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MASS MOVEMENTS IN CRYOSPHERIC ENVIRONMENTS AND THEIR IMPACT ON THE LANDSCAPE: EXAMPLES FROM THE CHILEAN CENTRAL ANDES

MOVIMIENTOS DE MASAS EN AMBIENTES CRIOSFÉRICOS Y SU IMPACTO EN EL PAISAJE: EJEMPLOS DE LOS ANDES CENTRALES CHILENOS

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RESUMEN: Los glaciares se caracterizan, entre otras características, por ser grandes esculturas del paisaje. La fuerza erosiva de su avance y retroceso deja huellas morfológicas como morrenas, circos glaciares, flautas, entre otros. Estos elementos son claros indicios del ambiente glaciar tanto pasado como presente y favorecen la comprensión de los procesos que originan un relieve de alta montaña. A pesar de esto último, existen otros fenómenos derivados del ambiente glaciar que pueden tener un impacto repentino e intenso sobre el paisaje. Tal es el caso de los movimientos en masa relacionados con los glaciares. Entre ellos se encuentran las avalanchas de rocas y hielo, los desprendimientos catastróficos de glaciares, las oleadas glaciares y las inundaciones repentinas de lagos glaciares. De igual modo, los flujos de detritos originados en frentes de glaciares de roca activos también constituyen ejemplos de estos últimos. En este artículo se analizan varios casos de movimientos en masa ocurridos en el último siglo en los Andes centrales de Chile (30°S-35°S). En primer lugar, se evalúan los efectos del avance glaciar de 1947 del glaciar Juncal Sur (33,10°S/70,11°W) sobre las cabeceras del valle del río Olivares, cuyas estrías glaciares son aún reconocibles en la actualidad. Casi en el mismo sitio, se informa el resultado de un avance glaciar de 1992 originado en un pequeño glaciar de valle debajo de la cara sur del Cerro Risopatrón (33,16°S/70,07°W), cuyo depósito de montículos se encuentra al final del frente de avance del glaciar Juncal Sur. Al mismo tiempo, se presentan evidencias geomorfológicas posteriores al catastrófico desprendimiento de 1980 del glaciar Aparejo (33,56°S/70,01°W), en forma de estrías y flautas glaciares, que se asemejan en gran medida a la condición previa al desprendimiento en 1956, lo que sugiere un posible evento previo de proporciones similares. Esta condición también se evidencia en el Glaciar Tinguiririca 3 (34,78°S/70,31°O), en la forma de un colapso potencial previo a 1970. Finalmente, también se reporta el impacto de un flujo de detritos originado en el frente glaciar del glaciar de roca CL105400105 (33,01°S/70,08°O). El evento, ocurrido en enero de 2024, dejó una marcada huella de detritos en el Glaciar Juncal Norte, cuyos potenciales efectos sobre el glaciar aún deben evaluarse. Con base en la evidencia analizada, afirmamos que es posible distinguir entre características geomorfológicas

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de diferentes movimientos en masa relacionados con los glaciares que coexisten en una sola ubicación. También proponemos que los grandes peligros glaciares pueden anular la huella de los cambios glaciares de largo plazo, lo que plantea un mayor factor de control para la construcción del paisaje. El análisis de estos fenómenos es relevante para evaluar la recurrencia de movimientos de masa en ambientes criosféricos, comprender sus causas y estimar su magnitud en zonas de alta montaña.

Palabras clave: glaciares; glaciares de roca; movimientos en masa relacionados con los glaciares; peligros glaciares, Andes, Chile.

ABSTRACT: Glaciers are known, among their many features, for being great landscape sculptures. The erosive force of their advance and retreat leaves morphological prints such as moraines, glacial cirques, flutes, among others. These elements are clear indications of both past and present glacial environment and favour the understanding of the processes that originates a high mountain relief. Despite the latter, there are other phenomena derived from the glacial environment that can have a sudden and intense impact on the landscape. Such is the case of glacier-related mass movements. These include rock and ice avalanches, glacier catastrophic detachments, glacier surges and Glacial Lake Outburst Floods. Similarly, debris flows originated from active rock glacier fronts also constitute examples of the latter. This contribution analyses several cases of mass movements that occurred in the last century in the central Andes of Chile (30°S-35°S). Firstly, the effects of the 1947 surge of the Juncal Sur Glacier (33.10°S/70.11°W) on the headwaters of the Olivares River valley are assessed, whose glacial striations are still recognisable today. At nearly the same site, the result of a 1992 glacier advance originated from a small valley glacier beneath the south face of Cerro Risopatrón (33.16°S/70.07°W) is reported, whose hummocky deposit lies at the end of the Juncal Sur Glacier surging front. At the same time, geomorphological evidence is presented after the 1980 catastrophic detachment of Aparejo Glacier (33.56°S/70.01°W), in the form of glacial striations and flutes, which extremely resemble the pre-detachment condition in 1956 suggesting a possible previous event with similar proportions. This condition is also evident on the Tinguiririca 3 Glacier (34.78°S/70.31°W), in the form of a potential collapse prior to 1970. Finally, the impact of a debris flow originating from the glacier front of the CL105400105 rock glacier (33.01°S/70.08°W) is also reported. The event, which occurred in January 2024, left a marked debris imprint on the Juncal Norte Glacier, whose potential effects on the glacier remain to be assessed. Based on the analysed evidence, we state that it is possible to distinguish between geomorphologic features of different glacier-related mass movements coexisting in a single location. We also propose that large glacier hazards can overthrow the imprint of long-term glacier changes, posing a higher controlling factor for landscape building. Analysing these phenomena is relevant for the evaluation of the recurrence of mass movements in cryospheric environments, to understand their causes, and to estimate their magnitude in high mountain areas.

Keywords: glaciers; rock glaciers; glacier-related mass movements; glacier hazards, Andes, Chile.

INTRODUCCIÓN

Glaciers are known, among their many features, for being great sculptures of the landscape. The erosive force of their advance and retreat leaves morphological prints such as frontal and lateral moraines, glacial cirques, glacial flutes, subglacial till, among others (Menzies and Ross, 2022). These elements are clear indications of both a past and present glacial environment and favour the understanding of the processes that originates a high mountain landsystem (Benn and Evans, 2014). Despite the latter, there are other phenomena derived from the glacial environment that can have a sudden and intense impact on the landscape. Such is the case of glacier-related mass movements (Iribarren-Anacona et al., 2015; Evans et al., 2021). These include rock and ice avalanches, sudden large-volume glacier detachments, glacier surges and Glacial Lake Outburst Floods (GLOFs). Similarly, debris flows originated from active rock glacier fronts along with landslides emplaced on glaciers also constitute examples of the latter (Deline et al., 2021; Evans et al., 2021). The geomorphological imprint assessment of glacier-related mass movements is a challenging task as the resulting erosive and depositional landforms usually coexist with those whose glacial origin is mainly linked to long-term glacier changes (Benn and Evans, 2014).

