Abstract  Antuco (37.4°S, 71.4°W; Chile) is a dominantly basaltic stratovolcano whose original ~ 3300 m altitude main cone experienced a catastrophic sector collapse at ~ 7.1 cal ka BP, producing a volcanic debris avalanche deposit (VDAD) with hummocky surface and ~ 6.4 km³ of volume. We carried out geological studies of its debris avalanche deposit, which was distributed to the W and displays a longitudinal facies transformation from edifice's mega-blocks and block to mixed facies in distal areas (up to 25 km from the scar). Our observations support the behavior of the avalanche beginning as a translational slide, and then as plug flow when confined within the Laja River valley. Clay abundance and high content of hydrothermally altered material may suggest active participation of water; flow velocities are estimated to ~100 m s⁻¹. We primarily identify the steep-sided flanks of the cone, and hydrothermal alteration promoted the edifice instability, while basement seismogenic structures may have ultimately triggered the landslide. Subsequent landslide-led events include the transformation of the volcanic activity with explosive eruptions producing a sequence of dilute pyroclastic density currents (PDCs) ending ~3.4 ky BP, and extensive lava effusion rapidly reconstructing the collapsed edifice. Moreover, the Antuco VDAD also blocked the natural output of the Laja Lake, increasing its level by ~200 m and then triggering cataclysmic outburst floods by dam rupture, preserved as high-energy alluvial beds with ages between 2.8 and 1.7 ky BP. The Antuco constitutes an excellent example of a critical chain of events initiated by a stratovolcano lateral collapse and warns for detailed hazard investigations to better comprehend its related impacts.

Keywords  Sector collapse · Volcanic debris avalanche · Facies analysis · Hydrothermal weakening · Volcanic activity · Edifice regeneration

Introduction

Volcanic lateral collapses (also known as “sector collapses”, “flank failures” or “flank collapses”) result from the separation of huge rock bodies (blocks and sheets) which move downslope beyond the flanks of the volcanic edifice (Siebert 1996). The landslide source is characterized by a scar-limited depression with an open side (Siebert 1984). These sudden gigantic landslides immediately result in fast and non-cohesive gravity granular flows termed volcanic debris avalanches, which are composed of a mixture of rocks and soil, controlled by particle–particle interactions as a result of a frictional or collisional regime (Nakamura 1978; Ui 1983; Schuster and Crandell 1984; Ui et al. 1986; Roverato and Dufresne 2021). Lateral collapses may be immediately followed by violent explosive eruptions, including the sudden explosive release of gas contained within the hydrothermal and magmatic systems (blasts), such as observed in the collapses of Bandai-san in 1888 (Nakamura 1978; Moriya 1980), Lamington in 1951 (Beloussov et al. 2020), Young Shiveluch in 1964 (Beloussov and Beloussova 1996), or Mt. Saint Helens in 1980 (Voight et al. 1981). These blasts can be followed by intense volcanic activity depositing thick successions of pyroclastic density currents (PDCs) and tephra fall (e.g., Siebert et al. 1987).

The primarily deposits formed by volcanic debris avalanches (VDADs) correspond to epiclastic, heterogeneous, and heterometric breccias (Bernard et al. 2021) with characteristic irregular hummocky surfaces, distinctive clasts (shattered, jigsaw cracks, and rip-up), and incomplete mixing of diverse lithologies (Roverato and Dufresne 2021). VDADs can be mapped using the combination of properties characterizing their sediments or facies (Walker 1992). VDADs infill the landscape and dam river catchments for thousands of years and can result in complete truncation of drainage systems from their sources (Tost et al. 2015). The drainage networks are modified to such a point that new lakes are formed, and the outlet of the older ones can be blocked, thus raising the threat of violent lake outbursts and flooding in the lowlands (e.g., Major 2020; Major et al. 2020a, b). On top of these collapse sequences, any PDCs are rapidly carved by new channels (tens of m incisions), producing extraordinary sediment delivery for decades after the eruption (Major et al. 2018, 2020a, b). Intense re-sedimentation commonly begins on ring-plane areas, particularly in wet or temperate climates; it is exacerbated by large areas of denuded landscape, still unstable regions, damming of river/stream systems, and the inherent instability of the VDAD (Procter et al. 2009). After erosive processes have concluded, VDADs may be preserved as terraces in the highest surfaces of the valleys (Tost and Cronin 2016).

