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Flow-type controls on tributary alluvial fan formation along the Andes (18-34°S)

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ABSTRACT

Debris flows, locally known as '*aluviones*' or '*huaicos*', in Andean tributary alluvial fans form distinctive facies associations that can be classified into High-density Flows (HdF) and Low-Density Flows (LdF) based on sediment-to-water ratios and transitions from highly dense, viscous flows to more diluted ones. This distinction, based on ground evidence and remotely sensed debris flow identification, establishes the first equivalence between field-based and optical satellite imagery observations using Google Earth. By analysing the activity of tributary alluvial fans over the past 20 years with open-access optical satellite imagery, we provide new insights into fan evolution and the extent to which lateral sediment inputs impact sediment transfer along axial river valleys of the Andes.

Our observations reveal that large-volume debris flows, typically associated with HdF, contribute to fan expansion and aggradation. In contrast, more diluted flows -ranging from hyperconcentrated to fluvial flows-promote fan destruction through incision of the feeder channel. Fans dominated by LdF facies associations often exhibit incision and progradation, forming new lobes at the fan toe. These lobes are frequently reworked by the main channel due to the limited sediment supply. Whether tributary fan sedimentation and progradation influence the main channel or if sediments are buffered on the fans largely depends on the characteristics of the flows and on the original topography of the fan. Accordingly, classifying debris flow surges into two distinct facies associations (AF1 and AF2, corresponding to HdF and LdF, respectively) enhances our understanding of fan dynamics and their influence on axial valleys at regional scale. This study underscores the importance of sedimentological flows characteristics in governing fan evolution, influencing both fan development across a broad latitudinal range (18-34°S) and sedimentary signal propagation along the Andes Cordillera. Moreover, the findings have significant implications for national debris flow hazard mitigation efforts and aligns with global strategies outlined in the Sendai Framework for Disaster Risk Reduction, promoting resilience and improved risk management in developing regions.

1. Introduction

Tributary alluvial fans are located at the junctions of tributary catchments with the trunk valleys in mountainous regions. Their evolution records changes in the upstream drained area, as well as in the main channel's lateral migration and avulsion processes (Bull, 1977; Harvey, 1997, 2010; Mather et al., 2017). This interdependence informs about the climatic and tectonic factors that ultimately control the formation and preservation of the fans. Consequently, tributary fans have been extensively studied in different tectonic and climatic settings. In addition, tributary fans play a vital role in modulating longitudinal sediment fluxes of rivers either by trapping sediments or routing them downstream (Bull, 1964; Hooke, 1967; Schumm and Parker, 1973; Mather et al., 2017; Cabré et al., 2020a).

The research on tributary fans evolution and fan-river interactions has examined fan-river relationship in different climatic and tectonic contexts using (i) topographic morphometric analysis of catchments and tributary alluvial fans (Milana and Ruzycki, 1999; Al-Farraj and Harvey, 2005, 2010; Gómez-Villar et al., 2006; Wang et al., 2008; Stokes and Mather, 2015), (ii) fan geomorphological and sedimentological changes in time (Mather and Stokes, 2017; Leenman and Tunnicliffe, 2020) or (iii) a combination of the previous (Wells and Harvey, 1987; Leeder and Mack, 2001; Colombo, 2005; Mather and Stokes, 2017; Cabré et al., 2020a).

Sedimentation on fans (buffering effect) might prevent sediments from entering the trunk valley and thus modulate the longitudinal sediment fluxes and geomorphological evolution (Whipple et al., 1998; Florsheim, 2004; Ferguson and Hoey, 2009; Lin et al., 2009; Mather et al., 2017). Additionally, their role in delivering sediments to the axial valley can influence river transport capacity (Mather et al., 2017; Leenman and Tunnicliffe, 2020; Savi et al., 2020) (Fig. 1). Thus, variations in sediment fluxes in the main channel, which inform about flux

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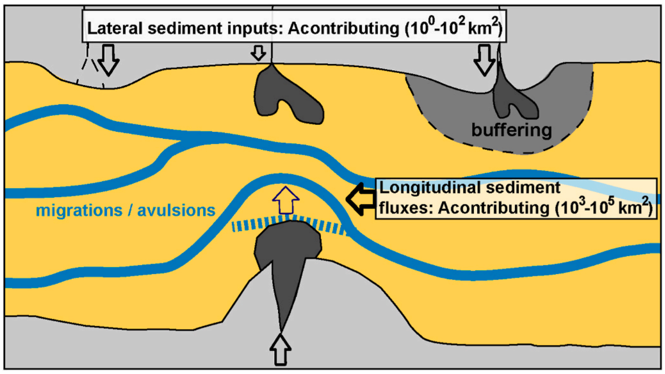

Fig. 1. Conceptual sketch of lateral (tributary catchments) and longitudinal sediment fluxes (trunk valley) of a fluvial system. Buffering of sediments happens on the fans together with lobe formation on the valley floor controlling migration and avulsions of the main channel triggered by lateral sediment inputs.

variations in watersheds at a regional scale (10^3–10^5 km^2 catchment area) record climatic or tectonic changes (Denny, 1967; Colombo et al., 2009; Colombo, 2010; Harvey, 2010, 2011; Stokes and Mather, 2015; Fryirs et al., 2007; M. L. Hsieh and Chyi, 2010a; Mather et al., 2017; Cabré et al., 2017; San Juan et al., 2024). The longitudinal propagation of the sedimentary signal along the trunk valley, influenced by lateral sediment contributions draining from much smaller contributing catchment areas (10°–10^2 km^2), remains partially understood due to a lack of comprehension of the mechanisms controlling fan evolution and their ability to supply, or not, sediments to the axial valley.

A recent study of debris flows in tributary fans in a valley of the arid Andes showed that localized intense storms within the same fluvial system and in regions with comparable altitudes and precipitation regimes only impact certain catchments, leaving others undisturbed (Cabré et al., 2020a). The stochastic nature and high temporal and spatial variability suggests that the response of lateral sediment fluxes to the main channel is likewise stochastic. Therefore, landscape evolution studies and models need to account for this variability as well. Yet, our ability to predict the stochastic delivery of sediments from fans into the main stem is currently hindered by an incomplete understanding of the formation mechanisms of tributary fans, which are often triggered by localized stochastic atmospheric disturbances rather than by broader regional shifts in climatic conditions. Therefore, we need to investigate the formation mechanisms of tributary fans by integrating the facies associations of individual flood events (*sensu* Cabré et al., 2020a) with the resulting geomorphic changes (*e.g.*, feeder channel incision). This approach will help determine the coupling status between fans and rivers, and thereby understand how longitudinal sediment fluxes are modulated by lateral sediment inputs under different hydrological regimes.

We want to demonstrate how the morphologic evolution and role of fans in longitudinal sediment fluxes of rivers depend on sediment storage characteristics (fan buffering). This will be achieved by including the sedimentology of recent flood events in tributary alluvial fans by the combination of ground and remote sensing observations. We will define characteristic facies associations for the identified flood events to understand how the flows characteristics controls fan evolution.

This paper characterizes the formation mechanisms and morphologic evolution of 28 tributary alluvial fans located in the Andes in different river hydrologic regimes along a latitudinal gradient (18-34°S) ranging from humid subtropical climate to hyper-arid, using available optical satellite imagery to map debris flow events between 2000 and 2024.

Debris flows in tributary fans impact human activity because these areas are prone to hazards such as floods and debris flows (Garcés et al., 2022). These fans can also influence valley floors by flooding large areas upstream. Additionally, sediment inputs from fans impact riverine ecosystems in the trunk valley, degrading freshwater quality (*e.g.*, Dame et al., 2023) and posing a threat to communities living in water-scarce and climate-sensitive areas.

2. Study area

The selected rivers that drain the Andes between 18 and 34°S (Fig. 2) have different hydrological regimes (Fig. S1) due to the climatic gradient, that ranges from arid to humid subtropical climate in NW Argentina in the Andes (Fig. 2b). The lengths of the rivers where the studied fans are located range from ~30 km in El Volcán river to ~250 km in San Juan River. The river catchment areas range from ~175 km^2 in Quebrada Marquesa to ~34000 km^2 in the Jáchal river, with altitudes ranging from ~900 to ~2600 m a.s.l.

These diverse hydrological regimes significantly influence the transport capacity of rivers and thus lateral mobility of channels and the width of valleys, thereby impacting the preservation of tributary alluvial fans. This is especially true when trunk valleys experience increased streamflow and a higher frequency of large floods, which trim the fans or carry their sediments downstream (Leeder and Mack, 2001; Larson et al., 2015). For instance, when the main channel is constricted, the formation of new fan lobes in the trunk valley accelerates the degradation of fans situated on the opposite side of the valley by pushing the main channel towards that side. These interactions between lateral and longitudinal sediment fluxes ultimately dictate the downstream displacement of sediments.

