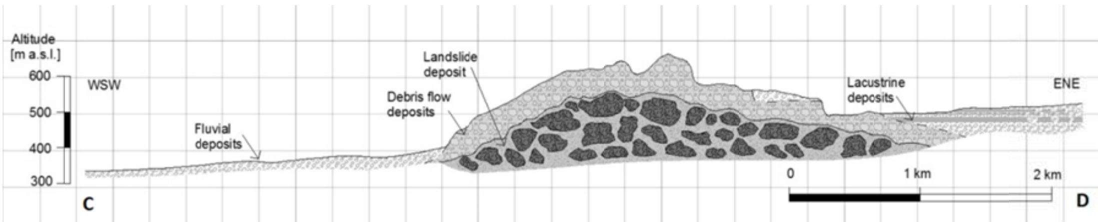

Fig. 7 Geologic cross section through the Sernio fan (location in Fig. 2 (c))

V. Proposed Emplacement Sequence and Residual Risk

Based on the previous description, in the present section the characteristics of the emplacement event are considered. The fan of Sernio is certainly subsequent to the Last Glaciation, like all the fans in Valtellina valley floor. During the LGM, the Adda glacier demolished indeed the fans of this Alpine valley floor, taking away their deposits. Afterwards, the evolutionary history of this fan could be more complex than the history of other fans; and the lack of dating and depth data makes the interpretation even more difficult. However, relying on the observation of the geological-geomorphological features of this study an event of rock avalanche is very likely to have created a Valchiosa proto-catchment.

The most likely trigger event is a strong ground motion during a large local earthquake. The main controlling factors of these deep-seated landslide features could be tectonic, in consideration of the proximity to the regional fault system (i.e. Insubric Line, Mortirolo Line) and the consequent occurrence of fault rocks.

The rock slide initiated in heavily jointed rocks: a prominent joint set dipping downslope with a dip angle of 65° formed the main sliding surface, while a subvertical backscarp extended up to the crown at 2,140 m a.s.l. in altitude (Fig. 8). The motion distance is up to 4,650 km from its source area, along a direction normal to the ridgeline. Having a source scarp and knowing the direction of the runout, the following question arises: how did it move? The answer to this question is doubtful, even if one of the "best guess" would be the transformation of the initial rock slide into a rock avalanche. The horizontal distance from the head of the scarp to the toe of the landslide (L) is about 4,650 m, with a vertical fall of 1,590 m from the top of the headscarp to the lowest point at the toe of the deposit (H), which yields a H/L value of 0.341. This value can be used to calculate a quite low apparent friction coefficient of about 19°.

The absence of sheepbacks in the scarp zone and glacial deposits in the basin suggests that the rock avalanche event is subsequent to the Last Glaciation. It formed a debris-body characterized by a very uneven topographic surface (Fig. 8), which is typical of the rock avalanche deposits; no data is available to define the volume of the blocks constituting the rock avalanche deposit. These blocks would have crossed the Valtellina valley floor extending both downstream and upstream with regard to the direction of the Valchiosa axis, and would have blocked the course of the Adda River as confirmed by the presence of lacustrine deposits (Fig. 7). The glacial deposits involved in the collapse would then be limited to the debris covering the pre-event substratum. The thicknesses of these glacial deposits can be valued like that of the present deposits observed in some areas of scarp.

Comparing the morphologies of the fan-basin systems of Malser Haide (Val Venosta - Norther Italy), considered by Jarman [3]. one of the five greatest areas of landslide in the Alps, and the fan-basin systems of Sernio, it is possible to note important analogies: apical zone of the fan situated inside the catchment basin for several hundreds of metres, very wide scarp subtending the catchment, very high ratio between fan surface and catchment surface. With reference to the recent history of the sedimentary fan, the observation of the DTM and the survey of the distal scarp allowed to identify, along the present topographic surface, recurrent events of debris flow. In particular, it is possible to reconstruct at least four events of debris flow, directly downstream of the Valchiosa catchment in the distal zone (multiples cones Fig. 4). The more recent events, that built the small fans at lower altitudes, demolished in part former deposits. Repeated events of debris flow would have modified more and more the surface topography of the fan: indeed it has become more and more regular and smooth (Fig. 8), hiding former chaotic deposits, arising from the rock avalanche. Nowadays debris flows represent the most important source of risk for the Sernio fan and in general for the fans with the same morphology. Available monitoring data of very similar fans (Gadria, Val Venosta in northern Italy) point out return times even less than one year [16].