A full geologic record accounting for the instability factors, the collapse dynamics, and the post-collapse impact on the surroundings of a volcano is rarely preserved and represents a valuable source of information on the critical chain of events that accompany and follow these events. One of these exceptional case studies is provided by the Mid-Holocene lateral collapse of Antuco volcano, which may have triggered a complex chain of impacts on the volcanic system itself and the surrounding landscape (e.g., Abele 1981; Moreno et al. 1984, 1986; Varela et al. 1988; Thiele et al. 1998; Lohmar 2000; Moreno et al. 2000; Moreno et al. 2018). Despite former works having constrained the general aspects and extent of this catastrophic event, a detailed description including its VDAD mapping and a stratigraphic framework for the syn- and post-collapse events has not been provided.
In this paper, we aim to better comprehend the critical chain of events promoting and closely following the lateral collapse of Antuco, through a detailed mapping of its VDAD, with a focus on its distribution, facies, contact relationships, morphology, and grain size.

Antuco volcano and its lateral collapse

Antuco (37.4°S, 71.4°W; 2979 m above the sea level, asl) is a composite stratovolcano located in the Southern Andes Volcanic Zone (SAVZ), Chile (Fig. 1A). It lies ~ 7 km NE of Sierra Velluda, a large eroded Pleistocene stratovolcano, both following a NE-SW alignment (Fig. 1B); the products of both systems are progressively more mafic with decreasing age (López-Escobar et al. 1981). The Antuco edifice has evolved through three stages (Figs. 2A and 3), from which the oldest activity (Early Antuco, EA: Fig. 2) began at ~ 150 ka BP and comprised the eruption of basaltic and andesite to dacite (52.0 to 64.5 wt% SiO2). It was followed by a basaltic and basaltic andesite phase (Late Antuco, LA; 50.9–53.0% SiO2) since the end of the Last Glacial Maxima (LGM) at ~ 17 ka BP (Martínez et al. 2018). This second stage was interrupted with the catastrophic lateral collapse of the edifice and was followed by the third stage (Post-collapse Antuco, PCA: Fig. 2) with the eruption of exclusively high MgO (> 5.0 wt.%) olivine basalt and mafic basaltic andesites (50.9–53.0% SiO2). Only small geochemical differences between LA and PCA make it difficult to discriminate between the products of both edifices; thus, the designation of PCA responds to a geomorphological criterion based on the existence of a clear, post-collapse cone. This collapse produced a VDAD of > 5 km³ (Fig. 2A, B; Moreno et al. 1984, 1986, 2000; Thiele et al. 1998, Lohmar 2000).

Both the landslide VDAD and scar have been described to a different extent by former authors. They were initially interpreted as of glacial origin by Brüggen (1941), while Vergara and Katsui (1969) proposed a subsiding caldera hypothesis. MacPhail (1966) described the VDAD as a massive lahar; however, he was right to consider Cerro Cóndor as a higher block resulting from a volcanic landslide, while Abele (1981) visionary described it as a volcanic debris avalanche, after visiting Mt. Saint Helens. The detailed and careful description provided by Moreno et al. (1984, 1986), Varela et al. (1988), and Thiele et al. (1998), suggested that

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**Fig. 1** Location map of Antuco volcano and the field control points in this contribution. Topographic profiles are shown in Fig. 5A and B. Toponyms are: ENEL= Hydroelectric power generation enterprise (www.enel.cl); BCA Bocatoma Central Abanico; LL Las Llagunillas; CH Chacay and SLC Salto Las Chicas

**Fig. 2** Antuco volcano. A) View from the W, showing the Antuco VDAD main body. B) Aerial view of Antuco, Sierra Velluda and the Laja Lake (looking NE). Photos by J.E. Romero and H. Moyano
a sector collapse was produced by a catastrophic, lateral phreatomagmatic Bandai-type explosion, forming a 5-km³ debris avalanche that would have traveled 40 km to the W, along the valley of Río Laja, with lateral ridges and hummocky surface. Moreno et al. (1984) in their geological study of Antuco volcano mention a ¹⁴C standard age of 9.7 ± 0.6 ka provided by ENDESA enterprise engineers, who found a piece of Nothofagus dombeyi while digging a channel in the VDAD. The tree trunk was covered by the avalanche deposit that they thought was a moraine. They also described two units which correspond to a rock avalanche deposit and a debris avalanche deposit, the first related to the main sector collapse and the latter to subsequent gravitational failures of the collapsed edifice. Later, Lohmar (2000) and Moreno et al. (2000) obtained one radiocarbon age in small wood pieces within the avalanche basal unit with a new uncalibrated age of 6.25 ± 0.1 ka BP but also re-estimated the run out of the VDAD up to 20 km from the vent and its volume to > 5 km³. Further radiocarbon analysis carried out in a paleosol above the avalanche provided by Clavero and Godoy (2010) reported an uncalibrated age of ca. 4.0 ka BP. Besides, it was described as having a hummocky surface with variable brecciation and some blocks partially maintaining their original internal stratigraphy.