This spatio-temporal relationship can become even more conspicuous when considering the cyclic component of glacier-related mass movements, such as the case of glacier surging (Evans and Rea, 2014). Although recent research has contributed significantly on the matter (Evans and Rea, 2014; Cook et al., 2018; Kääb et al., 2021; Jacquemart et al., 2022; Bondesan and Francese, 2023), regional assessments efforts are required in order to improve knowledge gaps related to unresolved questions such as:

- Can the recurrence of glacier-related mass movements overthrow the geomorphic imprint of long-term glacier changes (advance and retreat periods)?

- Is it possible to distinguish features of different glacier-related mass movements coexisting in a single location?

Table 1: Glaciers and glacier-related mass movements assessed in this study.

Glacier	Primary classification	Latitude (°S)	Longitude (°W)	Medium elevation (m a.s.l.)	Type of mass movement	Year	Reference
Rocoso Juncal Norte	Rock glacier	33.010	70.083	4,106	Debris flow	2024	This work
Juncal Norte	Valley glacier	33.024	70.101	4,556	Debris flow	2024	This work
Juncal Sur	Valley glacier	33.096	70.113	4,391	Glacier surge	1947	Lliboutry (1956)
Estero del Plomo Superior	Mountain glacier	33.165	70.071	5,091	Ice avalanche	1956, 2016	This work
Estero del Plomo Inferior	Valley glacier	33.174	70.098	3,452	Collapse	1992	This work
Aparejo	Glacieret	33.563	70.009	3,542	Glacier detachment	1980	Ugalde et al. (2024)
Tinguiririca 3	Valley glacier	34.782	70.309	3,990	Collapse	<1967	Kääb et al. (2021)

Source: Own elaboration.

This contribution analyses several cases of mass movements that have occurred in the last century in the Chilean central Andes (30°S-35°S). We present compiled evidence from recent and historical footage, aerial and satellite imagery, recently published literature along with a geomorphological mapping for most of the analysed events. The main objective of our study is to provide new insights regarding novel and little-known cases of glacier-related mass movements, as well as to provide a recognition of its common geomorphological features.

Our study site comprises 5 different mass movements events at 4 different locations (Figure 1) across the Valparaiso, Metropolitan and O'Higgins regions spanning 69 years from 1955 to 2024. Our analysis considers 1 mountain glacier, 4 valley glaciers, 1 rock glacier and 1 glacieret. Table 1 summarizes the specific details for each assessed glacier, along with their associated glacier-related mass movement, according to this study and to the information of the 2022 Chilean Public Glacier Inventory, published by the General Water Directorate (DGA, 2022).

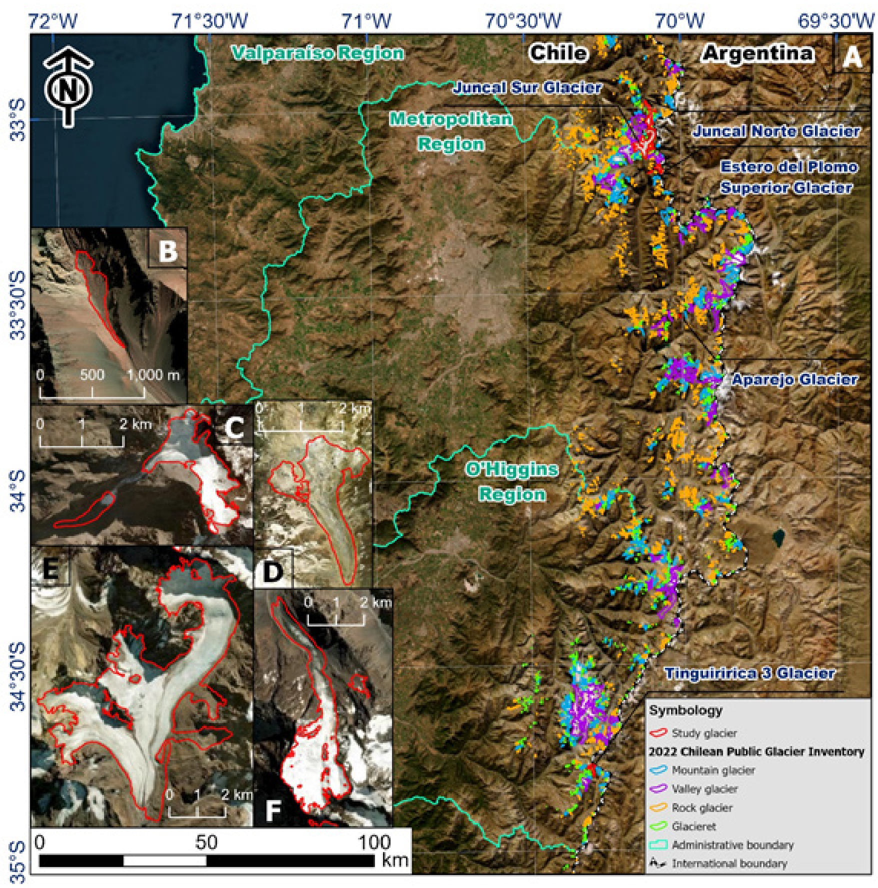


Figure 1: The study site comprises 5 different mass movement events in 4 different locations (Valparaíso, Metropolitana and O'Higgins regions from 1955 to 2024.
Note: A) Main view of the study area. B) Aparejo Glacier. C) Estero del Plomo glaciers. D) Tinguiririca 3 Glacier. E) Juncal Sur Glacier. F) Juncal Norte Glacier. Outlines from: Aparejo Glacier extracted from Ugalde et al. (2024a).

The climate of the study area is Mediterranean, with an extended dry season according to the Köppen classification (Peel et al., 2007). Although precipitation occurs mostly in winter (Carrasco et al., 2008), current temperature and precipitation trends have varied inversely, according to the 13 years-lasting megadrought of the central Andes (Garreaud et al., 2019), in the form of a general decrease in winter precipitation along with a sustained increase in mean air temperature.