3. Materials and methods

3.1. Selected tributary fans

We have selected 28 tributary alluvial fans from 11 rivers, situated at altitudes between 900 and 2600 m a.s.l., built at the confluences of tributary catchments with the main valleys that drain the Andes along a latitudinal gradient that ranges between ~18 and 34°S (Fig. 2). Four out of 28 fans are formed in ephemeral valleys, while the others are situated in perennial river valleys.

3.2. Fan planform change and main channel characteristics

The criteria for selecting the 28 fans are based on field observations conducted over the past decade, imagery available from Google Earth, and the inclusion of both more and less active fans. Additionally, the selection considers to present a diverse range of fan-river scenarios, such as main channel blockage, no blockage, triggering avulsions, among others. Using Google Earth satellite images from the period 2000–2024, we manually mapped the area of the flows visible in the available images (Table S1). Google Earth images have been used for mapping tributary alluvial fans (Mather et al., 2015; Mather and Stokes, 2017) and emerges as a great historical imagery archive accessible to any user. Specific details of the images used for each fan (acquisition dates) are provided in the supplementary information (Table S1). This work does not present a detailed frequency analysis of floods on the fans because it does not systematically use all available imagery archives. For example, in tributary fans situated in humid regions, smaller events occurring between the major mapped floods may have been overlooked due to the limited scope of the images used. However, it is not the scope of this work to present a comprehensive inventory of events for all the studied fans, but rather to correlate recorded events with (i) fan-river interactions and (ii) sedimentologic characteristics of flows.

The mapping of debris flow evidence within fans boundaries was carried out directly on images available in Google Earth, focusing on uniformly delineating flow areas within polygons based solely on their timing. This approach did not include detailed facies details, such as those shown in the March 2015 debris flows facies maps from El Huasco valley presented in Cabré et al. (2020a). Over the past decade, we have

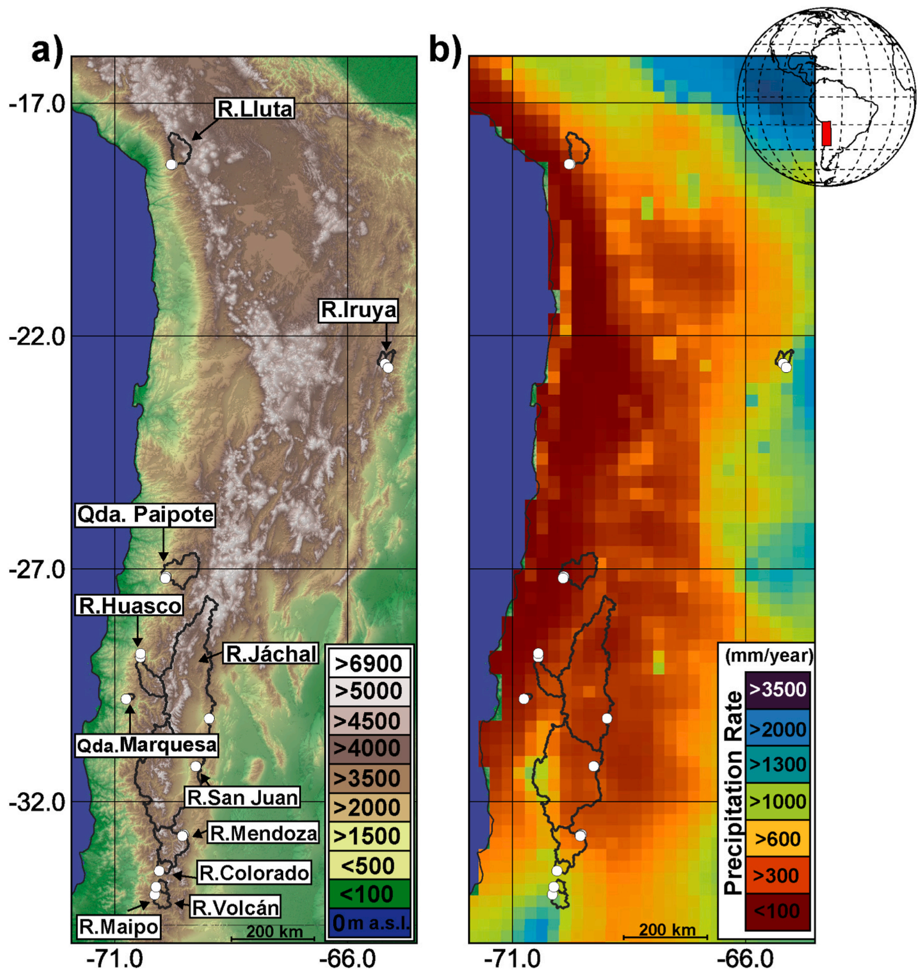

Fig. 2. a) Map situation of the selected fans in the Andes and the watershed drained areas upstream the studied fans. Fans are indicated with white dots. **b)** Accumulated annual precipitation from the Tropical Rainfall Measuring Mission (TRMM) gridded 0.25° × 0.25° product (TRMM_3B43 v7) in mm/year over the period from 01/01/1998 to 31/12/2019.

visited 11 of the 28 selected fans presented in this study in different occasions, primarily in the aftermath of the March 2015 debris flows, as part of research initiatives aimed at monitoring runoff erosion and geomorphic changes in tributary fans (Cabré et al., 2020a; Aguilar et al., 2020; Zegers et al., 2020; Garcés et al., 2022).

To relate the evolution of the fan to the valley where the fan is formed, we have extracted geomorphological metrics of valley floors from direct measurements on Google Earth. Additionally, fan catchment and main valley drained area at the intersection with the fan has been were derived using watershed and stream delineation in a Geographical Information System using the NASA Shuttle Radar Topography Mission (2013) (SRTM) Digital Elevation Model (DEM), generated using a C-band radar system that has a spatial resolution of 1 arc second (~30 m). The area drained by the catchments feeding the fans has been divided by the total area drained by the trunk valley at the fan-river intersection point. The ratio is introduced as a simple metric for comparing fans from different fluvial systems and climatic regimes along the Andes. With this relationship, we aim to find a common point for all the fans when evaluating them at the mountain range scale, which potentially defines the preservation of the fans in rivers with different hydrological regimes.

The width of the trunk valley has been measured just before, in front of, and downstream of the selected fans, and the average value has been considered. The streamflow ($m^3\ s^{-1}$) of the perennial rivers in Chile has been retrieved from Alvarez-Garreton et al. (2018) (available at www.camels-cr2.cl) and in Argentina from the National Water Information System of the Ministry of Public Works (https://snih.hidricosargentina.gob.ar). We provide all the streamflow time series starting in the year 1980 without further analysis to offer an overview of the streamflow of each river for the last 44 years for interested readers (Fig. S1).

3.3. Sedimentology of recent flood events

Debris flows reported in tributary alluvial fans of the Andes consist of complex consecutive surges with varying water-to-sediment ratios that can be classified into sedimentary facies (Cabré et al., 2020a; Aguilar et al., 2020; Zegers et al., 2020; Garcés et al., 2022). The flow types are identified based on their sedimentological and textural characteristics that are summarized in six facies types after Cabré et al. (2020a). The nomenclature for the facies types defined for the debris flows deposits of March 2015 presented in Cabré et al. (2020a) (Table 1) enables comparing facies between the debris-flow events and assists interpreting in imagery debris flows surges.

The facies maps of the March 2015 debris flow events for certain fans situated in the El Huasco river valley (Cabré et al., 2020a; Aguilar et al., 2020) have been applied to the calibration of sediment transport numerical models in tributary fans (Garcés et al., 2022). In this study, based on our field experience, we will group the five facies defined for debris flows in Cabré et al. (2020a) into two facies associations according to their rheological characteristics based on the work of Costa (1984, 1988) (Table S2). Additionally, we will outline the primary identifying features of both facies associations to support future research

Table 1
March 2015 debris flow facies types defined in El Huasco valley (29°S) in Cabré et al. (2020a). Graphical examples are available in Fig. S3.

Facies	F1	F2	F3	F4	F5	F6
structures	Thick lobes (widths 1–100m)	Multiple stacked Thin narrow lobes	Arcuate push ridges over longitudinal bars	Depositional bars	Sheet-like sands	Fine sheets
thickness	30–100 cm	10–30 cm	5–30 cm	<50 cm	1–2 cm couplets	–
Sedimentary features	Matrix-supported	Matrix-supported	Clast-supported (open framework)	Pebbles, cobbles and boulders in elongated shape	Medium to fine sands	Silts and muds with mud cracks
others	Interlocked boulder accumulations in lobe fronts	5–12% silty muds	in feeder channel and lobes at fan toe	in feeder channel and lobes at fan toe	Filling channels or scattered on depositional lobes	Wood fragments and palustrine vegetation
Facies Associations (this study)	AF1			AF2		Not considered in this study

efforts on debris flows mapping in tributary fans of the Andes.

