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Anomalous Alpine fans: from the genesis to the present hazard

Abstract The present paper aims at characterising Alpine anomalous basin-fan systems, in order to develop a method for hazard assessment for such fans. The review of previous studies revealed that anomalous basin-fan systems are often associated with deep-seated slope failure and present-day hazard is associated to debris flow occurrence. Taking into account these peculiarities, a modelling approach to assess the present day hazard in anomalous fans has been developed and applied to the Sernio fan (Valtellina, northern Italy). Debris flow inundation areas have been simulated by means of a numerical model (RApid Mass MovementS (RAMMS) debris flow), which includes a routine for the sediment entrainment. The range of the model parameters was defined based on previous studies, enabling a sensitivity analysis on the debris flow runout, as well as the flow height and velocity. Numerical results point out the paramount importance of entrainment phenomena on debris flow dynamic in anomalous systems, especially with reference to the bulking factor and debris yield rate that reach very high values, typical of basins with unlimited solid supply.

Keywords Anomalous fan · Debris flow · Hazard · Numerical modelling · Italy

Introduction

Large fans characterised by a high ratio of fan area to upstream basin area, hereafter referred to as anomalous fans, occupy a distinctive position in the frame of Alpine fans. Their imposing size has a striking influence on the morphology of Alpine valleys, which involves both the transversal valley profile and the longitudinal profile of the main river. The assessment of present hazards on these fans requires a wise recognition of active hydrogeomorphic processes, which can be similar or substantially different from those responsible for the initial formation of the fans. Jarman et al. (2011) studied large fans in Val Venosta-Vinschgau (northern Italy). They classified two types of alluvial fans: (1) allometric fans, remarkably proportionate to the area of their basin, built incrementally through depositional processes connected to stream and debris flows; (2) anomalous fans, characterised by excessive volume over and above normal production by conventional incremental processes, with genesis attributable to one or more catastrophic events.These authors further divided anomalous fans into two groups: "outsize fans" and "megafans", the latter featuring areas between 3.4 and 16.5 km^2 for basin areas between 5.3 and 18.6 km^2.

Examples of these anomalous fans can be identified all over the world, and some of them are located along the main valleys of the Alps (Crosta and Frattini 2004; Marchi et al. 2010; Jarman et al. 2011). As these areas are often characterised by an intense urbanisation, it is very important to assess their potential hazard. The main hazard in anomalous basin-fan systems is usually related to the occurrence of debris flows (De Finis et al. 2017a), favoured by the presence of large amount of loose debris in a small rugged basin with steep slopes. These conditions also control the runout process of debris flows in anomalous systems, with entrainment process being the controlling process to determine the magnitude of the event. Consequently, simulation of entrainment phenomena is crucial for numerical modelling of debris flows in anomalous systems.

Starting from the definition of anomalous fans proposed by the literature, the present paper aims at identifying the peculiar features of these systems, with reference to their genesis and their actual hazard ("Origin and main features of anomalous fans"). Based on previous studies in anomalous fans (De Finis et al. 2017b), in the present paper, a modelling approach was developed in order to predict debris flow hazard in anomalous systems ("Present hazards in anomalous fans"). The pseudo-3D model rapid mass movements (RAMMS) debris flow (Christen et al. 2010) was chosen among the several numerical models available to simulate debris flows, such as DAN-3D (Hungr 1995), FLATModel (Medina et al. 2008), MassMov2D (Bergueria et al. 2009), Trent2D (Rosatti and Begnudelli 2013), and r.avaflow (Mergili et al. 2017), which implements the general two-phase mass flow of Pudasaini (2012). RAMMS DEBRIS FLOW is a single-phase model, based on the Voellmy-Salm rheology (Salm 1993), which simulates the motion of the mixture as a homogeneous mass flow (bulk flows). RAMMS DEBRIS FLOW contains an experimental tool able to simulate entrainment phenomena (Schürch et al. 2011). The numerical model was applied to the Sernio fan, an anomalous fan located in Valtellina (northern Italy) ("Example: the Sernio anomalous fan"). Finally, the results are discussed and conceptual models of genesis and development of anomalous basin-fan systems are proposed ("Discussion and concluding remarks").

Origin and main features of anomalous fans

Anomalous basin-fan systems are characterised by very large fans formed at the outlet of small basin, and they can be defined as systems having a ratio between fan and basin areas higher than 0.2. The origin and evolution of the Alpine anomalous fans display distinctive features, often different from other fans.

The analysis of some historical rock avalanches (i.e. the landslide happened in 1881 at Elm in Switzerland, Hsü 1975) highlighted how this type of landslides can generate new hydrographic basins. In the international literature, there are many examples about large landslides inside small basins, causing the formation of anomalous fans (Table 1).

The formation of other anomalous fans has been ascribed to debris flows, which, because of local structural conditions, occur with high frequency and may involve large sediment volumes (e.g. Marchi et al. 2002; Comiti et al. 2014), which is consistent with the large availability of loose debris within the basin. As an example, in the Manival alluvial fan, which is one of the largest in the French Alps (4.3 km^2) and is located at the outlet of a 3.6-km^2 basin (Lopez Saez et al. 2011; Theule et al. 2012), intense debris flow activity is favoured by underlying geology, which controls location and development of rock couloirs and gullies (Loye et al. 2012). Loye et al. (2012) have proposed a conceptual model for the

Table 1 Examples of anomalous fans in the international literature, with their origin and main features

Location	Reference	Origin	Morphological features
North Long John fan (Owens Valley, California)	Blair (1999)	A large rock avalanche (subsequent debris flows partially buried the primary deposits of the rock avalanche).	Small basin and a fan-shaped deposit, characterised by a high spoon-shaped scar in the front part, lack of a drainage network, and large amount of loose sediments
Migiondo fan (Valtellina, northern Italy)	Guglielmin and Orombelli (2001)	Rock avalanche	Very high and steep scarps in the distal zone of the fan. Evidences of deep-seated gravitational slope deformation (DSGSD) in the basin, with the flowing zone of a rock glacier (but without its origin zone)
Malser Haide fan	Jarman et al. (2011)	Rock avalanche and subsequent debris flows	The fan is the largest fan in the Alps (with an area of more than 16 km^2), and it shows evidences of recent debris flows
Tibetan fan of Zhamu	Xu et al. (2012)	Two recent rock avalanches	The sediments originated from the two events can be identified along the scarp of fan

development of the geomorphic features involving a structural control of erosion in small Alpine catchments that may result, as in the case of Manival, in the formation of an anomalous fan. Another anomalous fan generated by debris flows is the Arroyo del Medio fan (northwest Argentina), which covers an area of approximately 9 km^2: no evidences of large scale landslides are reported (González Díaz and Fauque 1987; Marcato et al. 2009, and references therein), whereas rock falls in the headwaters are responsible for large availability of loose material in the debris flow source areas. Remarkably, debris flow-generated anomalous fans can be associated to different basin lithology.