METÓDO

Inputs and Datasets

We combined a revision of published literature regarding the analysed glacier-related mass movements events (Table 1), which includes the works of Lliboutry (1956), Muñoz et al. (2015), Kääb et al. (2021) and Ugalde et al. (2024a) for the Juncal Sur, Tinguiririca 3 and Aparejo glaciers cases. As for the Juncal Norte and Estero del Plomo glaciers events (Table 1) we present mostly conference-published data (Carrasco et al., 2024; Ugalde et al., 2024b) along with novel analysis described in the following section. We also employed historical archives comprising in-situ photographs from mid-20th century taken by Eberhard Meier, one of the mountaineers from the Andean German Club, or DAV (Deutscher Andenverein) on his 1950 expedition to the Nevado del Plomo massif, along with geographic maps from 1937 and 1954 for the Olivares River. The latter includes both Juncal Sur and Estero del Plomo glaciers (Barrera, 1937; Lliboutry, 1954).

As for the comparison analysis of the before and after situation for all events, we processed aerial photographs for the years 1955 and 1997, Hycon and SAF-GEOTEC surveys, respectively. We processed Planet-Scope imagery specifically for the Juncal Norte Glacier debris flow episode. High resolution Google Earth Pro archive imagery was employed for a revision of the last decade situation for the assessed glaciers. Complementarily, elevation for all glacier outlines was derived from SRTM data (Farr et al., 2007). Table 2 provides a summary of the details for the referred inputs.

Table 2: Collected historical maps, aerial photographs and satellite images for the revision of glacier-related mass movements events in this study.

Year/Date	Survey	Source	Spatial resolution (m)
1935	Map	Barrera (1937)	n/a
1954	Map	Lliboutry (1954)	n/a
1955	Hycon	IGM	1.5
1997	GEOTEC Flight	SAF	1.5
2000	SRTM	USGS	30
20/02/2017	Airbus	Google Earth Pro	0.5
19/01/2023	Airbus	Google Earth Pro	0.5
27/01/2023	Airbus	Google Earth Pro	0.5
23/03/2023	WV02-Maxar	ESRI Basemap	0.5
26/01/2024	PlanetScope	Planet	3

Source: Own elaboration.

In order to identify detailed geomorphological features, we also used high-resolution 4K UAV images captured by a DJI Mavic Mini 2 survey performed on December 4th, 2022, at the Salto del Olivares (headwaters of the Olivares River), which was helpful for a geomorphological mapping of the Juncal Sur and Estero del Plomo glaciers foreland.

We processed all aerial photographs with the Agisoft Metashape Professional software (version 1.8). No Digital Elevation Models (DEMs) were generated attending the absence of Ground Control Points (GCP) measured in the field. However, a series of local GCP were used for each aerial dataset relative to recognizable features (rocks outcrops and boulders) on high-resolution Google Earth Pro imagery. All datasets were projected to the Universal Transverse Mercator (UTM) 19S zone. On the other hand, PlanetScope data was processed on ArcGIS Pro 3.2 for a false-colour combination using near-infrared, red and green spectral bands.

The comparison of Google Earth Pro imagery with the resulting photogrammetric aerial ortomosaics was performed visually on the referred software. Glacier outlines were generated for the year 1955 for all glaciers included in this study by manual delineation on ArcGIS Pro 3.2.

A geomorphological mapping of the headwaters of the Olivares River which, according to Lliboutry (1956), corresponded to the 1955 Juncal Sur Glacier's foreland, was performed by the direct analysis of the in-situ imagery captured by the UAV survey. For the latter, a 360° composite image was processed on Microsoft Image Composite Editor (ICE) v2.0.3 along with the Insta 360 Studio 2024 v4.9.2 visualizer. The specific mapping of the geomorphological features was then carried on building raster images on Inkscape v1.3, and then exported to high-resolution figures.