The sedimentological analysis of the March 2015 debris flows for El Huasco river valley (29°S, 70°W) provided, for the first-time, insights into the debris flow characteristics following an extreme hydrometeorological event that impacted large areas of the Atacama Desert in Chile (Cabré et al., 2020a; Aguilar et al., 2020). The field criteria used to define F1 to F6 is based on classical sedimentological works (*e.g.*, Wells and Harvey, 1987), with the main characteristics summarized in Table 1.

To simplify and translate sedimentological interpretations for all the

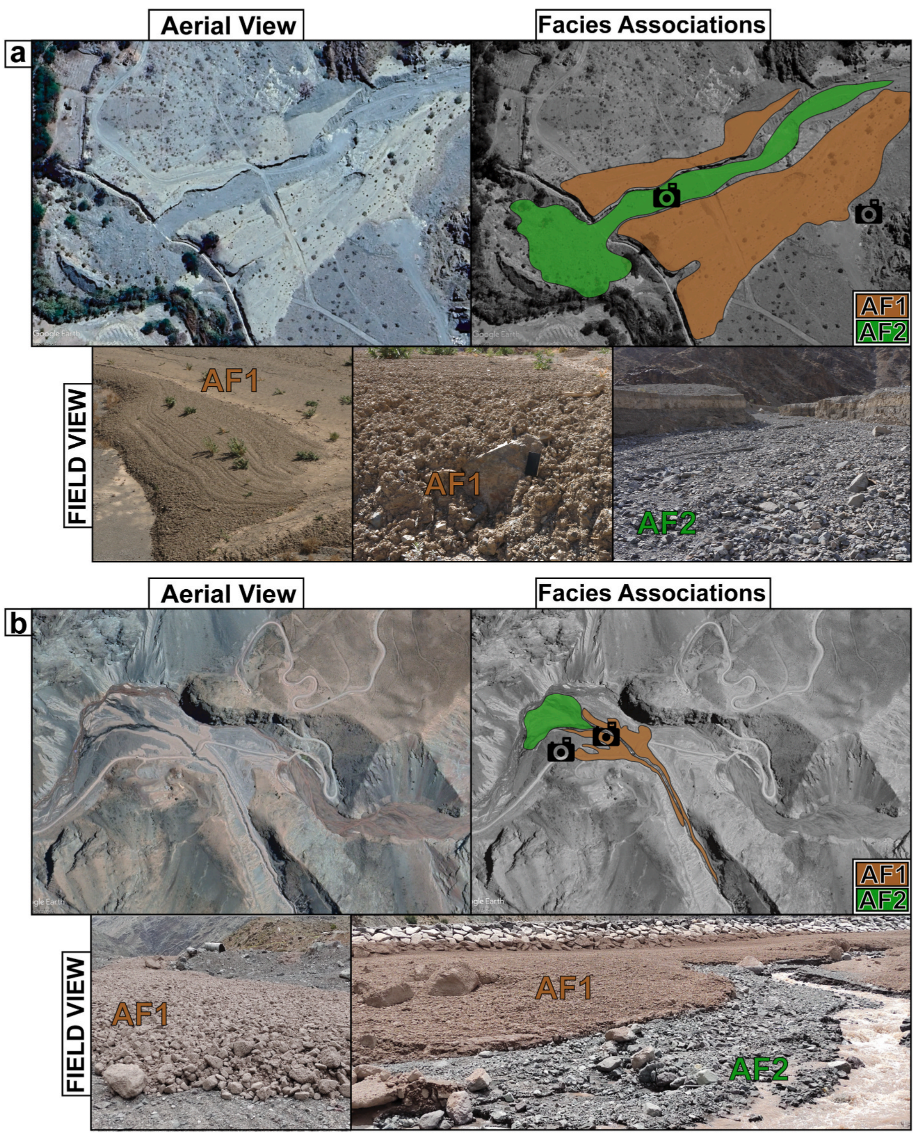

Fig. 3. Examples of how to define AF1 and AF2 facies associations on open access optical satellite imagery in Google Earth. Ground truth evidence in field pictures showing the characteristic sedimentary features are also provided. **a)** El Huasco_1 fan picture of the March 2015 debris flow and **b)** Alfalfal_1 fan pictures of the January 2023 debris flows.

studied fans, we have grouped F1, F2 and F3 into the facies association ‘AF1’, and F4 and F5 into the ‘AF2’ facies association. The criteria for identifying debris flow events as either AF1 or AF2 in optical satellite imagery, which will be further discussed in subsection 4.2, differ from ground-based sedimentary facies and focus on remotely sensed facies associations. F6 will not be considered as a single facies association in this study.

Since we cannot achieve a level of detail when mapping sedimentary facies from satellite optical imagery unless we go to the field, we adopt the approach proposed in Fig. 3, where the five facies are grouped into two Facies Associations (AF1 and AF2). As illustrated in Fig. S2 for Huasco_1, F1-F2 are classified as AF1 and F3-F5 as AF2. This method allows us to categorize each event in the fans according to its facies associations (AF1; AF2 or AF1+AF2). This simplification facilitates comparisons of fan formation mechanisms using a simple metric. To demonstrate the equivalence and/or distinction between sedimentary facies defined in the field and those identified using satellite imagery, we provide supporting examples in Fig. 3, Figs. S3 and S4, showing both ground and remote sensing data.

The simplified facies association classification (AF1 and AF2) is based on Costa (1988) concept of defining boundaries or limits of water-sediment ratios. In Costa (1988) approach, the sedimentology of deposits is defined as a function of their concentration in volume of sediment and water. The presence of facies associations, either more cohesive debris flows (AF1) or more diluted flows (AF2), is fundamental to the evolution of fans and rivers. These facies associations strongly control the geomorphological changes in the fans, such as erosion or feeder channel incision. Additionally, changes in the valley floors, i.e., temporal dams (F6 deposition) or main channel avulsions driven by lateral sediment inputs, influences also the fans situated downstream (Leeder and Mack, 2001; Savi et al., 2020).

There will be differences within the same facies between fans related to the areas covered by the flows, the thickness of the associated deposits, as well as the size of the clasts and the amounts of fines, as these are parameters depend on the source areas and sediment characteristics within the catchments (*e.g.*, Stokes and Mather, 2015).

In this work, we will not explore in detail the formation of temporary lakes and the related sedimentation of F6 facies of Cabré et al. (2020a), although we highlight their relevance as paleo-hydraulic records of river floods and lateral debris flow damming of the main river. This relevance is due to the similarities with the deposits used for ^{14}C dating of river blockages during the Holocene (Veit, 1996; Colombo et al., 2000; Colombo, 2005; Riquelme et al., 2011; Cabré et al., 2017; San Juan et al., 2024).

4. Results and geomorphological interpretation

4.1. Geomorphologic fan evolution

Here we present the fan evolution determined between the years 2000 and 2024. The difference in the number of flows among the fans is significant. The difference primarily arises from fans located in climates characterized by more frequent and intense precipitation, along with large volumes of sediments in the catchments, resulting in more debris flows. In regions where the annual precipitation exceeds 600 mm year^{-1}, we observe up to a maximum of 7 events (Fig. 4). On the other hand, in regions with annual precipitation rates below 100 mm, we typically find only one or two debris flow events within the studied time period (Fig. 4).

Examples of fan activation (number of events) from planform change are shown in Fig. 5. We acknowledge that this number represents the minimum occurrences of fan activation because the images used do not uniformly cover all areas with a dense temporal resolution. Consequently, in the more active fans, it is possible that some minor events were not captured in this study. However, all major events that we consider to truly influence the evolution of the fans have been

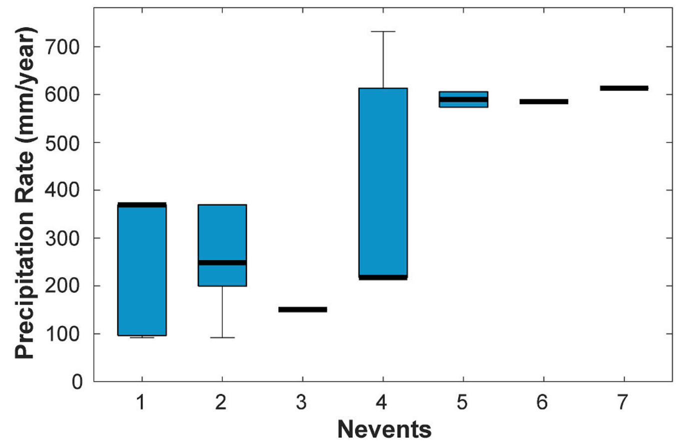

Fig. 4. Precipitation rate (mm/year), derived from TRMM (see map in Fig. 2b), is plotted against the number of events (Nevents) identified during the studied period. The thick black line inside the box contains the median value and the whiskers represents the interquartile range.

considered.