A quite common feature of the anomalous fans can be detected in the main valley. Actually, the landslide body or massive debris flow deposits that form the fan can also block the main valley, therefore damming the receiving river. Unless failure of the landslide dam occurs shortly after channel blockage (Costa and Schuster 1988; Korup et al. 2006; Tacconi Stefanelli et al. 2016), a silting process in the lake upstream the fan takes place (De Finis and Bini 2014). The result of these processes is a profile of the valley floor often characterised by a morphological step several tens of meters high.

In synthesis, based on its typical morphological features, anomalous fans can be defined as fans having:

- Ratio between the area of the fan and the basin area higher than 0.2 (Fig. 1a);
- High and steep scarps at the fan toe (Fig. 1b);
- Wide landslide scarps characterising the head of the basin or, at least, a part of this (in particular in anomalous fans dominated by landslide);
- Large amount of sediments within the basin, because of the lithological and structural weakness of the outcropping rocks;
- The fan apex moved backward within the basin (Fig. 1c);
- Frequent presence of silty deposits in the main valley upstream of the fan, with a morphological step along the longitudinal valley profile.

Present hazards in anomalous fans

At present day, the main hydrogeomorphic hazard in anomalous basin-fan systems is related to the occurrence of debris flows (Cavalli and Marchi 2008; Comiti et al. 2014; Loye et al. 2012), favoured by the small size of the basin, the availability of large amount of debris, and the high slope both in the basin and in the fan area. These conditions can also affect the runout process of debris flows in anomalous systems: considering the same rheological conditions, they can enhance erosion and entrainment processes and then increase the magnitude of the event. Actually, the entrainment can increase the volume of the debris flows even by several orders of magnitude (Hungr et al. 2005; Coe et al. 2008; Iverson et al. 2011; McCoy et al. 2012, and references therein; Frank et al. 2015), depending not only on the rheology of the flow, but also on the availability of debris along the flow path. Being a large amount of debris typical of anomalous systems, with the same rheological conditions, the enhancement of volume arising from entrainment in anomalous systems can reach very huge values. Unfortunately, in the scientific literature, there are few cases of anomalous basin-fan systems in the Alpine area, in which the frequency and magnitude are monitored. Available monitoring data of Gadria basin (Val Venosta, northern Italy) point out average debris flow frequency of approximately one event per year, with debris volumes reaching 40,000 m^3/y (Comiti et al. 2014), in which the source volume is estimated to be 10–20% of the depositional one (De Finis et al. 2017b). Similarly, along the Illgraben river (Switzerland), every year debris flows involve about 100,000 m^3 of sediments, with an erosional rate equal to 0.25 m/s (Frank et al. 2015).

As data arising from monitoring systems in anomalous systems are seldom available; a suitable way of evaluating the relevance of entrainment phenomena in these systems, and then the related hazard for the fans, is a parametrical study based on a modelling approach. Therefore, starting from the few available data previously described, in the present paper, a parametrical modelling of debris flow in an anomalous system is proposed, in order to reproduce and point out the peculiar features of debris flow dynamic, especially in terms of volume increasing.

Debris flow modelling method

In order to model the debris flows, various types of simulation approaches can be used, from empirical-statistic ones (e.g. Scheidl and Rickenmann 2010) to physically based deterministic approaches (e.g. Takahashi 1991; Christen et al. 2010). In the present study, the numerical model RAMMS DEBRIS FLOW 1.6.25 SLW

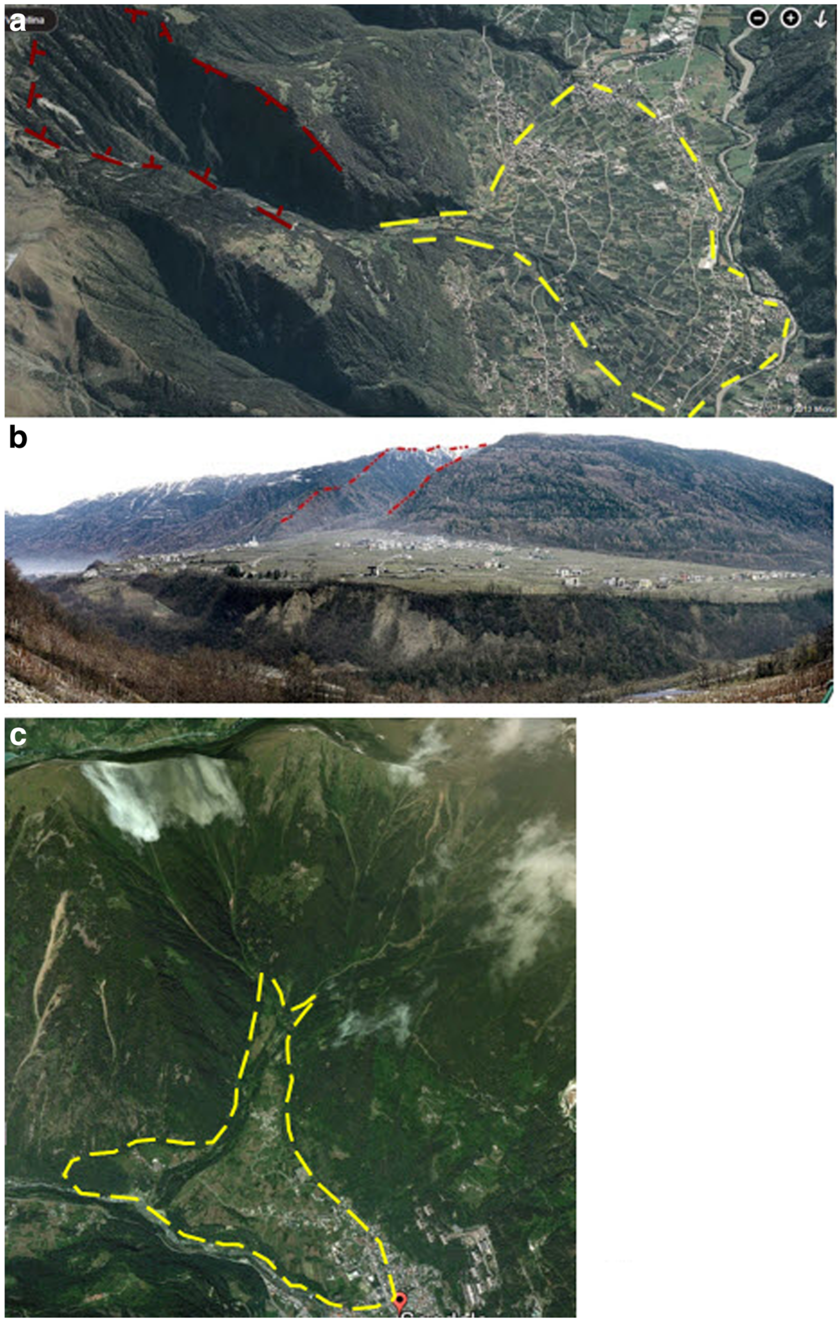

Fig. 1 Examples of some anomalous alpine fans. **a** the Ponte in Valtellina fan. **b** the Sernio fan. **c** the Migiondo fan