The VDAD blocked the outlet of the Laja Lake, which rose ca. 200 m above its original water-line level. After a still unidentified time, when the large lake water-line level fluctuated, it collapsed triggering a massive violent high-energy lake outburst downward the Laja River into the Central Depression covering thousands of km² (Moreno et al. 1984, 2000, 2018; Thiele et al. 1998; Lohmar 2000; Clavero and Godoy 2010; Romero et al. 2021a).

**Methodology**

**Scar morphology, pre-collapse edifice, and deposit volume**

To measure the collapse scar and the VDAD, we used Google Earth ® images (Supplementary Material 2): on these, the horizontal and vertical accuracy have root-mean-squared errors (RMSEs) of 39.7 m and 1.355 ± 0.5284 m, respectively (Potere 2008; Sharma and Gupta 2014). The pre-collapse volcanic edifice was obtained by projecting the flanks of the remaining volcano edifice and using a ~ 300-m-diameter summit crater (Fig. 5), as in most conic stratovolcanoes in the Southern Andes. The VDAD volume was estimated by dividing the avalanche distribution into 7 polygons with likely regular observed thicknesses (Fig. 6). The areas of these polygons were multiplied to their average thickness; these average values were obtained from 51 individual points where the highest and lowest
altitudes of vertically continuous outcrops of the VDAD were subtracted from Google Earth © (Supplementary Material 2), especially at exposures where longitudinal and transversal thickness variations indicated deposit thinning out to the margins of the valley, thus allowing a more realistic estimate.

Facies analysis and mapping

Fieldwork was carried out during discrete field trips between January 2011 and November 2018. Further field mapping was carried out by January and December 2020. We present a total of 70 field sites visited during the 2020 campaign, distributed to the W of Antuco along the Laja River valley (Fig. 6). The observations were carried out at natural outcrops (mainly creeks, rivers, and cliffs) together with roadcuts along the CH-45 international route and private roads of ENEL (hydroelectric power generation enterprise). At each field site, we mainly performed facies descriptions (Figs. 7, 8 and 9) and textural features of the VDAD (the general aspect of the deposits, geometrical relationships, microstructures, and relative abundance among their constituents, e.g., Roverato et al. 2011, 2018). The nomenclature and terminology utilized to describe the scar morphology follow Bernard et al. (2021), while our facies mapping is inspired by de Vries and Davies (2015) and Bernard et al. (2021).

Sedimentological characterization of samples

Nine samples were collected for grain size analysis. These samples consist of 200 g bulk sediment, seven of which were collected in the matrix of basal facies (two), matrix facies (two), and mixed facies (three), while the other two were obtained from the PDCs lying on top of the VDAD (OL-1 and -2). Samples were dried for 72 h at 30 °C, and then manually sieved between > 4 mm and < 63 µm, at seven half-phi intervals (phi were dried for 72 h at 30 °C, and then manually sieved from the PDCs lying on top of the VDAD (OL-1 and -2). Samples collected in the matrix of basal facies (two), matrix facies (two), ples consist of 200 g bulk sediment, seven of which were col -

Radiocarbon dating

Together with the documentation of the VDAD contact relationships, nine samples suitable for 14C dating were obtained from paleosols, wood pieces, and charcoal at deposits below, above, or inside the VDAD (Table 1 and Fig. 4). Six samples collected in January and December 2020 were analyzed at Direct AMS (Bothell Washington, United States; https://www.directams.com), while the other four were sampled between the years 2000 and 2018 and then analyzed at Beta Analytic (Miami, Florida, USA; https://www.radiocarbon.com/), all for accelerator mass spectrometry (AMS) dating. Obtained ages were calibrated with SHCal20 (Hogg et al. 2020) with software CALIB rev. 8.4 (Stuiver and Reimer 1993). Ages are given as calibrated ranges of years before present (BP, present considered to be 1950; Supplementary Material 1) according to 2σ confidence level (95.4%), while ages in literature are expressed also as Anno Domini (AD). The obtained ages (Table 1) are subject to uncertainty, particularly within paleosols, due to any kind of external contamination (e.g., meteoric water, decomposition, or reworking of older material) plus the inherent analytical uncertainty (e.g., statistical, AMS instability, and subtracted background).