The lateral inputs from the fans influence the fluvial system to varying degrees, depending on the characteristics of the fluvial system being studied. Thus, in ephemeral systems like those we have investigated (Paipote, Marquesa) (Fig. 5c), fans are formed during extreme precipitation events (March 2015, 2017) (Aguilar et al., 2020; Cabré et al., 2020a) and remain stable until the next event. This is because in ephemeral axial systems, the lack of permanent flow prevents reworking between storms. Conversely, in fans where the axial system is formed by a perennial river, the interaction becomes essential. For example, when a debris flow deposits in the trunk valley, it may cause a migration or avulsion of the main channel to the opposite side of the valley if the position of the main channel is influenced (Fig. 5b). Additionally, there are fans that, while not directly influencing the main channel, still contribute with sediments to the alluvial plain, which are subsequently reworked by rivers. Our mapping reveals the varying degrees of fan activity and facilitates the examination of fan-river interactions. This encompasses the spatial influence of the fan on the main river and flooded areas, illustrating how lateral sediment inputs currently shape fluvial systems in the Andes.

In Fig. 4, we observe fans with up to seven events and others with only one event (Table 2). Upon closer inspection, these events show varying behaviours: some flows reach the trunk valley, while others remain buffered in fans (Fig. 6). We can count the number of times flows reach the axial valley and asses their potential to block the river and form temporary lakes (Table 2). Specifically, fans like Iruya_1 and Iruya_2 illustrate how lobes deposited at the fan toes can block the axial valley, creating temporary lakes upstream of the fans (Fig. S5).

Fig. 6 further illustrates that events on fans such as Iruya_3 and Iruya_4 prominently build up the fans, with almost all sediment volumes confined to the fan area before the debris flow event (dashed black lines in Fig. 6). In contrast, other events show flows extending beyond the pre-debris flow area, spreading across large areas of the valley floor and forming a new, telescopic-like lobe (Fig. 6a)., *sensu* Colombo (2005). This significantly impacts the main channel, causing an avulsion to the opposite side of the valley, thus drastically modifying the geomorphological landscape for subsequent debris flow events. Fig. 6 also demonstrates how fans formed during the 2015–2016 event completely disappeared by the 2016–2018 period due to the erosion of the main channel, which reworked and transported the sediments downstream. This ‘plume’ effect resulting from the reworking of the debris flow sediments by the river can be observed in several examples in Fig. 6.

Without delving into excessive detail, we can observe the effect of topographic compensation on the fans, particularly evident in Iruya_3

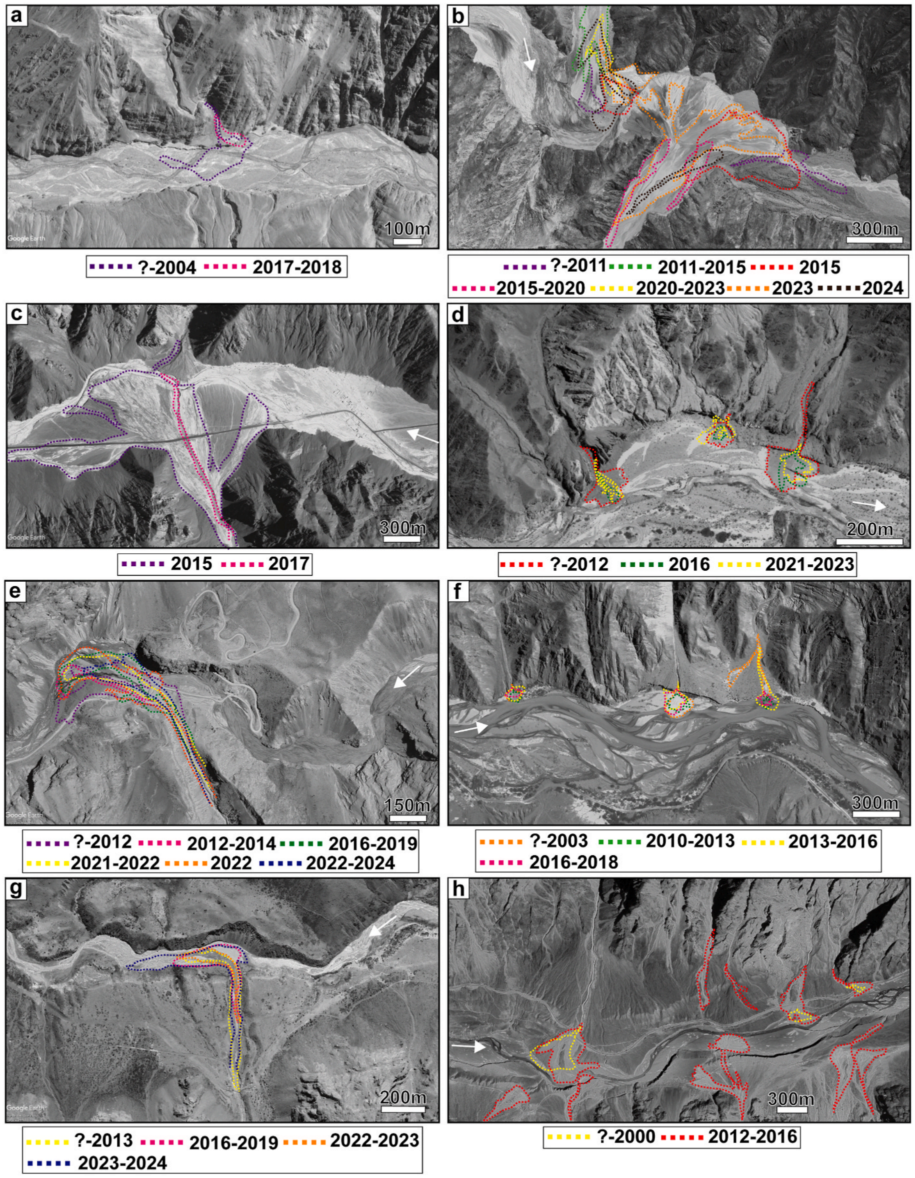

Fig. 5. Examples of mapped fan activity for some of the studied fans, with a color-coded legend for each flood event. The observation period (details in Table S1) spans approximately from the year 2000–2024. **a)** Río Lluta fan (Lluta_2). **b)** Río Iruya Valley fans (Iruya_1 and Iruya_2). **c)** Quebrada Paipote (Paipote_1). **d)** Río Jáchal fans (Jáchal_1–3). **e)** Río Colorado fan (Alfalfal_1). **f)** Río San Juan fans (SanJuan_1–3) **g)** Río Maipo fan (Damas_1) **h)** Río Mendoza fans (Mendoza_1–7).

and Iruya_4 (Fig. 6), where a distinct radial avulsion pattern is observed. This pattern is less apparent in more entrenched fans or those with strong interactions in narrow valleys (Fig. 6). However, it is interesting to note that fans already trimmed before the debris flow event tend to form new lobes at the fan toe, depositing the sediments into the axial valley and directly contributing sediment inputs from the tributary catchments to the main axial fluvial system. This configuration (depicted in Fig. 1) illustrates how some fans act partially as sediment buffers, while others, due to the entrenched feeder channel, deliver sediments (by-pass). This concept of fan-river coupling, explored in studies by Harvey (2002), Stokes and Mather (2015), Cabré et al. (2020a), and Savi et al. (2020), explores its significance in fan interactions with the axial valleys.

4.2. Facies associations definition

For the March 2015 in the Huasco_1 fan we find F1 to F6 facies with F1 and F2 present only on the upper fan surface, approximately 7–8m above the main river level. Facies F3-F5 are present in the feeder channel and in the newly formed lobe at the fan toe (Fig. 7). F6 facies are consistently identified in the upstream segment of the fan, associated with temporary river blockages. Although these lakes prevail for several years after the debris flow event, the reduction in flooded areas in the valley reveals the sediments associated with F6 (Fig. 7d).

The resulting facies association of the March 2015 event shows stacked debris-flow surges, resulting in large sediment volume accumulations in the upper fan surfaces before the feeder channel became entrenched. In contrast, during the May 2017 event, debris flows sediments bypassed the fan via the feeder channel towards the main river. The feeder channel, initially formed during March 2015, facilitated the formation of new lobes or the enlargement of the March 2015 fan toe lobes (Fig. 7a–Fig. S2). Facies types F3 and F4 are present in the feeder channels, while F3, F4 and F5 facies types are found in the fan toe lobes.