(Christen et al. 2010; Bartelt et al. 2013) was used. It is a single-phase model, based on the Voellmy-Salm rheology (Salm 1993), which includes the resistance parameters μ (a Coulomb-type friction coefficient that scales with the normal stress) and ξ (a turbulent drag coefficient that scales with the velocity squared). As an initial condition, RAMMS can use a block release of source material of a predefined volume or an inflow hydrograph at an arbitrary position in the channel.

The model describes the propagation of the debris flow using the equations for granular flows in three dimensions, given by the coordinates of the topographic surface of the digital elevation model in a Cartesian coordinate system (*x*, *y*, *z*), and at time (*t*). Considering the field variables flow height *H* (*x*, *y*, *t*) and flow velocity U (*x*, *y*, *t*), the mass balance equation is given by:

$$\dot{Q}(x, y, t) = \partial_t H + \partial_x (HU_x) + \partial_y (HU_y)$$

where $\dot{Q}(x, y, t)$ denotes the mass production source term, and U_x and U_y are the depth-averaged velocities in horizontal directions *x* and *y* (Christen et al. 2010). The momentum balance equations in the Voellmy-Salm rheology depend on the frictional coefficients μ and ξ, which determine the flow behaviour: μ prevails when the flow is slow or next to stop, whereas ξ prevails when the flow is fast moving (Scheidl et al. 2013). A simplified representation of the total resistance S used in the numerical model is as follows:

$$S = \mu\rho Hg cos\phi + \left(\frac{\rho g U^2}{\xi}\right)$$

where ρ is the bulk density, g is the gravitational acceleration, ϕ is the slope angle, H is the mean flow height, and U is the mean flow velocity (Bartelt et al. 2013).

The numerical tool allows to investigate the runout distance and inundation patterns, as well as the flow heights and velocities at any time and in every (x, y) location.

3.2 Entrainment model

Generally speaking, debris flow entrainment modelling has been introduced into runout models using algorithms considering either the properties of the debris flow (Medina et al. 2008) or the erosion layer properties (Hussin et al. 2012). In the present paper, the entrainment is simulated in RAMMS by means of the Schurch erosion algorithm, which is an empirical algorithm based on the field data collected at the Illgraben (Berger et al. 2011; Schürch et al. 2011). In this algorithm, the entrainment phenomenon is defined using the maximum potential erosion depth e_m and a specific erosion rate dz/dτ e_m is calculated as a function of the basal shear stress τ:

$$e_m = \begin{cases} 0 \text{ for } \tau < \tau_c \\ \frac{dz}{d\tau}(\tau - \tau_c) \text{ for } \tau \geq \tau_c \end{cases}$$

where τ_c is a critical shear stress considered equal to 1 kPa (as below this value little erosion was observed in the experimental site; Schürch et al. 2011), and dz/dτ is assumed to be equal to − 0.1 m/kPa. Normally, the erosion rate is set to a default value equal to − 0.025 m/s (Berger et al. 2011) and it is active from when the critical shear stress τ_c is exceeded until the actual erosion depth reaches the maximum potential erosion depth, which corresponds to the thickness of the debris along the flow path.

Input parameters

A common *caveat* for all numerical simulation tools remains model calibration (i.e. appropriate choice of flow resistance parameters). Model parametrisation based on the back-calculation of well-documented past events is generally preferable.

In order to evaluate the capability of the simulation tool to reproduce debris flows in anomalous system, a back analysis was carried out in one of the few monitored basins in the Alps, the Gadria anomalous fan. In particular, the debris flow occurred in July 2013 (described in detail in Comiti et al. 2014) was simulated and allowed to point out that the introduction of entrainment in the simulation brings about a change in the best-fit values of the frictional parameters (De Finis et al. 2017b). The back analysis on the Gadria case (see De Finis et al. 2017b, for a more comprehensive description) showed that the entrainment simulation involves not only a significant increase in the debris flow volume, but also a decrease in the ξ value, which corresponds to an increase in the flow velocity, better describing the actual dynamic of the