Results: the Antuco VDAD

Scar morphology and pre-collapse edifice

The source of the Antuco VDAD corresponds to a semi-circular deep-seated scar opened to the W (Fig. 3), which cuts through the edifices of both EA and LA, at an altitude ranging between ~ 2100 and ~ 2500 m asl. The scar has a length (Ls) of 1.7 km and a width (Ws) of 4 km, achieving an elongation factor (EFs = Ls/Ws) of 0.43. The pre-collapse cone-shaped edifice was steeper to the N-NW (average slope of ~32%) while gently sloping to the SE (~15%; Fig. 4A).

The pre-collapse summit would have been ~ 3300 m asl (Fig. 4A, B), thus achieving a minimum height of 900 m above the pre-collapse remnants. This projection allows us to estimate the volume of the collapsed summit as ≥4.3 km3 considering a mean basal radius of 2.13 km. The scar side walls are steep and form cliffs between 30 and 60 m high in the NE rim (Fig. 4C), where pre-collapse lava flows, sills, and pyroclastic layers are exposed (Fig. 4D). Some post-glacial-Early Holocene lava flows, radially disposed over the volcanic edifice, were cut by the scar. Over the east rim of the caldera, the upper ~ 10 m corresponds to post-collapse pyroclastic deposits (PCA stage: Fig. 4D). The depression floor has also been filled up with the PCA stage volcanics (Fig. 4C, E), which represent a new nested cone of about 2.7 km²; thus, the sliding surface cannot be observed. The PCA lavas mostly extend to the W and have been estimated at 4–6 km³ in total by Martínez et al. (2018).

VDAD distribution, volume, and morphology

The Antuco VDAD is distributed up to 25 km W from the collapse scar, along the Laja River valley (Fig. 5A). Its maximum width is ~9 km at a distance of 5.3 km from the scar, between Los Pangues creek and El Toro plain. However, the width ranges between 2.3 and
### Table 1 Radiocarbon ages for samples related to the Antuco VDAD

| Laboratory code | Submitter ID | Sample type | Location | Stratigraphic unit | Fraction of modern | Radiocarbon age | Cal yr BP | Relative area under distribution |
|-----------------|--------------|--------------|----------|--------------------|-------------------|-----------------|-----------|----------------------------------|
|                 |              |              | North    | East               | pMC 1σ error      | BP 1σ error     |           | 2σ (95.4%)                      |
| D-AMS 040,733   | QAVA-20–02   | Wood         | 37° 20.879’S 71° 30.148’W | Dry wood in the basal facies of VDAD at el Abanico | 33.73 0.13 | 8730 31 | 9542–9766 | 0.992 |
|                 |              | Wood         | 37° 23.220’S 71° 29.543’W | Dry wood in the basal facies of VDAD at el Abanico | 6250 60 | 69.49–7261 | 1.000 |
| D-AMS 040,736   | PLS-ANT–04   | Sediment (bulk) | 37° 28.093’S 71° 8.805’W | Silt–clay below tephra fall deposits at Río Pino-Paleolake | 56.51 0.21 | 4585 30 | 50.49–5198 | 0.595 |
| D-AMS 040,735   | PLS-ANT–02   | Sediment (bulk) | 37° 29.183’S 71° 8.220’W | Paleosol below El Pino tephra fallout*–International border | 61.64 0.23 | 3887 30 | 4352–4407 | 1.000 |
| BETA-494091     | 220,517–6   | Charcoal     | 37° 21.613’S 71° 33.383’W | Charcoal in early post-collapse PDC deposit Trupan | 65.33 0.24 | 3420 30 | 3486–3721 | 0.907 |
| D-AMS 040,734   | PLS-ANT–01   | Sediment (bulk) | 37° 23.594’S 71° 27.722’W | Charcoal in paleosol below post-VDAD first lava flow | 67.06 0.18 | 3210 22 | 3342–3449 | 0.981 |
| D-AMS 040,737   | PLS-ANT–05   | Sediment (bulk) | 37° 22.107’S 71° 23.317’W | Silt–clay above the VDAD at El Toro plain | 67.47 0.2 | 3160 24 | 3232–3399 | 1.000 |
| D-AMS 040,738   | PLS-ANT–07   | Sediment (bulk) | 37° 23.817’S 71° 27.320’W | Paleosol above the VDAD and below alluvial deposits | 71.2 0.28 | 2729 32 | 2746–2867 | 1.000 |
| BETA-494090     | 220,517–1A  | Charcoal     | 37° 10.488’S 72° 57.433’W | Charcoal in flood deposit-Arenas Negras de Trupan Laja–Santa Juana | 79.43 0.3 | 1850 30 | 1697–1757 | 0.533 |