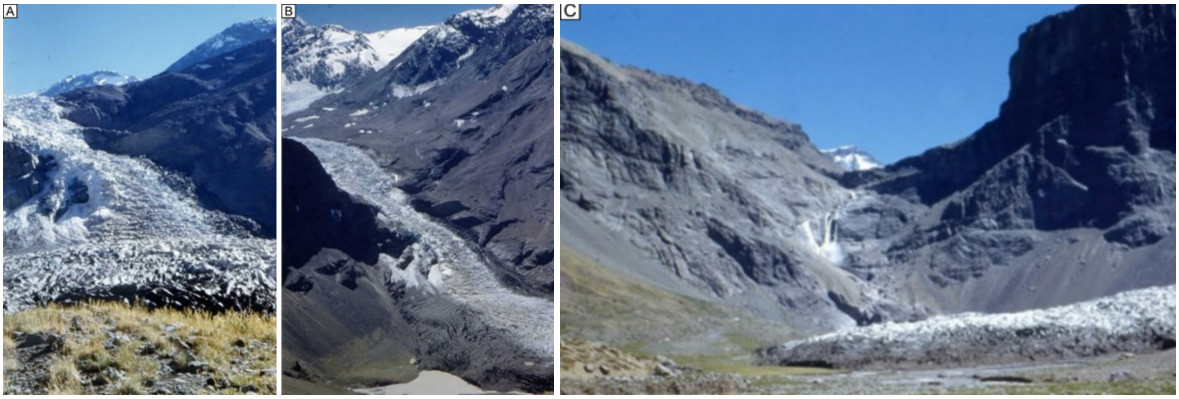


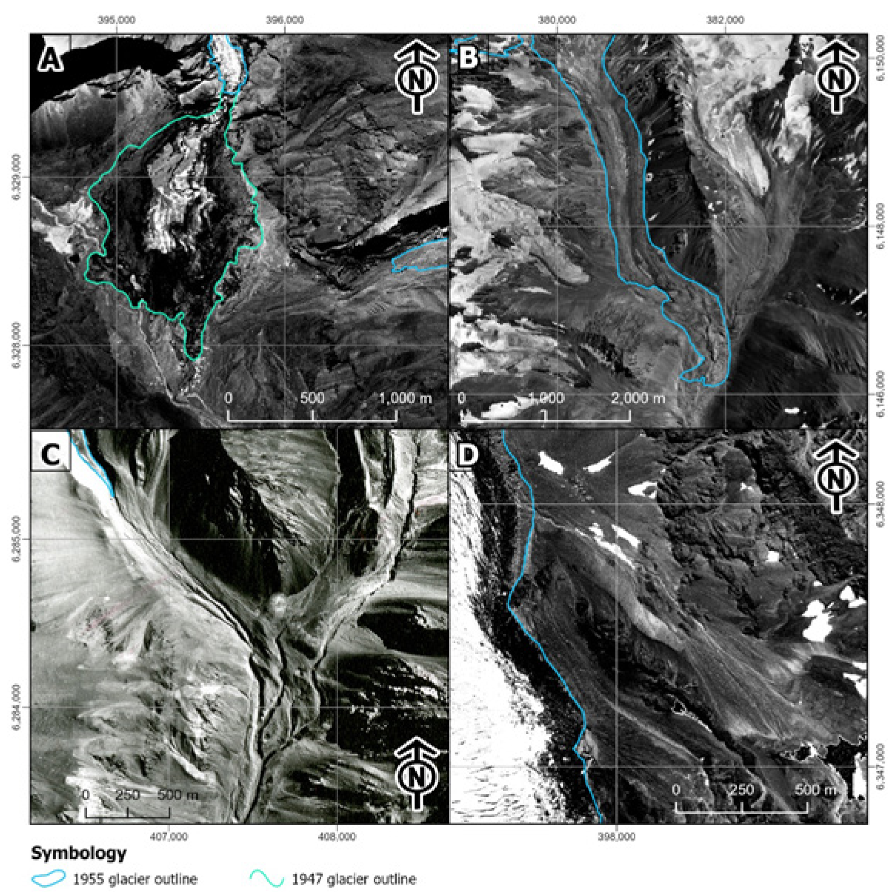
Figure 2: 1950 pictures showing Juncal Sur Glacier's front in the form of a small piedmont glacier. Note: A) crevassed Ice cascade bottom at the main valley, with several meters thick. B) chaotically crevassed glacier tongue in the middle course. C) Landscape view to the north, exposing the piedemont glacier. Credits: In-situ archive photographs taken by Eberhard Meier of DAV (Deutscher Anden Verein).

RESULTADOS

1947 Juncal Sur Glacier Surge

At the highest peaks surrounding the main glaciated area, thick and conspicuous volcanic rocks outcrops, mainly composed by andesites, basalts and ignimbrites, which corresponds to the large Farellones Formation (Rivano et al. 1990; Fock, 2005). In this context, the Juncal Sur Glacier surge was first reported by French glaciologist Lous Lliboutry as a sudden glacial advance in 1947 (Lliboutry, 1954; 1956). According to the author, the glacier advanced 3 km reaching the area below the Salto del Olivares cirque, 600 m below the original position of the front, as can be observed on Humberto Barrera's 1937 cartographic map (Barrera, 1937), constituting a small piedmont glacier (Lliboutry, 1954; 1956). This episode has been catalogued as suspected surging activity by numerous authors in recent literature, such as Malmros et al. (2016) and Falaschi et al. (2018). Lliboutry (1954) highlights the occurrence of a small GLOF due to the collapse of an ice dam which blocked the Olivares River after the sudden advance of Juncal Sur Glacier. Both the piedmont glacier and the blocked river are documented by the

Figure 3: 1955 historical glacier outlines.
Note: A) Juncal Sur and Estero del Plomo glaciers. B) Tinguiririca 3 Glacier. C) Aparejo Glacier. D) Juncal Norte Glacier.



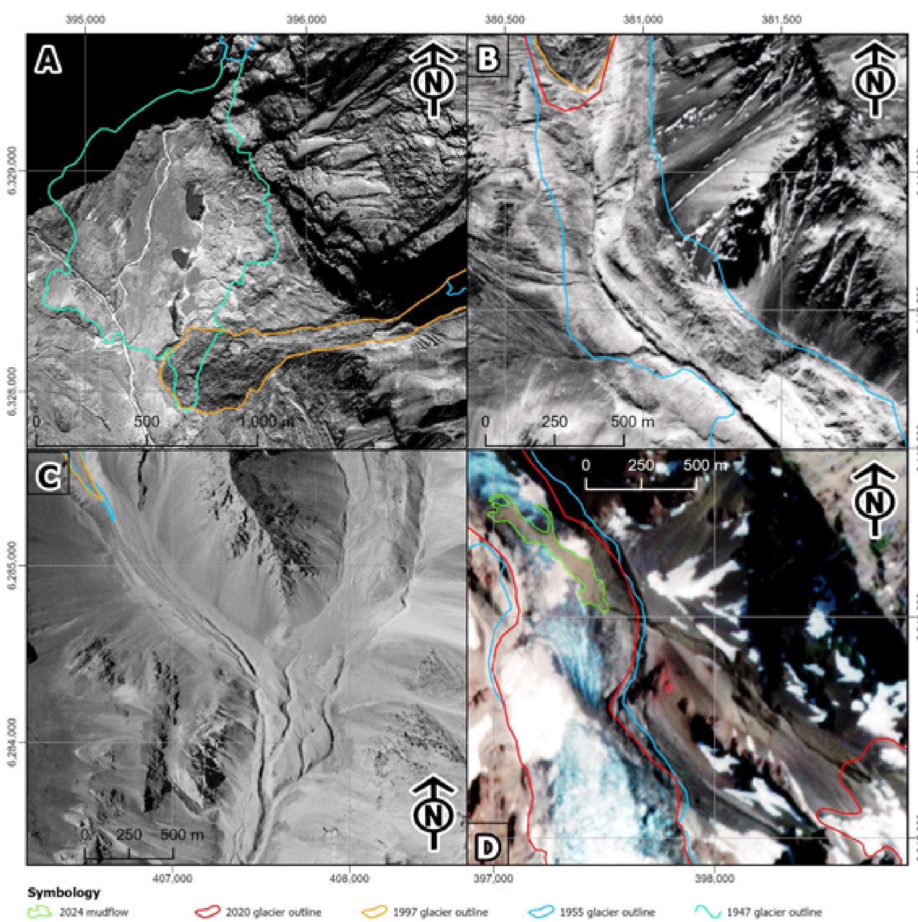
1950 in-situ photographs by DAV's member Eberhard Meier (Figure 2), which show a highly crevassed ice cascade followed by a chaotically crevassed glacier tongue.