To illustrate our findings, we provide a series of facies maps for the Huasco events in 2015 and 2017 (Fig. S2). These maps enable us to observe instances where the fan expands through the deposition of F1 and F2 facies, while more diluted flows accumulate at the base, shaping and modifying the fan morphology. Furthermore, the formation of new

Table 2
Tributary alluvial fans morphometrics, number of events, number of times that the debris flows reached the axial valley and, number of times that dammed the valley.

	LAT	LONG	Altitude (m a.s.l.)	Afan (km^2)	Ariver (km^2)	Afan/ Ariver	Precipitation Rate[a] (mm/year)	N events	Ntimes reach river	Ntimes dam river	Valley width (km)
Alfalfal_1	−33.486	−70.046	1879	34.5	662	0.05221	585	6	5	1	0.23
Damas_1	−33.994	−70.144	1854	20.5	1036	0.01976	732	4	4	0	0.18
El Salto	−33.830	−70.115	1688	7.0	459	0.01531	606	5	4	0	0.24
Huasco_1	−28.895	−70.449	1083	12.9	2813	0.00459	200	2	2	2	0.31
Huasco_2	−28.817	−70.448	912	4.8	2904	0.00165	200	2	0	0	0.48
Iruya_1	−22.590	−65.199	2689	14.4	385	0.03733	573	4	2	2	0.90
Iruya_2	−22.596	−65.194	2683	11.0	385	0.02860	573	5	3	2	0.31
Iruya_3	−22.677	−65.126	2092	6.4	874	0.00726	613	7	4	0	0.44
Iruya_4	−22.680	−65.127	2086	9.5	874	0.01089	613	7	5	0	0.55
Jachal_1	−30.211	−68.969	1467	0.9	24430	0.00004	150	3	3	0	0.87
Jachal_2	−30.212	−68.971	1451	0.1	24430	0.00000	150	3	3	0	0.34
Jachal_3	−30.215	−68.975	1463	0.9	24430	0.00004	150	3	3	0	0.05
Lluta_1	−18.316	−69.764	1674	10.0	2590	0.00387	248	2	2	0	0.26
Lluta_2	−18.315	−69.789	1571	13.3	2590	0.00514	248	2	2	0	0.39
Marquesa_1	−29.797	−70.757	1204	7.1	175	0.04057	111	1	1	0	0.24
Mendoza_1	−32.717	−69.554	2242	10.9	3838	0.00285	369	2	2	0	0.48
Mendoza_2	−32.708	−69.542	2164	1.5	3838	0.00039	369	1	0	0	0.61
Mendoza_3	−32.702	−69.536	2084	1.1	3838	0.00027	369	2	2	0	0.61
Mendoza_4	−32.714	−69.532	2089	23.8	3838	0.00619	369	2	2	0	0.59
Mendoza_5	−32.705	−69.522	2083	1.5	3838	0.00039	369	1	0	0	0.61
Mendoza_6	−32.729	−69.543	2104	21.1	3838	0.00550	369	1	1	0	0.48
Mendoza_7	−32.737	−69.549	2151	7.9	3838	0.00206	369	1	1	0	0.59
Paipote_1	−27.171	−69.892	1259	82.9	3833	0.02163	92	2	2	0	0.55
Paipote_2	−27.169	−69.901	1241	15.7	3833	0.00410	92	1	1	0	0.18
Paipote_3	−27.204	−69.917	1144	1.1	3833	0.00027	92	1	0	0	1.12
SanJuan_1	−31.242	−69.246	1290	1.3	22731	0.00006	218	4	4	0	0.59
SanJuan_2	−31.242	−69.251	1304	2.7	22731	0.00012	218	4	4	0	1.13
SanJuan_3	−31.243	−69.262	1286	1.3	22731	0.00006	218	4	4	0	1.07

[a] from TRMM (1998–2019).

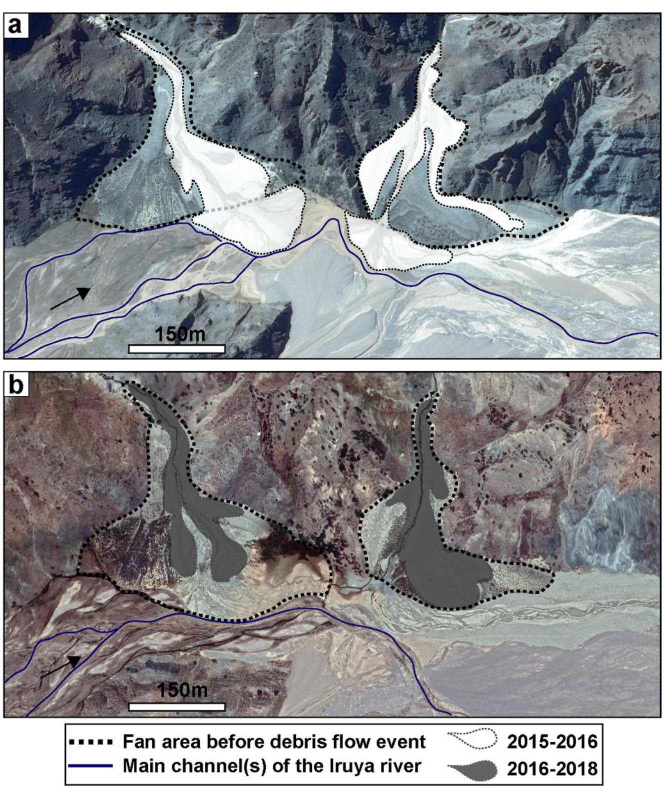

Fig. 6. Fan-river coupling endmembers in the Iruya river watershed on optical satellite imagery from Google Earth. **A.** Fans partially coupled during the 2015 and 2016 debris flow event, contributing sediment to the main channel and forming a new fan lobe that led to main channel avulsion. **B.** Fans completely uncoupled during the 2016–2018 debris flow event, buffering all debris flow deposits on the fan surface.

lobes at the fan toe promotes main channel avulsions, which can trigger downstream erosion of fans that were previously shielded from river trimming, as demonstrated in analogue experiments (*e.g.*, Savi et al., 2020).

Once we have all the flows identified in the fans and account for the temporal sequencing of debris flow surges, we can discuss which facies associations are predominant in each fan. By identifying the facies associations present at different times in the fans, we can construct a time series to understand how the distribution of facies associations varies over the studied period. This analysis will help us to identify fans where one facies association predominates over another (see subsection 5.1, Fig. 8).

The identification of AF1 and/or AF2 in the fans using optical imagery available from, i.e., Google Earth, is based on the criteria outlined in Table 1 and the equivalence with ground sedimentary facies evidence presented in Fig. 3, Fig. S3 and the methodological framework of facies identification is detailed in Cabré et al. (2020a). It is important to differentiate between the two main mechanisms of sediment transport that lead to distinct AF1 and AF2 characteristics observable in optical satellite imagery.

AF1 facies association results from high viscosity and high-density flows, characterized by lobate debris flow patterns that form due to frictional freezing and sudden flow cessation (Iverson and Vallance, 2001). In contrast, AF2 facies association can be readily identified by the presence of bedforms typical of Newtonian flows.

5. Discussion

5.1. Fan formation controls

We observe how the facies associations in the fans vary with time (Fig. 8). Rather than attributing these variations solely to climatic triggers, our analysis reveals distinct patterns. Some fans show a characteristic formation of AF1+AF2, where initial AF1 deposits are subsequently overlain or dissected by AF2. This sequence suggests an evolution from cohesive debris flows initially, transitioning to higher