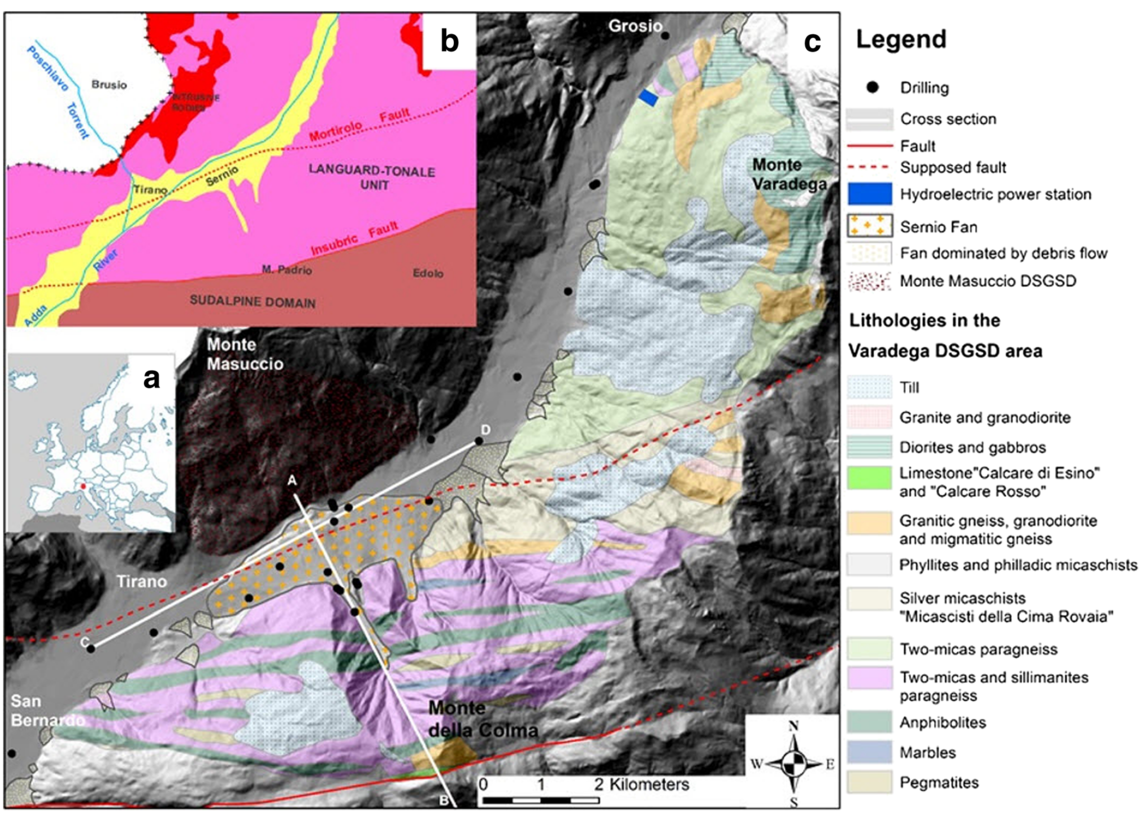

Fig. 2 (a) Location of the study area; (b) structural framework; (c) Geological map of the deep-seated gravitational slope deformations area in which the Sernio basin-fan system lies

event (De Finis et al. 2017b). The frictional parameters obtained for the Gadria anomalous fan are quite different from the values identified to be typical of debris flows by Scheidl et al. (2013), who collected the frictional coefficients (μ and ξ) obtained by the back analysis of several events occurred in the Alps. On the contrary, the Gadria values are very similar to the values obtained for the Illgraben anomalous fan (Frank et al. 2015), allowing to observe that:

- μ in anomalous system is ranging from 0.04 to 0.12, which are values lower than the typical value for debris flow (about 0.18, according to the data in Scheidl et al. 2013);
- ξ in anomalous system is higher than 500, which is a value much higher than the typical values for debris flows (about 200–250, according to the data in Scheidl et al. 2013).

Even if these observations are based on the analysis of only two cases, they can represent a starting point for further studies on anomalous systems.

Example: the Sernio anomalous fan

Structural, geological, and geomorphological setting

The Sernio basin-fan system (Fig. 2) is located in a large Alpine valley, namely Valtellina, which is situated in the Rhaetian Alps of northern Italy. 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 dip northwards. As a result of this tectonic setting, the study area is composed by two main structural domains: the Sudalpine and the Austroalpine, separated the one from the other by the Insubric line. More in detail, the Sernio basin is located just to the north of the Insubric line (Fig. 2b), bringing about a wide presence of fault rocks.

The lithologies outcropping in the area belong to the Languard-Tonale tectono-metamorphic unit of the Austroalpine domain (Spalla et al. 2003) and they are gneiss and mica-schist of low/middle degree, with intercalations of amphibolite, marble, quartzite, and pegmatite (Fig. 2c). The schistosity is mainly dipping towards South with 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 Sernio alluvial fan is included in the category of anomalous fans because of its ratio (equal to 1.5) between the fan area (about 4.5 km^2) and the basin area (about 3 km^2). Moreover, it shows all the characteristics of the fans dominated by landslide, such as a steep slope (20%) and an apex moved 1.8 km backward within the basin. The hydrographic network is not well developed. The basin presents a large and steep scarp that bounds the upper basin. This zone shows the arcuate bowl shape (Fig. 3), typical of the source area of a rock avalanche. The head of the scarp is about 2140 m a.s.l. and its base around 1830 m a.s.l. Moreover, the basin is bounded by side scarps (Fig. 3) having a length of about 7850 m. Along the head, there are morphological signs typical of deep-seated gravitational slope deformation (DSGSD) (Fig. 3): dividing of crests, trenches, counterslopes,

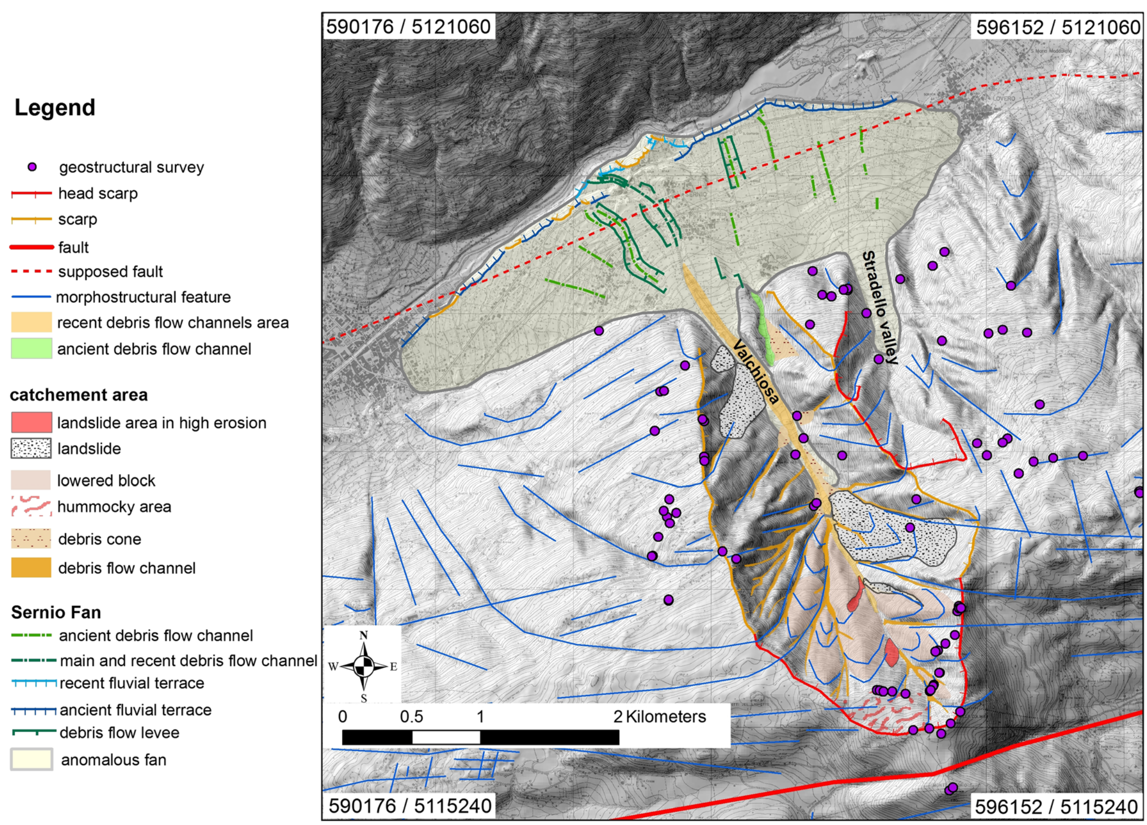

Fig. 3 Geomorphological map of the Sernio basin-fan system (UTM coordinates)