Following the obtained outlines for 1955, we estimate the elevation of Juncal Sur Glacier's front to be at 3,100 m a.s.l. whereas the lowest position of the remnant ice of the small piedmont glacier is estimated at 2,790 m a.s.l. (Figure 3). Notably, current elevation of the glacier's front is estimated at 3,776 m a.s.l. according to the 2022 Chilean Public Glacier Inventory (DGA, 2022).

Pre-1962 Tinguiririca 3 Glacier Collapse

The Tinguiririca 3 Glacier overlies the southern flank of the homonymous active volcano. At the east is constrained by several stratified rock units, mainly Jurassic to Cretaceous clastic formations (Río Damas, Leñas-Espinoza, or Baños del Flaco), together with several Middle Miocene intrusive (Charrier, 2018; Sernageomin, 2003). The large north-south valley conformed southwards is frequently affected by large alluvial deposits or rockfalls, according to the steep slopes (>35°; Ramírez et al., 2023). In this situation,

Figure 4: Current and historical glacier outlines.
Note: A) Juncal Sur and Estero del Plomo glaciers. B) Tinguiririca 3 Glacier. C) Aparejo Glacier. D) Juncal Norte Glacier. Background image for panels A, B and C: 1997 aerial imagery. Background image for panel D: January 26th, 2024, PlanetScope image (colour infrared composition)



the glacier position was improved by the N-S configuration of the main geological structures and contacts, behaving as an area prone for the development of further mass movements due to its weaker geological setup.

Kääb et al. (2021) first proposed a poten-tial large pre-1970s detachment of Tinguiririca 3 Glacier. This hypothesis is sustained by a 1962 glacier front's elevation at 3,650 m a.s.l. (derived from Figure 19 on Kääb et al., 2021) in contrast to the current glacier's front elevation at 3,380 m a.s.l. (DGA, 2022), a feature that is shared with the Tinguiririca 3 Glacier's front position in 1997 (Figure 4B). In a more severe contrast, the 1955 scenario (Figure 3B), shows the glacier reaching, roughly, a minimum elevation of 3.100 m a.s.l. (a configuration which agrees with the results of Muñoz et al., 2015).

Such elevation differences accounts, at the same time, for a glacier retreat of 3,800 m from 1955 to 1962 followed by an advance of 1,200 m to its current position. On the other hand, Kääb et al. (2021) report positive elevation differences up to 120 on the glacier tongue from 1962 to 2000, suggesting thus a regrowth process of Tinguiririca 3 Glacier, and, at the same time, negative elevation differences of 10 to 15 m for the same period in the 1962 glacier's forefield, equivalent to the 1955 Tinguiririca 3 Glacier's tongue (Figure 3B), indicating the degradation of the glacier portion after its either sudden advance or detach before 1955.

This evidence suggests either a glacier catastrophic detachment, a glacier surge or even a large ice/rock avalanche. The latter is highly improbable as no escarpment is visible at the headwaters of Tinguiririca 3 Glacier. Nonetheless, the geomorphic imprint of the glacier's anomalous behaviour, likely in the form of a mass movements process, still remains in the form of debris stripes and large deposits of glacier moraines (Figure 4B, this study, and Figure 19 on Kääb et al., 2021). These features are shared with the glacier forefield configuration of Aparejo Glacier, as is assessed in the following section. Although we cannot assure, based on our evidence, the occurrence of previous glacier-related mass movements from Tinguiririca 3 Glacier, the observed glacier variations since 1955 allow us to sustain that glacier collapses are likely to be recurrent.

1980 Aparejo Glacier Catastrophic Detachment

In a similar scenario as the latter, Aparejo Glacier is found in a short north-south valley which inherit some of the structural weakness given by the poorly preserved, Mesozoic siliciclastic units (Colimapu and Lo Valdés formations). These units conform the surrounding slopes and the glacier bed (Ugalde, 2016; Kääb et al., 2021). The rocks have a hard vertical bedding, significant weathering and are commonly unstable, conditioning landslides or debris flows down valley.

In this configuration, the March 1st, 1980, Aparejo Glacier catastrophic detachment released an ice volume of 11.7 x 106 m^3, equivalent to the 90% of the total volume of the glacier (Ugalde et al., 2024a). The mobilized mass reached a distance of 3.7 km down valley at an estimated speed of 110 km/h leaving a geomorphological imprint which still persist to the day.

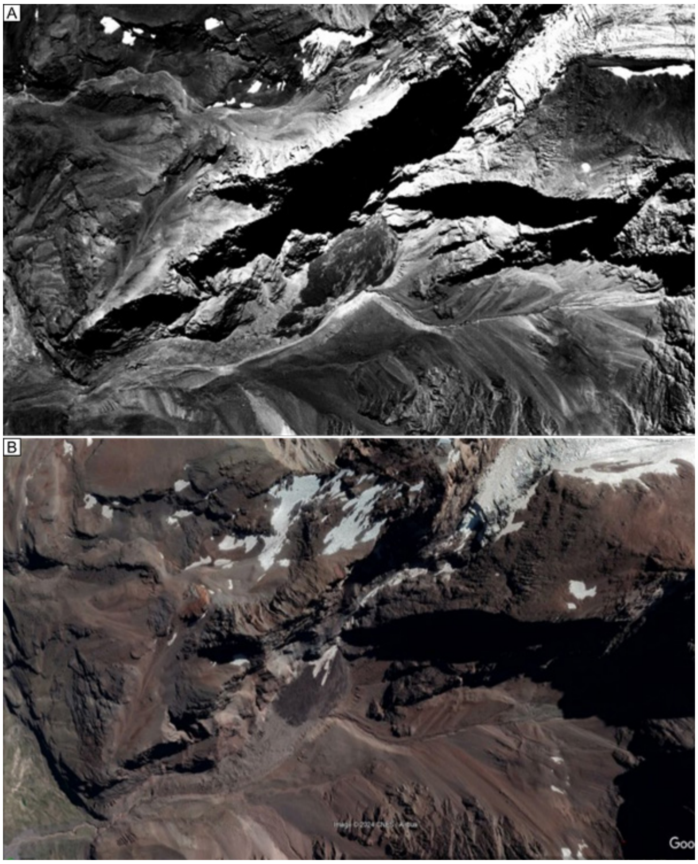
Although only 10% of the glacier remained after its sudden detachment, a small glacieret is still preserved within the same basin of the original glacier (Ugalde et al., 2024a). This recovering process of Aparejo Glacier can also highlight the possible recurrence of earlier glacier detachments. This idea has been already suggested by Kääb et al. (2021) when comparing the existence of debris stripes observed in the glacier forefield in 1956 aerial photographs and current satellite imagery.