*El Pino Tephra fallout deposit has been previously reported by Romero et al. (2020) east of Antuco
The VDAD displays a typical hummocky surface; these hummocks vary from monolithologic (block facies), as in El Toro plain, to polythiolologic (mixed facies), as in Los Cipreses plain and Los Canelos. They are generally isolated conical to half-ellipsoid in shape, and their size varies from 1.5 to ca. 25 m high and up to 50 m long. In addition, ridges can be observed too, mainly at the bottom of the VDAD between Campamento Viejo and the avalanche front. They reach up to 1.0 km long and 3.0 to 30 m high. The overall cross-section profile of the avalanche consists of the deposit filling the concave Laja River valley, while on the surface, it is convex by the pile-up of debris to the central proportion of the deposit.

Considering the maximum height of the scar head-wall and the deposit front as 2500 and 630 m asl, respectively, the drop or fall of debris is estimated as ca. 170 m higher than in the surrounding topography (e.g., El Toro plain, ~1500 m asl). With increasing distance from the current summit (i.e., 6.9 to 7.8 km), the size of the larger megablocks (e.g., Los Cipreses megablock) decreases to c. 50–100 m long, in some cases still limited by normal faults (Fig. 7F) whereas their internal stratigraphy is still preserved (Fig. 6G). In that area, outcrops have been exposed to a deep gorge formed by the erosion of the Laja River (>200 m high: Fig. 6G).

**Facies**

At least five different facies are recognized within the deposit. From proximal to distal areas of the deposit, they consist of toreva megablock facies (TmBF), edifice block facies (EBF), mixed facies (MF), bulldozer facies (BZF), and basal-matrix facies (BMF: Fig. 5B). Only 45% of the VDAD surface is uncovered or slightly covered by post-collapse sediments (mainly the high-energy alluvial and fluvial deposits) allowing the recognizable of these facies; thus, the map is mostly based on these outcrops (Fig. 5B). The map represents the dominant facies observed in each site (Fig. 5B); however, more than one single facies may be present. Moreover, due to their distribution, BMF is not cartographically represented as their outcrops are constrained to the lower regions of the vertical exposures.

TmBF is observed between 3.2 and 9.6 km W-NW from the summit. The Cerro Cóndor (~4 km from the summit), consists of a 4-km-long and 1.7-km-wide toreva megablock which rises to 500 m above the surrounding topography and is mostly composed of intact, rotated, and well-stratified remnants of the collapsed edifice’s W flank (Fig. 6B, C). The sequences are composed of rhythmic 2- to 5-m-thick basaltic and basaltic andesite lava flows, with aphanitic and porphyritic texture, interbedded with scarce scoria fallout deposits and intruded by abundant aphanitic-to-microporphyritic microgabbroic dykes. These beds vary from dark gray to reddish color and display an incipient folding (Fig. 6C); however, their most prominent structures correspond to normal faults organized in host-and-graben fashion, orientated N25–75°E, which have configured a “domino-like” arrangement of blocks from which hanging walls are displaced downwards to the W and NW, in some cases transversally dissected by N-NW-trending strik-slip faults (Fig. 6C). Near Salto Las Chilcas, up to 200-m-length megablocks are affected by numerous polydirectional dykes and are included within an interclast matrix composed of highly fragmented reddish scoria (Fig. 6D). Other blocks in the N side of the Laja River, also in the proximities of Salto Las Chilcas (e.g., Cerro Las Romazas: Fig. 6E), contain irregular lenses of intact volcanioclastic sequences, apparently surrounded by hydrothermally altered beds with a clay-rich matrix. At Cerro Las Romanzas, the deposit hangs from the E-SE side of the valley, up to 1670 m asl, thus about 170 m higher than in the surrounding topography (e.g., El Toro plain, ~1500 m asl). With increasing distance from the current summit (i.e., 6.9 to 7.8 km), the size of the larger megablocks (e.g., Los Cipreses megablock) decreases to c. 50–100 m long, in some cases still limited by normal faults (Fig. 7F) whereas their internal stratigraphy is still preserved (Fig. 6G).
EBF facies is narrowly observed between 4.3 and 6.2 NW from the Antuco current summit at El Toro plain and represent 0.6% of the avalanche surface (Fig. 6B). Internally, it corresponds to gravel to boulder-size angular to subangular broken lava blocks of monolithologic gray porphyritic basalts (Fig. 7A). Some of them develop a jigsaw fit texture (Fig. 7B). Individual subangular basaltic clasts reach up to 3.5 m in size, display conchoidal fracture (Fig. 7C), and they are especially abundant forming monolithologic hummocks located at El Toro plain (Fig. 7D, E).