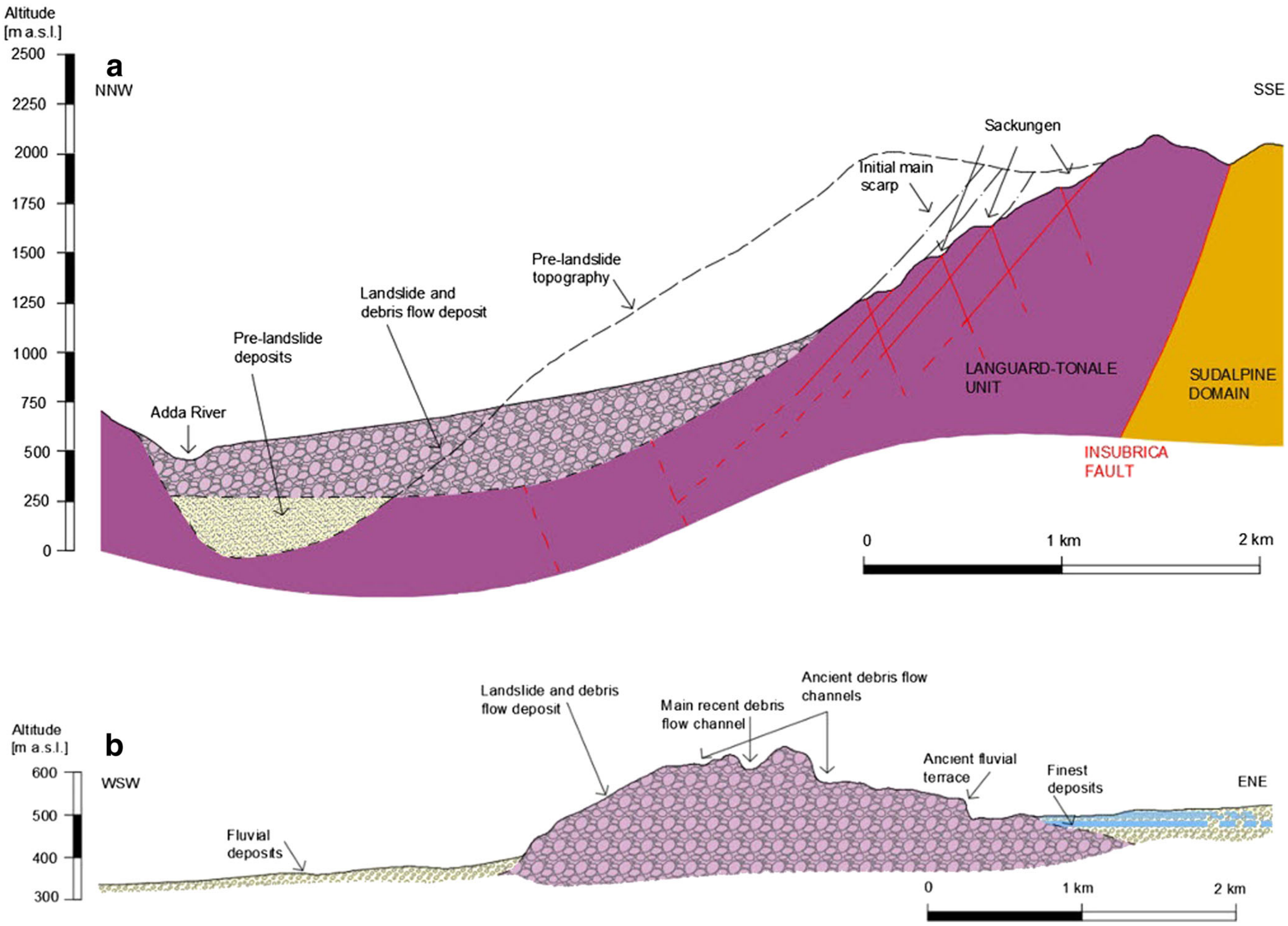

Fig. 4 Interpretative cross-sections of the Sernio basin-fan system. **a** A-B. **b** C-D (see Fig. 2c for location)

lowered blocks, and hummocky areas. Actually, the basin is located within a wide zone of about 55 km^2 characterised by morphologies typical of deep-seated gravitational slope deformations (Fig. 1c). Within the basin, no evidence of glacial erosion can be detected and glacial deposits are present only above the main scarp zone which bounds the head of the basin. As a consequence, the basin can be considered subsequent to the Last Glacial Maximum.

Based on these geomorphological features, an event of rock avalanche is very likely to have created an initial basin. The rock avalanche 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 2140 m a.s.l. in altitude. In order to estimate the likely volume of debris involved in the collapse, the pre-failure paleo-topography of the source zone was reconstructed. 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 maximum volume of 1000 Mm^3. It formed a debris body probably characterised by a very rugged topographic surface (Fig. 4a), which is typical of the rock avalanche deposits. The deposits crossed the Valtellina valley floor and blocked the course of the Adda river: actually, upstream of the fan lacustrine

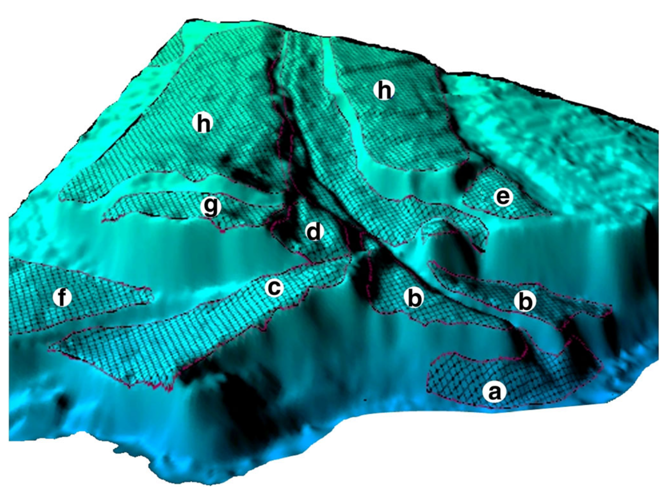

Fig. 5 Depositional events identified on the Sernio fan, from the most recent (a) to the oldest one (h)