Indeed, the whole geomorphological imprint of Aparejo Glacier forefield seen on pre-event imagery, such as 1950's aerial photographs (Figure 3C), resembles that of post-event imagery like the 1997 aerial photographs (Figure 4C) and beyond in time (Figure 15a on Kääb et al., 2021). In consequence, we cannot rule out the possibility of at least one glacier catastrophic detachment before 1955 released by Aparejo Glacier, sharing the recurrence with the Tinguiririca 3 Glacier scenario.

1992 Estero del Plomo Glacier Ice Avalanche and Possible Collapse

The Estero del Plomo glaciers are located relatively close to the Juncal Sur Glacier, but on the eastern flank of the valley and between 3,200 m a.s.. and 5,550 m a.s.l.. The more significative surrounding heights are conformed by Miocene volcanic

Figure 5: Estero del Plomo Glacier area.
Note: A) 1955 Hycon aerial photograph. B) 2017 archive Google Earth Pro satellite image (CNES/Airbus).

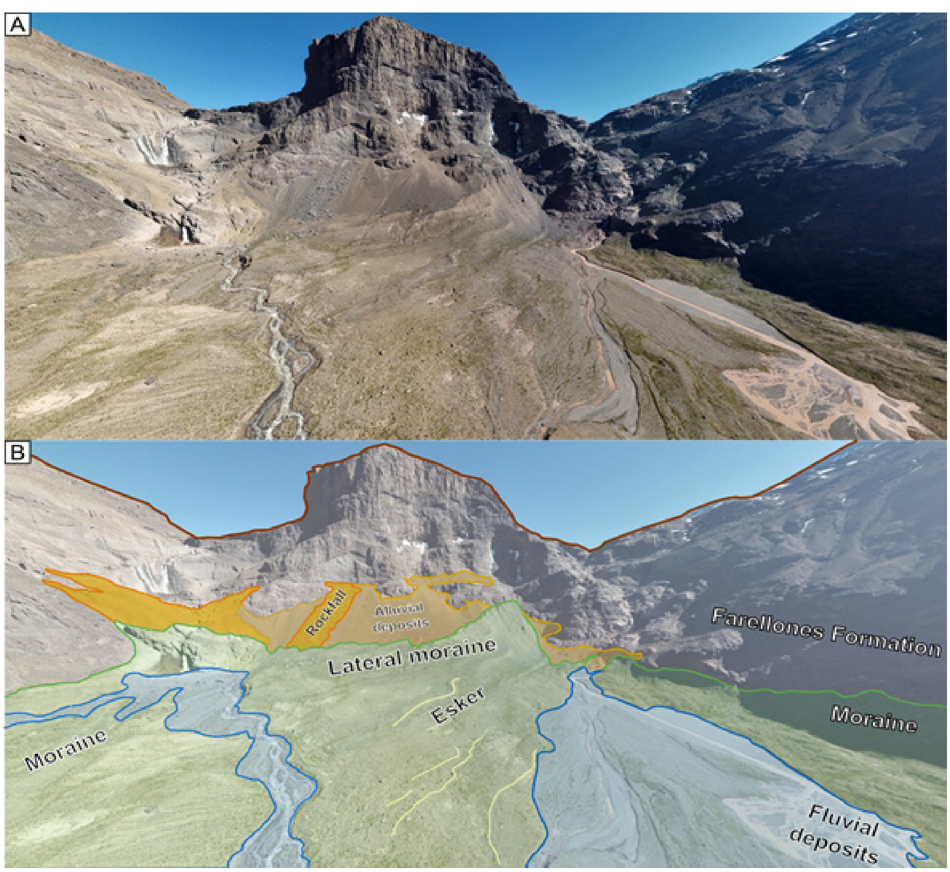


and volcaniclastic rocks belonging to the Farellones Formation, dipping slightly to the north (Rivano et al., 1990). In contrast, its competence and preservation are considerable better than the Tinguiririca 3 or Aparejo glaciers bedrock context. Nevertheless, there are other recent deposits submitted to differential erosion and weathering.

The Estero del Plomo glacier complex is composed by a mountain debris-free glacier and a valley debris-covered glacier. The latter occupies the lowest position within the Estero del Plomo creek. Although both glaciers are separated by a 750 m drop, the upper Estero del Plomo Glacier provides an ice and snow mass input to the lower glacier in the form of successive ice avalanches detached from its front (Figure 5). This highly recurrent process has allowed the lower valley glacier to sustain its extension and, likely, its mass, on an unaltered way through time, at least since 1955 (Figure 5).

However, in March 1992 the Estero del Plomo Inferior Glacier began an advancing period of nearly 1,4 km reaching and elevation of 2,790 m a.s.l., 400 m below its 1955 glacier front's elevation. This process was comprised by 3 different pulses reaching its maximum extent in July 1992.

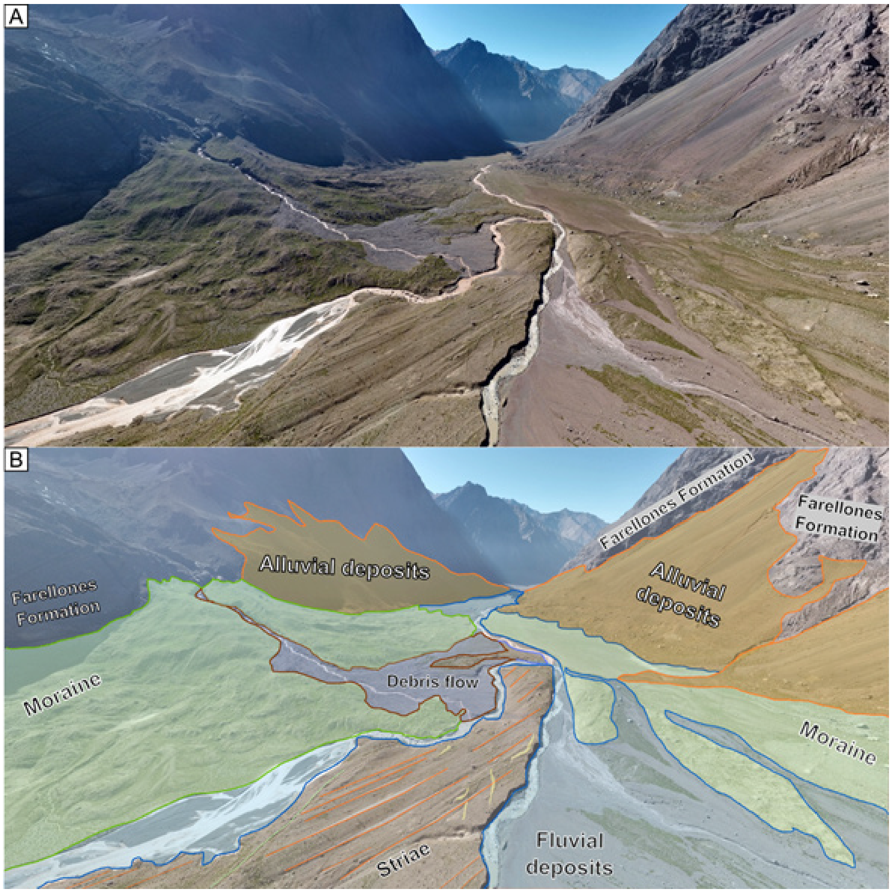
Figure 6: These old and recent landforms.
Note: A) North view of a High-definition UAV capture, with the Juncal Sur Glacier upwards. B) Main geomorphological features identified over the landscape; the moraine relicts are partially covered by alluvial deposits and crosscut by fluvial deposits. Also, the moraine was partially redeposited or reworked, evidenced by eskers (irregular, tan lines) and hummocks (not in sight).