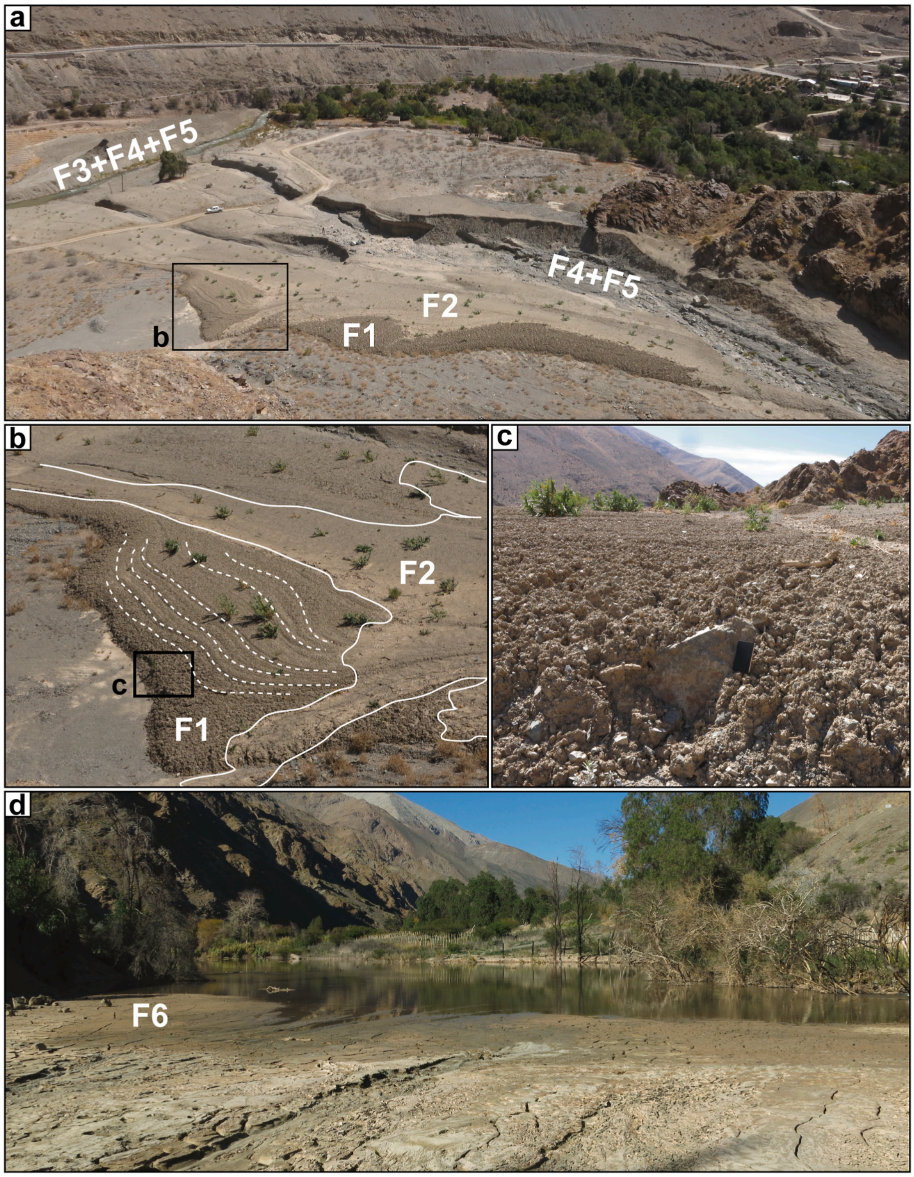

Fig. 7. Facies defined in Huasco 1 fan and oblique views (**a-b**) and detail of F1 in the field (**c**). **d**). F6 facies of the upstream dammed lake.

water-to-sediment ratios later due to increased rainfall intensity and runoff, suggested by the inferred presence of bedform in the imagery. Conversely, fans where only AF2 is present indicate that the fan configuration prevented the preservation of AF1 facies, likely due to subsequent reworking by the AF2 flows. This scenario is exemplified in Huasco_1 during the May 2017 debris flow event, where all debris flow surges were confined and deposited in the feeder channel (Fig. S2). Consequently, the preservation potential of AF1 facies association, if initially present, is minimal under these circumstances.

The presence of fans with varying total number of events during a specific period should not lead to any conclusions regarding occurrence frequency, as in this study the sampling was not exhaustive. Our focus is not on analysing event frequencies or correlating facies associations in fans of the Andes with regional climate conditions. Instead, we aim to understand how fans, characterized by different facies associations, serve either as sediment buffers or as sediment bypass zones in fluvial systems of the Andes.

When a fan is predominantly constituted by AF1, it expands and occupies the main-stem valley within a few years, resulting in the formation of multiple temporary lakes (see Iruya_2, Fig. S5). In contrast, fans dominated by AF2 are dissected (Figs. 3 and 6) and transfer sediments directly to the valley floor without blocking the main channel. Consequently, the prevalence of these sediments in the axial valley is minimal, as the river quickly reworks and incorporates them into the floodplain or transports them downstream. Therefore, the river sediment-transport capacity significantly determines the prevalence of the new lobes formed at the tributary fan toes. Fans with an area ratio below $2{\cdot}10^{-4}$ (see Table 2), such as those in San Juan and Jáchal, do not expand despite numerous debris flow events (4 and 3, respectively), due to the river's discharge power and subsequent high channel lateral mobility that trims fan toes. Similar conclusions have been drawn in analogue modelling experiments (Stancanelli and Musumeci, 2018; Stancanelli et al., 2015; Savi et al., 2020), where it has been observed that high sediment transport capacity and lateral mobility of the river limit the growth of tributary fans. However, further studies are needed to assess the hydrological regimes and the hydraulic role of the main-stem in preserving tributary fans in the Andes axial valleys, which is beyond the scope of this study.

Those fans formed in ephemeral valleys (4 of the total evaluated) are located in arid or hyper-arid regions and have exhibited minimal activation in the last 20 years. These fans are theoretically expected to be preserved due to their location in ephemeral valleys. However, this is

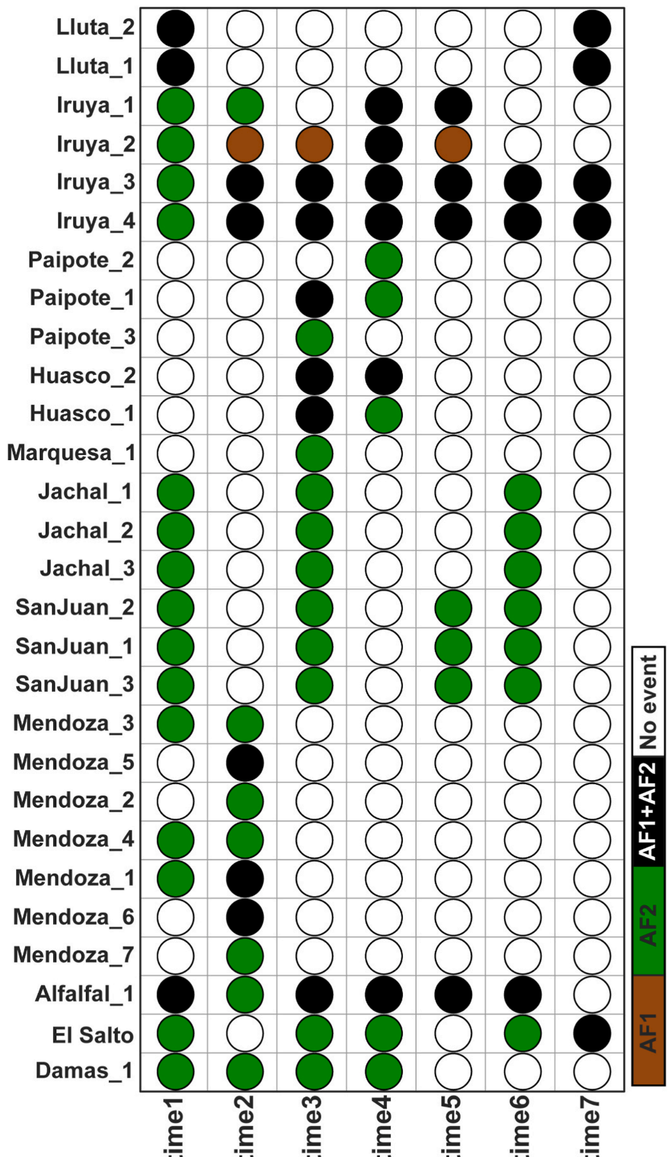

Fig. 8. This diagram illustrates the facies associations in each fan based on the events documented in the temporal analysis. The timing (1–7) is relative for each fan, spanning a 24-year period from around the year 2000–2024 (check Table S1). A timing of 1 'time 1' indicates events closest to the beginning of this period, while a timing of 7 'time 7' represents events occurring towards the end (2023–2024). White dots signify periods with no documented events in the fans. Given that we do not analyse regional trends in triggering mechanisms, comparison of facies associations across fans are not conducted. The fans listed on the Y-axis are arranged by latitude from north to south: Lluta_2 (~18°S) and Damas_1 (~34°S).

not always the case. We have observed that these fans, primarily formed during extreme rainfall events (*e.g.*, March 2015 or May 2017), become active during regional storms that simultaneously activate multiple catchments. These rainstorms generate surface runoff that results in large flash floods (Wilcox et al., 2016; Aguilar et al., 2021; Cabré et al., 2020b). If a fan was activated shortly before a flash flood traverses the axial valley, post-storm mapping reveals erosion of the fan by the axial drainages, thereby restricting the expansion of these fans in the ephemeral valleys.

5.2. Role of facies associations in the construction and destruction of tributary alluvial fans

In confined valley settings, the formation and preservation of fans benefits from the deposition of cohesive debris flows and diluted debris flows (Figs. 3 and 6 and Fig. S4). High-density flows contribute to build-up of fans, while cohesionless debris flows, hyper-concentrated deposits and tractional flows facilitate the coupling between the tributary catchments and the trunk valley. References to studies such as Mather and Stokes (2017), Moreiras et al. (2018), Vergara Dal Pont et al. (2018), and Cabré et al. (2020a) provide insights into these processes in other mountain ranges and/or regions of the Andes. This interaction is illustrated by the formation of distal lobes at the fan toe, resembling telescopic-like fans *sensu* Colombo (2005).