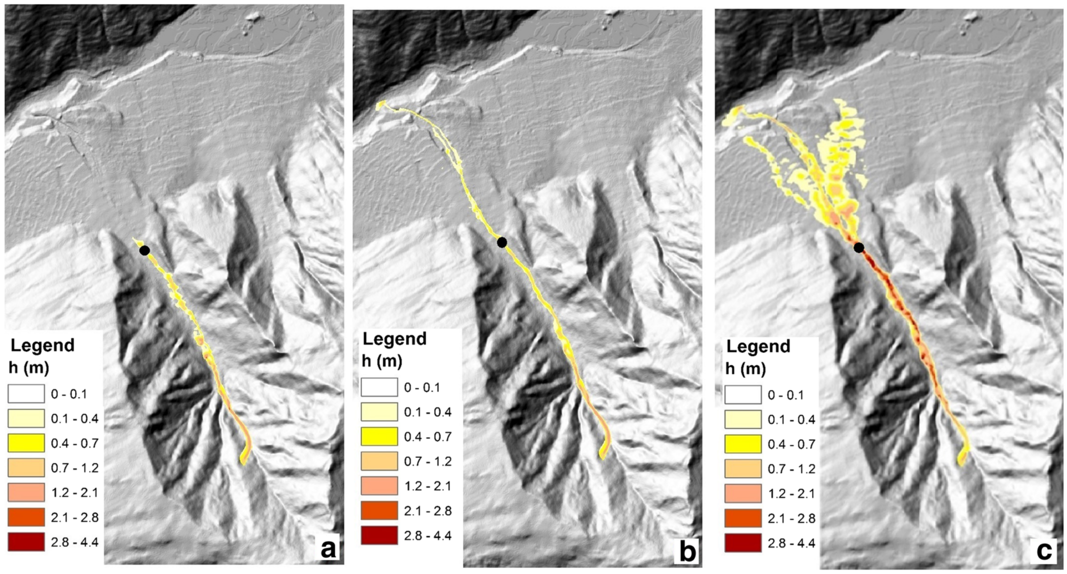

Fig. 6 Sensitivity analysis of the debris flow depth for different values of the frictional coefficients. **a** omitting entrainment with $\mu = 0.2$ and $\xi = 400$. **b** omitting entrainment with $\mu = 0.12$ and $\xi = 400$. **c** considering entrainment with $\mu = 0.13$ and $\xi = 300$

deposits are detected in the available stratigraphies (Fig. 4b). The fan is frontally confined by the opposite flank of the valley (Fig. 3) and laterally bounded by the coalescent fan of the Stradello valley (towards its northeast side, Fig. 3), which has characteristics very similar to the Sernio system (i.e. small basin surrounded by an extensive scarp and embayment of the fan apex within the basin). The elevation of the valley floor of Valtellina ranges from 420 m a.s.l. downstream of the Sernio fan to 500 m a.s.l. just upstream the fan (interpretative cross section CD in Fig. 4b), showing a morphological step of about 80 m. According to this hypothesis, the maximum thickness of the deposits is greater than 170 m (Fig. 4b) and the fan is formed by over 525 Mm^3 volume of debris. This value is just an estimate of the minimum volume of the fan: 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.

The area surrounding the basin is prone to scarp retreat, and it probably constituted the source area of several events of debris flow, which buried the initial fan formed by the landslide. A detailed interpretation of the DTM of the fan is allowed in identifying deposits attributable to different events of debris flow (Fig. 5):every new event partially eroded and destroyed the oldest deposits; based on the morphological evidences, a relative age can be identified from the most recent debris flow ("a") to the oldest one ("g"). All these events can be interpreted as debris flows, whereas the event connected to the "h" deposit (Fig. 5) shows very peculiar morphological features (e.g. strong irregularities of the topographic surface and the thickness of the deposit, about 30 m), leading to connect it to a landslide event.

Parametrical modelling of debris flow

In order to simulate the dynamic of debris flows in the Sernio fan, the numerical approach described in the previous section was applied, by using the numerical code RAMMS. With regard to the source area of debris flow in the Sernio basin, it was defined based on in situ surveys, which allowed identifying the most likely instability area and its volume. More in detail, the source area was assumed in the upper part of the catchment, and it corresponds to the most critical zone among the landslide areas identified through the geomorphological survey (Fig. 3). It is mainly made of loose debris on a steep slope (about 45°), having a thickness ranging from 3 to 5 m. The source volume (estimated to be equal to 10,000 m^3) was used as the initial condition of the numerical simulation (mass block release in RAMMS).

A sensitivity analysis on the frictional parameters was carried out considering $\mu = 0.05 \div 0.20$ and $\xi = 200 - 600$ (according to the review in Scheidl et al. 2013), observing the changes in the flow velocity and runout distance (Fig. 6). The results show that a decrease of the frictional parameter μ

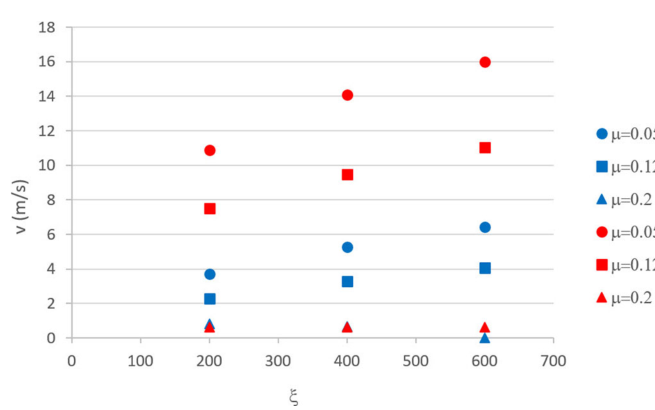

Fig. 7 Changes of flow velocity at the control cross-section (see Fig. 6 for location) for different values of the frictional parameters. In blue are the simulation without entrainment, whereas in red are the simulation with entrainment

involves an increase in the flow velocity (Fig. 7) and in the runout distance, but not a significant widening of the flow path. The same increasing trend in flow velocity can be observed by reducing the frictional parameter ξ. If the entrainment phenomena are not considered, the flow velocity is generally smaller and the volume cannot change during the flow motion. As a consequence, the flow remains confined within the channel and avulsion processes can be locally observed just closed to the sharp channel bends. The runout completely changes if the entrainment is considered, leading to a significant increase in the debris flow volume (final volume ranging from 150,000 to 250,000 m^3), for any combination of the frictional parameters (Fig. 8); as a consequence, the flow always exits from the channel and floods large areas of the fan. The bulking factor (defined as the eroded volume versus the initial volume) ranges from 14 and 23. These values of the bulking factor are higher than the values recently pointed out by Frank et al. (2016): these authors observed that the bulking factor decreases with the increase of the initial volume, and they obtained bulking factors about 10 for the same erosional rate and an initial volume equal to 1000m^3.