Although it was originally considered as a high magnitude ice avalanche detached from the Estero del Plomo Superior Glacier (Carrasco et al., 2024), this hypothesis was then discarded considering the segmented advance in the form of pulses and the resulting ice deposit which, as can be seen in 1997 aerial photographs (Figure 4A), was still connected to the upslope valley glacier.

Nowadays, there are well preserved morphologies occupying the glacier fore-field which, notably, are in conjunction with the Juncal Sur Glacier surge imprint below the Salto del Olivares. On that sense, we considered the anomalous advance of Estero del Plomo Inferior glacier to resemble surge-like behaviour triggered by a series of ice avalanches from the upper glacier, although we don't have surface velocity data before, during and after the event to assure the latter. However, in terms of the possible recurrence of this complex process, the 1955 morphologies resemble the post event situation at Estero del Plomo creek, suggesting a possible previous glacier advance.

Figure 7: Most significative morphologies.
Note: A) Southeast view of a High-definition UAV capture, with the Estero del Plomo creek valley downwards. B) Main geomorphological features identified over the landscape; the moraine relicts with hummocky-like texture are covered by alluvial deposits and crosscut by a unique debris flow and fluvial deposits. Also, the original till plain was eroded and polished, due to the striae (orange lines) and irregular incisions (tan lines).



2024 Juncal Norte Glacier debris flow

Like the Juncal Sur and the Estero del Plomo glaciers, Juncal Norte Glacier covers Neogene volcanic successions of the Farellones Formation, mainly disposed in a subhorizontal way. Although this glacier is located close to the other two previously mentioned, its drains to the north, originating the Juncal River, a tributary of the Aconcagua River on the same name basin.

Juncal Norte Glacier is the second largest glacier of the Aconcagua Basin. It is a valley glacier which comprises an elevation range of 2,900 m, with a tongue-shaped front located at 2,903 m a.s.l. and a maximum elevation of 5,865 m a.s.l. There are no records of glacier hazards, such as GLOFs, surges or catastrophic detachment, having originated at this glacier. However, on January 25^{th}, 2024, Juncal Norte Glacier was impacted by a debris flow which originated from the glacier front of the CL105400105 rock glacier (33.01°S/70.08°W), also referred to as Juncal Norte Rock Glacier.

The latter is located at 3,916 m a.s.l. and has an extent of 0.25 km^2. Specifically, the debris flow detached from the northeast front of Juncal Norte Rock Glacier, travelling a distance of 1.4 km with an elevation difference of 620 m. The debris flow covered an area of 0.055 km^2 (Figure 4D) with an estimated length of 700 m. The potential effects on ablation and, thus, on the subsequently retreat of the glacier remain to be assessed.

We observe from pre-event aerial imagery from 1955 (Figure 3D) an already existing gully at the easter lateral moraine of Juncal Norte Glacier with a small creek coming from the same source area as the 2024 debris flow. This suggest previous alluvial activity likely to have originated from Juncal Norte Rock Glacier, however it is worth noting that there weren't as many large scarps recognizable on its glacier front as those which can be seen in recent imagery (Figure 4D).

Geomorphologic Imprint

The field observation at the upper Olivares River valley allows to characterize several glacial and periglacial morphologies, which implies a relative temporality and phenomenon over imprint. Figure 6 summarizes a majority of these old and recent landforms. The main Juncal Sur Glacier basal till is well preserved and have a widespread distribution at the beginning of the valley. Eskers and flutes were built over the principal deposits. Fluvial incisions and alluvial and rockfall deposits cover the northern area, close to the volcanic bedrocks. There is a high contrast in the surrounding hills slope and the deposit-filled valley, condition that helps to preserve successive accumulative processes.

On the other hand, the ice avalanche and further collapse from Estero del Plomo Inferior Glacier left landmarks down valley, especially over the previous hummocky-like moraine or lower infills. Figure 7 exposes some of the most significative morphologies. Some are given by previous processes, but also there are deposits derived from the glacier's collapse, represented by a large debris flow in an east-west trend. The basal till is also polished and eroded, which is registered by striae, irregular incisions and flutes (Figure 7B). Later, the alluvial deposits and rockfalls covers the proximity of the steep glacier valley flanks, overlying portions of the exposed bedrocks and older deposits.

DISCUSIÓN

Glacial-related Landforms, Recurrence, and Impact in the Geomorphological Record

The identification of recurrent glacial landforms in high altitude environments has significative issues. Each iteration of glacial advance or retreat, as well as the glacial deposition by moraines, partially erase the previous geomorphic features that allows to identify former events. The cannibalization and overprint of these advances is tough when is necessary to determine cyclic, glacier-related mass movements, especially if those are mixed with older glacier deposits and/or other exogen factors such as alluvial and fluvial deposits.

The lack of monitoring or scarce historical records, the homogeneity of the debris composition and the dynamism of high-altitude environment generates other difficulties in the adequate characterization of the glacial mass movements in the recent past. Remote sensing tools, such as aerial photographs record, are helpful in larger scales, but there are still large areas with absence of detailed analysis. Despite any other independent proxy or information source, there are still some mechanisms to recognize recurrence and relative temporality in the glacial depositional record.