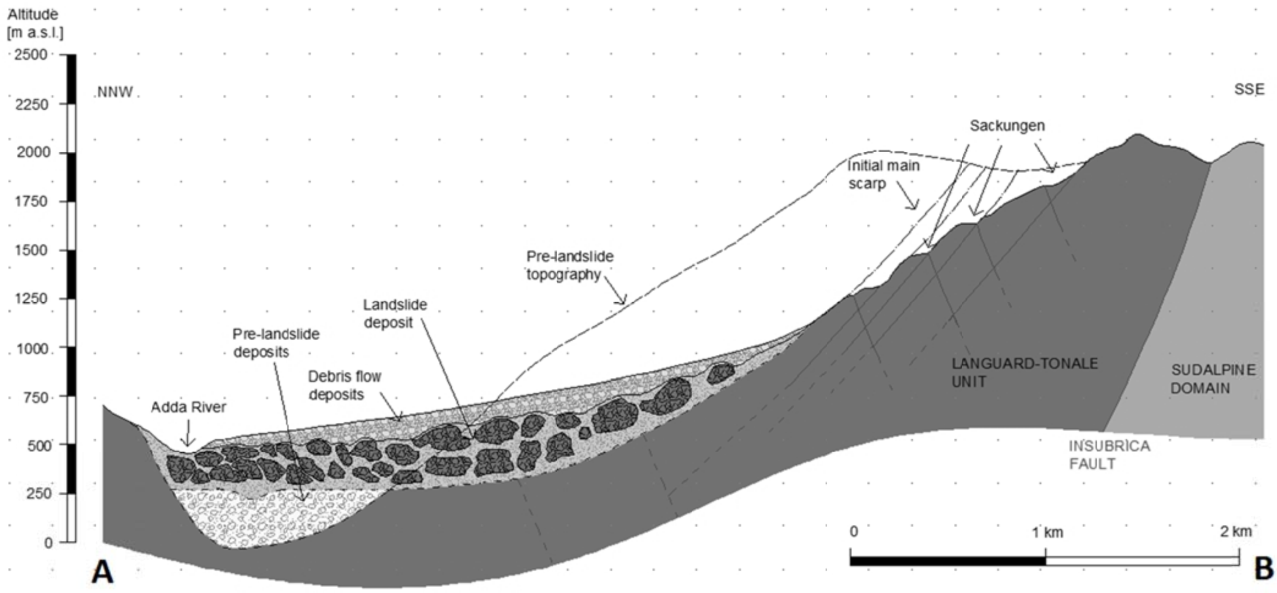

Fig. 8 Geological cross section through the Sernio fan-basin system (location in Fig. 2 (c))

VI. Conclusion

This research allowed reconstructing the formation and evolution of the Sernio fan-basin system, considered anomalous because of its high ratio between the cone area and the catchment area. Based on the available data, its genesis is attributable to a rock avalanche originated in a deep-seated gravitational deformations area. This catastrophic event created the Valchiosa catchment and a fan-shaped landslide dam along the valley floor of Valtellina, which is also attested by the morphological step (about 80 m high) originated by the same cone with the Valtellina valley floor.

The identification of the Sernio fan as a rock avalanche deposit raises several important issues for future hazard analysis. Firstly, it suggests that massive landslides may be more common than previously thought in Alpine area, even if further studies of other deposits are required in order to understand how frequently such events occur in this region, especially those close to main faults.

The recent history of the sedimentary fan is instead dominated by several violent events of debris flow, occurred in different times. These events have entirely covered former deposit. Therefore, considering the morphological characteristics of this fan-catchment basin system, it would be useful to study the dynamic of debris flow along these kind of sedimentary fans, characterized by a very wide apical zone inside the hydrographic catchment. For this reason, future research will be aimed to understand if the particular feature of the fan can affect the debris flow path and its evolution.

Finally, nowadays the intrinsic fragilities characterizing fans dominated by landslide are especially: the difficulty of water-supply and the instability of both the head of the catchment and the scarps in the distal zone [14].

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