Comparison with values of debris flow volumes and channel debris yield rate, i.e. the volume of entrained sediment per unit channel length, reported in the literature helps evaluating the severity of the debris flow scenario simulated in the Sernio basin. Knowing the debris flow volume and the length of the channel interested by erosion, the channel debris yield rate was calculated for the Sernio basin, obtaining values ranging from 50 to 100 m^3/m. Such high values of the channel debris yield rate fall in the range indicated by Hungr et al. (1984) for debris flow channels with bed material consisting of dep talus or moraine and high, potentially unstable side slopes. Similar or even higher values have been proposed by Thouret et al. (1995) for event scenarios depicted in a basin of the French Alps prone to extreme debris flows and were observed in field experiments carried out in Kazakhstan (Rickenmann et al. 2003). A major debris flow triggered by an extreme rainstorm in the easternmost sector of the Italian Alps (Marchi et al. 2009) featured mean channel debris rate of 35 m^3/m, with maximum values of 41 and 108 m^3/m, close to those simulated by the model RAMMS in the Sernio basin. Figure 9 compares the debris flow volumes simulated by RAMMS (with sediment entrainment) in the Sernio basin-fan system with a sample of 263 debris flows documented in the Eastern Italian Alps from 1847 to 2015 (sample from Marchi and D'Agostino 2004, with updates for the most recent years). The values, which fall close to the upper envelope of the scatterplot, are consistent with the features of high intensity debris flows in a small basin with unlimited solid supply: such conditions are actually met in anomalous basin-fans systems, as outlined in the previous sections of this work. It is also possible to note that slightly higher volumes have been observed, also in smaller basins, for debris flows directly originated by the mobilisation of large landslides.

Discussion and concluding remarks

The paper has analysed the genesis and the debris flow hazard in anomalous basin-fan systems, meant as systems having a very high ratio between fan area and basin area. The analysis of cases history allowed to identify the main features of these systems, as well as to define a conceptual scheme of their origin and evolution (Fig. 10). The genesis of anomalous fan is often due to the collapse of a sector of a deep-seated gravitational slope deformation. This collapse generally occurred after the last glacial maximum and resulted in a rock avalanche evolving in a debris avalanche. Because of the flow confinement during the runout, it created a fan-shaped deposit. If the fan deposit was longer than the width of the main valley, it blocked the valley, forming landslide lake. Afterwards, the erosion by the main watercourse formed high and imposing scarps at the fan toe, which are often affected by local failures. In the meantime, the proto-basin was enlarged because of the high slopes and the weak rocks, bringing about the scarp retreat along the head of the basin. These instabilities supplied the basin with large amount of debris available to be entrained during debris flow events, which nowadays constitute the main hazard within anomalous

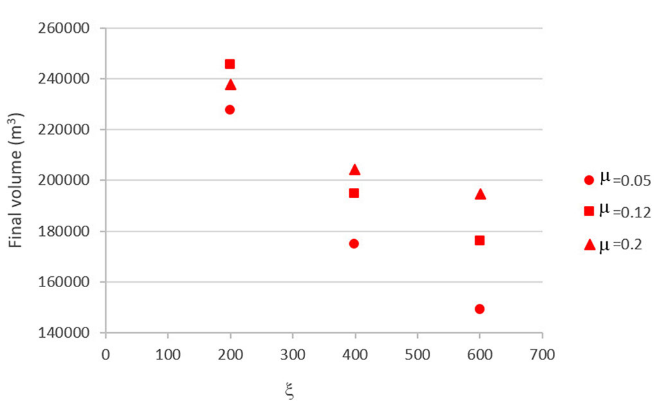

Fig. 8 Changes in the debris flow volume at the control cross-section (see Fig. 6 for location) for different values of the frictional parameters

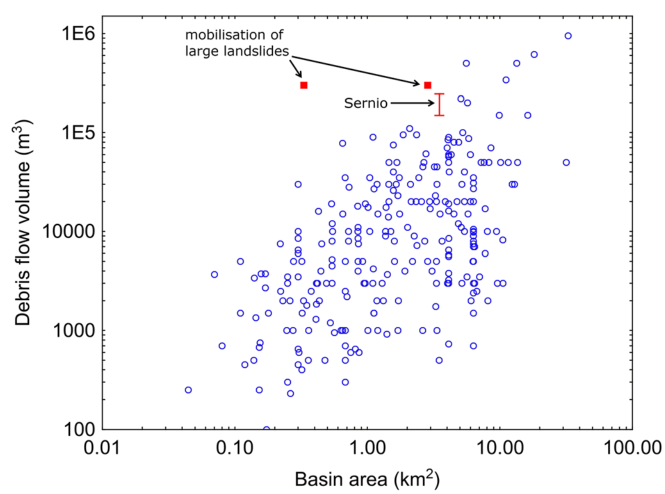

Fig. 9 Comparison of the debris flow volumes simulated for the Sernio basin-fan system with a sample of debris flows in the Eastern Italian Alps