The common attributes of the glacial-related mass movements are the chaotic distribution on lower landscapes, as the bottom of the valleys or as the filling of previously eroded drainages. The large-scale hummock texture, deposits with poor selection and absence of internal structures are some of the typical features on these landforms (Figures 6B, 7B). In the 5 previously exposed cases, the glacial-related mass movements are significatively fast, widespread and chaotic. The post depositional phase is commonly unstable and, therefore, susceptible to progressive erosion. Nevertheless, if the glacier related mass movement was triggered by an atmospheric phenomenon, it is more likely for its geomorphological imprint to be recorded in historical time scales.

As for the recognized geomorphological features at the Salto del Olivares, the lateral moraine position of Juncal Sur Glacier (Figure 6B) is in well agreement with the small piedmont glacier conformed after its 1947 glacier surge (Figure 2C). Considering the complexity of the hydrological network which characterizes surging glaciers (Jiskoot, 2011), it is also possible that the development of eskers resulted as part of Juncal Sur Glacier advance. On a similar pattern, the Estero del Plomo Inferior glacier forefield (Figure 7B) still preserves its frontal moraine, with a hummocky-like texture as a result of its 1992 advance period (Figure 4A). Although the conjunction with the Juncal Sur Glacier surge imprint (Figure 6B) poses an additional barrier on the geomorphological recognition of relict glacial features, the scale of both events, in the order of few kilometres, allow us to differentiate the resulting deposits and, thus, to distinguish between glacier related mass movements events.

Main Conditioning and Triggering Factors for Glacial-related Mass Movements

As mentioned before, glacier surges, GLOFs, debris flows, among other glacial-related landforms have the capability to change significantly and rapidly the base level or the sedimentation rate, especially in high altitudes scenarios. The damming of drainage networks due to glacier advances episodes (like the 1947 Juncal Sur glacier surge, for instance, Figure 2A) and their subsequent outburst, along with the catastrophic collapse of large, confined glaciers like the Estero del Plomo Inferior and Aparejo glacier, and possibly Tinguiririca 3 Glacier, change abruptly the apparently stable mountain landscapes.

However, none of this process would have occurred if it were not for a complex interaction between conditioning and triggering factors on the cryospheric environment. For instance, Lliboutry (1956) states that the Juncal Sur Glacier surge was the result of successive wetter years at the beginning of the XX Century followed by dryer years. On the other hand, the 1980 Aparejo Glacier catastrophic detachment was the result of an extreme basal friction reduction due to the infiltration of snowmelt and precipitation after a sudden increase in the zero-degree isotherm elevation (Ugalde et al., 2024a).

A similar hypothesis is proposed for the Juncal Norte Glacier debris flow, which would have occurred after an intense heat wave on January 2024 with air temperature reaching 20°C at 3,000 m a.s.l. on the previous days (Ugalde et al., 2024b), allowing snowmelt to infiltrate throughout the Juncal Norte Rock Glacier and, thus, emerging in the form of a debris flow.

As for the 1992 Estero del Plomo Inferior Glacier advance, it is reasonable to assume that the recurrent ice avalanches detached from the upper glacier favoured a positive mass imbalance and, thus, acted as a conditioning factor for the glacier sudden advance, however, whether a larger ice avalanche triggered the resulting collapse, or whether another triggering factor was involved, like an earthquake for instance, still remains to be further investigated. Lastly, the triggering factors for the pre-1962 Tinguiririca 3 Glacier collapse are not clear and remained yet to be assessed. However, based on our evidence, we can state likely at least two large collapses happened near mid XX century: one before the 1955 record and another in between 1955 and 1962.

Glacier-relater Mass Movements Recurrence *versus* Long-term Geomorphic Imprint

The latter sections exposed some of the characteristics for glacier-related mass movements, their main conditioning and triggering factors and at least two periods at the past century where those features were more common to occur. As it was exposed, the reiterative glacier advances and retreats leaves geomorphic imprints that can be partially covered or eroded by large, catastrophic, high-sedimentation rate glacier-related mass movements.

Despite this abrupt configuration, is it possible to recognize and reconstructs former geomorphic landscapes with remote sensing tools as a complement to control and validate field data. In a broad perspective, the large mass movements are not completely destructive nor erosive to fully overthrow the older imprints of glacier changes, as each of our five examples exposes. This idea is mainly reinforced by the fact that glacier-related hazards are strongly linked to the intrinsic glacial dynamics of the glaciers which originate the process.

The analysis of the geomorphological evidence resulting from these phenomena is a key element for the evaluation of the potential recurrence of past, and maybe future, mass movements in cryospheric environments, to understand their causes, and to estimate in greater detail their magnitude for hazard assessments in high mountain environments.

CONCLUSIONES

In this contribution we expose 5 different glacier-related mass movements events at 4 locations across the Valparaiso, Metropolitan and O'Higgins regions: the 1947 Juncal Sur Glacier surge, a pre-1962 Tinguiririca 3 Glacier collapse, the 1980 Aparejo Glacier catastrophic detachment, the 1992 Estero del Plomo Glacier Ice avalanche and possible collapse, and the 2024 Juncal Norte Glacier debris flow.

Through historical footage, aerial and satellite imagery, recent published literature and geomorphological mapping, the large and significative changes were shown in each case. For the five localities here revised, there could be at least two main periods, in the past century, where the glacier-related mass movements were more frequently: at the 50'-60' decades and in the early 80'. In each case, there are geomorphological features directly derived by occurrence of mass movements that covers and erode the former glacier advances and retreats, building a new base level and changing the high-altitude landscape meta-stable equilibrium.
Based on the analysed evidence, we state that it is possible to distinguish between geomorphologic features of different glacier-related mass movements coexisting in a single location, as is the case of Juncal Sur and Estero del Plomo glacier at the Salto de Olivares. At the same time, large glacier detachments and glacier advances, such as Juncal Sur, Aparejo and, possibly, Tinguiririca 3 glaciers overthrew the imprint of long-term glacier changes, posing a higher controlling factor for landscape building.

The cryospheric hazards, still less understood and revised as other phenomena, are here analysed to highlight the necessity of a long-term monitoring of the more recurrent mass-movements events, for past and potential future scenarios, especially in areas with population, strategic industries, tourism and conservation initiatives.

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