Cabré et al. (2020a) demonstrated that cohesive debris flows facies were responsible for the deposition of large volumes of sediments in the upper surface of tributary fans in the El Huasco river valley (29°S). In contrast, low-density flows such as diluted debris flows and hyper-concentrated to stream flow deposited sediment within the fan feeder channels or in the lobes formed at the fan toe on the valley floor. These different flows with varying sedimentological properties illustrate how debris flows control the geomorphic evolution of fans, influencing sediment fluxes in fluvial systems of the Andes.

The integration of facies associations recorded for each event in the studied fans, and their role in fan evolution -whether in formation or destruction of the fan-is depicted in Fig. 9. This figure considers the geomorphological expression of the evolution based on sediment supply and flood power at every time the fan is active and categorizes flow types by water amount and sediment supply, based on Costa (1984, 1988), Hutchinson (1988) and Iverson (1997) limits for typical unit weight values (Fig. 9b).

When combining both figures (Fig. 9c), we can qualitatively plot the debris flow events for fans where field controls exist: Lluta_1; Lluta_2, Huasco_1; Huasco_2, Damas_1, Marquesa_1, Paipote_1; Paipote_2 and Alfalfal_1 fans. To simplify the information of Fig. 9b into Fig. 9c, we classify debris flows into Low-density (LdF) and High-density Flows (HdF) (Harvey, 2012). This classification helps integrate variations in their composition and corresponding unit weights, as observed in fans where bedforms cover larger areas with thinner accumulations (AF2).

Low-density flows unit weights are <1.8 t m^{-3}, indicating a greater proportion of water relative to sediments. In contrast, High-density flows have unit weights >2.4 t m^{-3}, with less water and a higher proportion of sediments (Costa, 1984, 1988; Hutchinson, 1988; Iverson, 1997). These flows are more viscous and display slower movement, often resulting in thick lobe accumulations on the fans (AF1), due to mechanisms like frictional freezing.

Summarizing all facies associations into High or Low-density flows indirectly allows us to infer specific triggering factors within catchments (*e.g.*, intense rainfall, higher presence of landslides, etc.). However, the local terrain conditions such as soil-types, infiltration capacities, etc. significantly influence the composition and density of debris flows, and therefore detailed field studies are needed for accurate assessment.

We observe that most fans lie between the deposition and progradation domains, with only three events in Alfalfal_1, Damas_1 and Huasco_1 fans occurring at the boundary between progradation and dissection. Most events falling in deposition domain in Fig. 9c are consequence of AF1+AF2 deposition, while all the events that fall on the limit of deposition and progradation, or within progradation, are represented by the AF2 facies association. The amount of sediment available during the rainfall events that trigger runoff is always sufficient to prevent any event at any fan from falling completely within the dissection domain. However, such diluted events might not leave significant deposits on the fan or on the fan toe, meaning our analysis of multi-temporal satellite imagery may have overlooked them. Nevertheless, any such events are of sufficient magnitude to cause significant geomorphic change in the fans identifiable in the imagery.

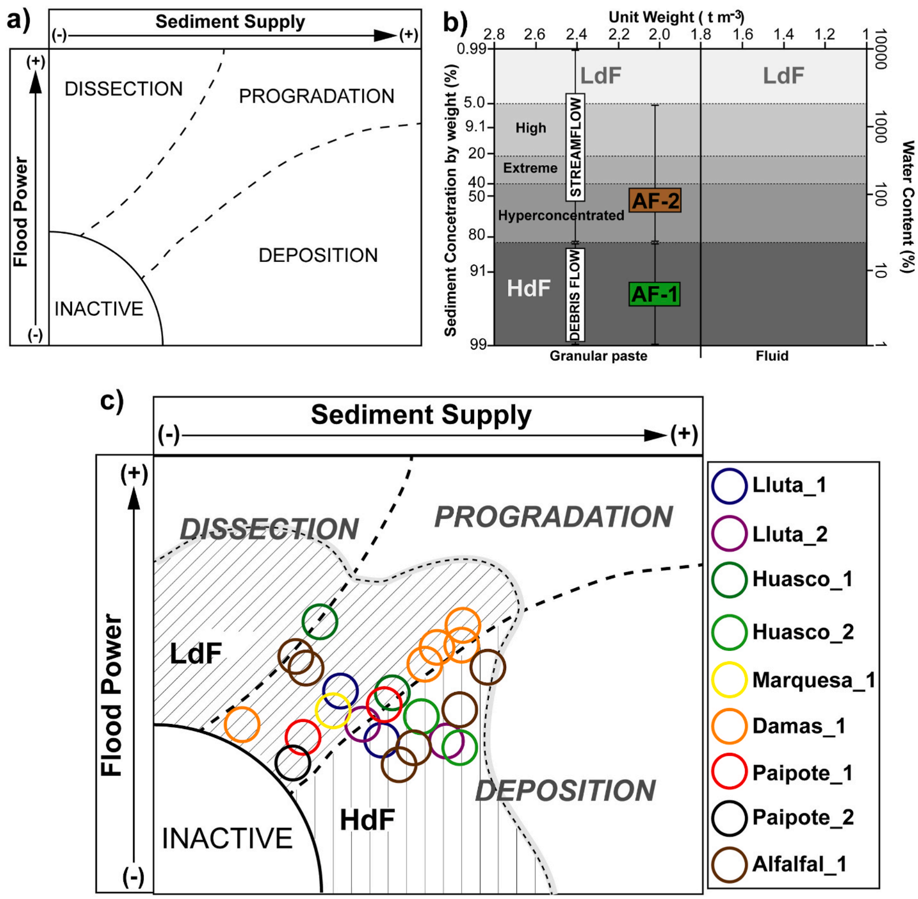

Fig. 9. **a**) Diagram modified from Harvey (2012) illustrating sediment supply and flood power relationships and **b**) diagram modified from Mather (2007), previously defined in Hutchinson (1988), showing flow types dependent on water amount and sediment supply based on unit weight values from Costa (1984, 1988), Hutchinson (1988) and Iverson (1997). Readers can refer to Costa's (1988) rheological characteristics of flow types in Table S2 **c)** The proposed graph after combining diagrams **a**) and **b**), depicting reported flood events for visual comparison for 9 fans that were visited multiple times in the field. All 28 fans are plotted in Fig. S6.

In conclusion, we see that most events at the studied fans result in progradation, indicating that these fans have an immediate effect on longitudinal sediment transport, either by providing 'new' sediments to the trunk valley and/or segmenting sediment transport downstream along the mainstem.

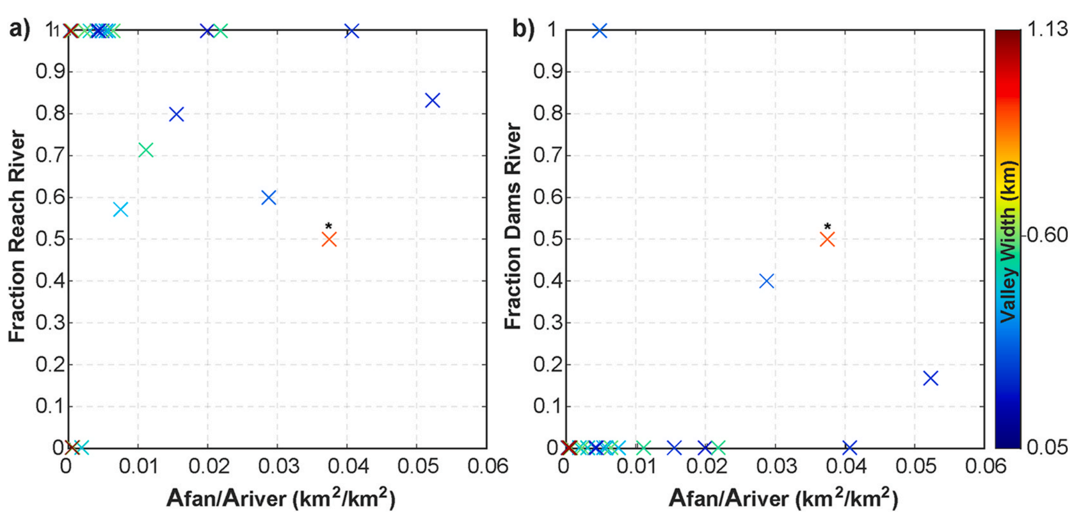

Fig. 10. Plots of all fans show the ratio of fan catchment area divided by river catchment area on the x-axis, versus the fraction of flow that reaches the river (**a**) and the fraction of flows that dam the river (**b**). The colour legend of the z-axis represents valley width in kilometres. These plots illustrate that valley width is not the primary control of main channel blockages. An asterisk (*) denotes the Iruya_1 fan, a fan which is strongly influenced by its neighbouring fan (Iruya_2), a highly active lateral sediment input that further amplifies the impact of Iruya_1 to the axial valley.