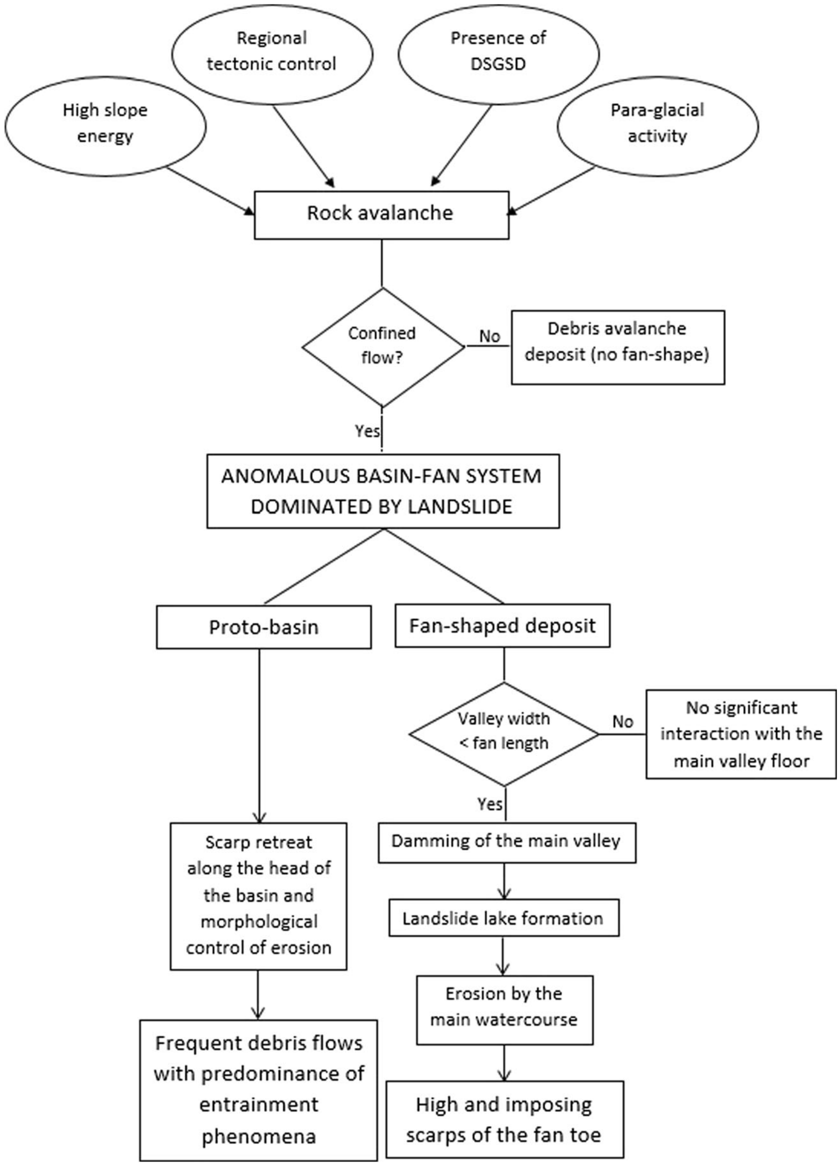

Fig. 10 Flow chart describing the origin, evolution, and related hazards in anomalous basin-fan systems dominated by landslide

basin-fan systems. These anomalous systems dominated by landslides can be compared to other anomalous systems whose origin is ascribed to debris flows (Fig. 11). In the early stage of the basin formation, the two kinds of systems can show similar features, but the peculiar controlling factors are quite different:

- In debris flows-dominated systems, the local structural conditions and lithological constrains influence the gully network characteristics, in terms of both initiation and subsequent development;
- In landslide-dominated systems, the regional tectonic control favours the development of DSGSDs, characterised by the presence of small instabilities at the slope foot, especially in those areas where the fracturing degree of the rock mass is highest.

The system development is progressive for the debris flows-dominated systems, with erosion and mass wasting processes which follow the orientation of the joint systems as well as of the presence of weak rocks. On the contrary, in landslide-dominated systems, a sudden failure within the DSGSD brings about the formation of a proto-basin, which is afterwards widened because of scarp retreat and erosional processes.

On the basis of the peculiar features that characterise landslide-dominated anomalous systems, this study has outlined the various steps required for an integrated analysis of these systems in Alpine valleys: they encompass the recognition of the geostructural settings responsible for large scale instabilities that caused fan formation, geomorphological characterisation of the basin-fan system and the valley stretch conditioned by the presence of the fan, analysis of the

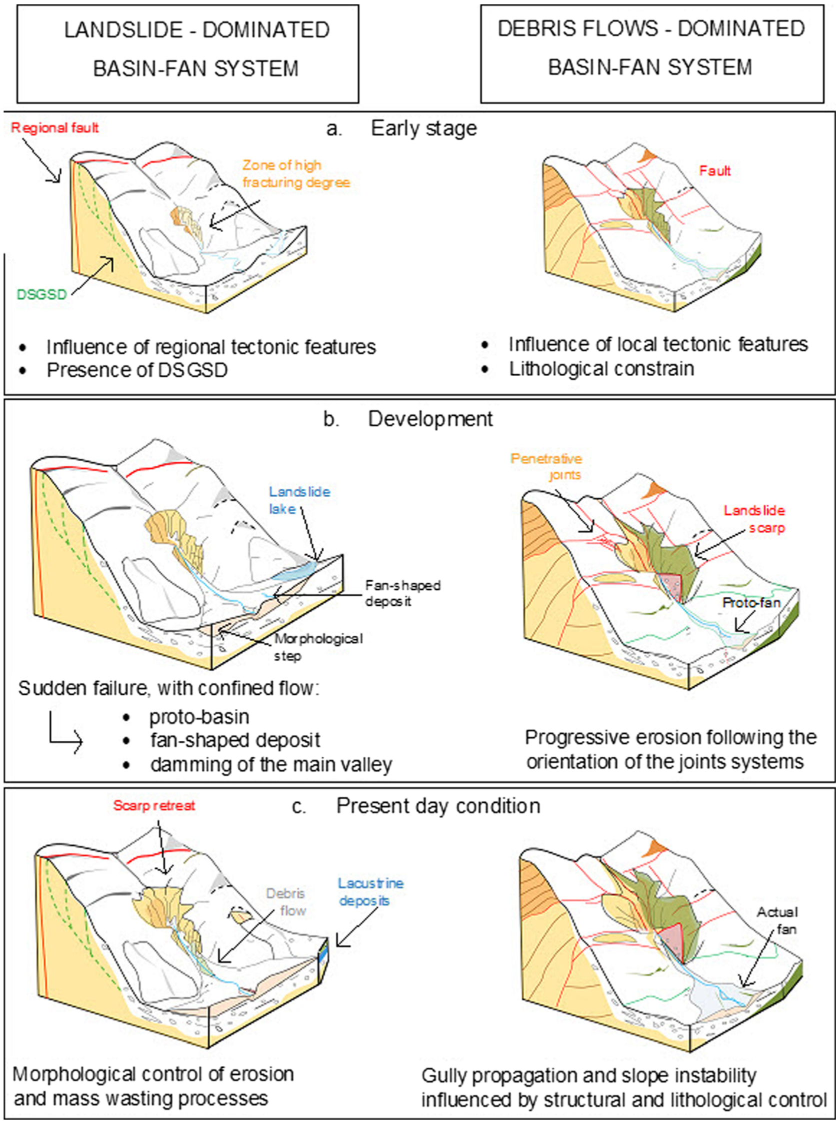

Fig. 11 Conceptual model describing the genesis and development of anomalous basin-fan systems dominated by landslide compared to systems dominated by debris flows

topography of the fan surface, and assessment of present debris flow hazards.

The analysis was applied to an anomalous fan of the Alps: the Sernio fan (Valtellina, northern Italy). The identification of the Sernio fan as a rock avalanche deposit presents several important issues for the present day hazard, which was studied by a parametrical modelling of the debris flow dynamic, through the RAMMS DEBRIS FLOW numerical model, considering the variability of the frictional parameters as shown in Scheidl et al. (2013).

The simulations carried out for the basin-fan system of Sernio demonstrated that entrainment phenomena cannot be neglected in hazard forecasting especially on anomalous systems, as it increases debris flow volume even more than in any debris flow system. These latter actually reach the high values typical of basins having unlimited solid supply even with short recharge times, causing a relevant increase in the hydrogeological hazard, in term of magnitude of the debris flows, runout distance, and extension of the depositional area.

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