5.3. Fan-river interactions

Our analysis indicates that there are fans where all debris flow events have reached the trunk valley (Fig. 10a). However, the number of times where the fans blocked the river is low (Fig. 10b). The fact that many fans deliver sediments to the river at any event is, a priori, an indicator that debris flow events might be influencing the river in the longitudinal valley. Moreover, the fact that these fans do not block the river also implies that the rivers have high transport capacities. While one might initially assume that debris flows reaching the trunk valley without blocking the main channel occur because the valley is wide, Fig. 10 reveals that most fans where sediments reach the valley do not exceed 0.6 km in width (except for one fan). This suggests that there may not be a direct relationship between valley width and the preservation or occurrence of the main channel blockages.

As shown in Fig. 10b, during most events, fans are not capable of blocking the river, spanning the entire range of valley width values in the dataset studied. This observation is interesting as it suggests that valley width may not significantly determine fan evolution over the studied timescales (*e.g.*, Harvey, 1996; Hobley et al., 2011; Harries et al., 2023). Instead, the formation or destruction of fans seems to be controlled by the steady-state conditions of the river, such as the regional base level and climatic conditions reflected in the drainage watershed of the main river, which are considered constant in the evaluated time series.

Therefore, the only distinguishing factor influencing fan formation or destruction appears to be related to the characteristics of the flows. The defined facies associations simplify the evaluation of flow types in each fan activation event, eliminating the need for field visits. In conclusion, when AF1 is present or dominates over AF2 during the same event, the fan buffers sediments by stacking debris flow lobes vertically. This is evidenced by the thickness of deposits in Lluta_1; Lluta_2 (Figs. S4d–f), and Alfalfal_1, observed in the field and shown in Figs. S4a–c. Conversely, when AF2 predominates, fans tend to prograde either through entrenched feeder channels or by incising new channels in the fan, causing destruction and the formation of new lobes at the fan toe.

Interestingly, the cumulative effect of numerous debris flow events can be observed in the characteristics of the trunk valley upstream of the fans. Thus, fans contribute to the formation of a broad and extensive alluvial plain with multiple active channels upstream, compared to the narrower average sections located downstream of the fan. The river's transport capacity diminishes as it divides among multiple channels. This indicates that the cumulative effect of multiple debris flow events creates a large accumulation zone upstream of the fans (Fig. 5b–Fig. S5). This 'segmentation effect' on longitudinal sediment transfer is solely caused by the formation of tributary fans and do not require large landslide events (*e.g.*, d'Odorico-Benites et al., 2009; Antinao and Gosse, 2009) to widen the valleys (*e.g.*, Harries et al., 2023). Therefore, as a recommendation for future research, it will be necessary to consider both the number of events (frequency) and their potential to block the river.

Some studied fans situated in an ephemeral drainage system have received only one event, thus having little potential to segment longitudinal sediment transfer. In contrast, we observe that fans causing most river blockages are found within variable valley widths such as the Iruya_1 fan (*) (Fig. 10). Iruya_1 is an example of a fan with five events recorded in the studied period that is strongly influenced by another fan situated on the opposite side of the valley. In Iruya_2, two out of five flow events are dominated by AF1 facies associations, indicating large areas of deposition in the valley and presumably substantial sediment volumes capable of blocking the valley flooding large areas upstream. The cumulative effects of neighbouring fans are not explored in this study. However, they likely exert a strong influence on the longitudinal segmentation of fluvial systems in the Andes as exemplified in Fig. 5b and Fig. S5.

The high incidence of main channel-blocking events is likely accentuated by the combined effect of two fans at the same point along the axial valley, rather than being solely attributed to a single fan (Fig. 10). This 'double activation' effect on both sides of the valley is significant because it amplifies the influence of fans on the axial system and, therefore, the longitudinal sediment fluxes, contributing to segmentation that has persisted for at least two decades in the river segments.

We observe that one fan we visited during fieldwork (Huasco_1) has caused two main channel blockages despite experiencing only two debris flow events over the studied time span. This can be attributed to the narrow valley width section of 0.31 km, where the two events created a new lobe at the fan toe, leaving a small space for the main channel (<5m). The relatively short time interval between the two events, despite occurring in an arid climate region (03/2015 and 05/2017), has resulted in the maintenance of a semi-permanent blockage upstream. This blockage has led to the formation of a large floodplain with vegetation and a marshy environment, with river exhibiting a streamflow of $<3\ m^3/s$ in between extreme hydrometeorological events and annual snowmelt season (Fig. S1). Consequently, this has reduced the river's streamflow before reaching the fan, decreasing its transport capacity and, consequently, the erosion capacity at the base of the new fan lobe formed. As a result, the partial river blockage has persisted for nine years.

We acknowledge that the limited and irregular availability of optical images in the Google Earth catalogue over the considered period may result in missing short-duration river blockages. However, these potential blockages, caused by small-magnitude flood events, do not significantly affect longitudinal sediment fluxes or valley evolution. Therefore, their absence on the imagery (mapped flows) does not impact either the fan evolution or the longitudinal sediment flux analysis.

5.4. Consequences of human interventions in tributary alluvial fans of the Andes

Tributary alluvial fans are the only areas in Andean valleys where slopes are gentle enough for buildings and where agriculture can thrive. Despite their importance, the occupation of these areas has often been poorly planned, particularly in the arid regions of the Andes (Cabré, 2019; Dame et al., 2023). The fact that some fans have not been active in the last 20 years is a latent hazard that disregards infrequent debris flows, leading to the misconception of the hazard by the communities that settle there (Figs. S7 and S8). Fig. S8 provides examples to underscore the importance of studying tributary alluvial fans along the Andes Cordillera, a topic that remains poorly studied. Thus, understanding the sediment dynamics and geomorphology of these fans can help in mitigating natural hazards effect on communities under development in the Andes. This objective aligns with the Sendai framework for disaster risk reduction (United Nations, 2015), which emphasizes the need to understand risk and enhance disaster preparedness. By aligning our results with this framework, we can foster safer, more resilient, and sustainable communities inhabiting tributary fans in the Andean valleys.

6. Conclusions

The definition of facies associations (AF1 and AF2) facilitates the understanding of how tributary alluvial fans are formed during episodic sedimentation events. Currently, most national inventories of debris flows from geological surveys, such as those by SERNAGEOMIN in Chile and INGEMMET in Perú (*e.g.*, SERNAGEOMIN, 2017; Uribe, 2020; INGEMMET, 2021), consider debris flows as a single volume of sediment without further interpretation of their surge sedimentology. Moreover, our division into facies associations can help clarify the fan-river coupling status and therefore the longitudinal sediment transfer along the axial valleys.

We provide a simple but effective mapping criterion to relate ground sedimentary facies to AF1 and AF2 facies associations in tributary fans of the Andes, which can be mapped using open-access optical imagery for any tributary fan. We believe this method can be easily implemented by national organizations responsible for debris flow inventories, eliminating the need for field visits to validate each fan.

The spatial variability in fan activation causes significant segmentation of longitudinal sediment transfer along the axial valley, as exemplified by the partial damming caused by new lobes formed at the fan-river intersections. The heterogeneous yield of sediments from catchment to fans, or from fans to the trunk valley, has been described as the coupling dynamics of these geomorphologic systems (*e.g.*, Mather et al., 2017). This results in selective sediment supply to the alluvial fans or towards the trunk valley (*e.g.,* Jaeger et al., 2017; Cabré et al., 2020a). Therefore, tributary fans provide ideal locations to investigate local effects of atmospheric perturbations, in contrast to the regional signatures preserved in the longitudinal valleys of the Andes (Veit, 1996; Riquelme et al., 2011; Cabré et al., 2017).

CRediT authorship contribution statement

Albert Cabré: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Germán Aguilar:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Ferràn Colombo:** Writing – review & editing, Visualization, Investigation, Conceptualization. **José Luis Antinao:** Writing – review & editing, Investigation. **Diego Iturra:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Albert Cabré reports financial support was provided by National Agency for Research and Development (ANID) and DAAD-PRIME. Jose Luis Antinao reports financial support was provided by National Agency for Research and Development (ANID). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsames.2025.105442.

Data availability statement

Imagery is available in Google Earth so it is the DEM used. Locations of the studied fans is available on a *.kmz file in the supplementary information. All data is available in the main text or the supplementary materials. Any additions material requests should be directed to A. Cabré. Imagery is available in Google Earth so it is the DEM used. The studied fans are in a kmz file.

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