MF corresponds to the most common type of facies (~49% of the uncovered VDAD surface) and are found between ~4 and 24 km W from the current summit, mostly surrounding the TmBF, EBF, and BzF facies. They correspond to indurated or semi-indurated fine-to-coarse grained (clay to cobble) interclast matrix containing abundant angular polythiologic volcanic clasts (c. 40%); these clasts have decametric to metric size and display jigsaw fit (Fig. 8A) and correspond to basaltic and basaltic andesite lavas, with aphanitic to porphyritic texture, and different degrees of hydrothermal alteration (mainly Fe oxides). About 7% of these clasts correspond to black, glassy, or vitrophyric non-vesicular basaltic fragments with subangular to subrounded shape, conchoidal fracture, and jigsaw fit (Fig. 8B). The interclast matrix has diverse coloration depending on its lithologic components (generally varying from gray to reddish or brown (Fig. 8A–D).

BzFs are exposed between 9.3 to 13.6 km W-NW from the summit, at Cerro Abanico mound (Fig. 5) which corresponds to highly deformed mixed facies which were affected by ductile deformation and thrust-faulted, probably by the Los Cipreses Toreva moment (Fig. 8E, F). These facies are composed of a chaotic mixture of metric angular clasts of basaltic lavas with jigsaw cracks and

**Fig. 5** Facies of the Antuco VDAD. A) Distribution of the Antuco VDAD. Polygons are accounting different areas represented by mean deposit thicknesses (1= 14.8 km² - 85.4 m; 2= 9.26 km² - 159.3 m; 3= 6.62 km² - 116.8 m; 4= 6.0 km² - 90.8 m; 5= 5.7 km² - 176.2 m; 6= 5.75 km² - 215 m; 7= 48.7 km² - 3 m). B) Detailed map of the VDAD dominant facies. Toponyms are described in Fig. 1.
abundant jigsaw fit blocks, still preserving a faint stratification and without any compositional mixing between the relicts of these beds, but forming laterally discontinuous patches of different lithologic domains (Fig. 8E). These facies are highly deformed, soft to moderate compaction and exhibit abundant surface gullies by post-depositional erosion.

Extremely sheared basal-matrix facies (BMFs) are observed at the bottom of the avalanche (Fig. 8D). These facies consist of multicolored (mainly gray, yellow, and reddish), semi-indurated matrix composed of fine sand to silt (Fig. 8G), resulting from the extreme fragmentation of the volcanic rocks. This matrix supports 5 to 15% angular to subrounded poly lithologic crushed volcanic clasts with sizes ranging from fine pebble to small cobble (Fig. 8G). These clasts present low-to-moderate hydrothermal alteration (mainly Fe-oxides as ilmenite, hematite, and goethite), whereas the matrix contains clay minerals (i.e., kaolinite and montmorillonite). At the very bottom of these units, the contact with the underlying pre-collapse substratum is flat; however, the ~1.5 m between the substratum and the avalanche body is characterized by a sole (e.g., Schneider and Fisher 1998) containing extremely chaotic injections of fluidized substratum, developing mingling and multicolored sediments (Fig. 8H). Additionally, this basal region contains clastic dykes of the substratum that cut into the VDAD (Fig. 8H).

Fig. 6 Field observations of the toreva megablock facies (TmBF). A) VDAD extension seen from the W (courtesy of C. Jorquera). B) VDAD seen from El Toro plain. C to G) show exposures toreva megablocks.
Grain size, lithologic components, and textural characteristics

A summary of the grain size characteristics and their sedimentological parameters is given in Table 2. The samples of the basal facies matrix (1 and 2) are bimodal (Fig. 9A), gravelly muddy sand (mean to ~7.1 µm), and muddy sandy gravel (mean to 12.8 µm) with poorly to very poorly sorted (22.8 and 19.8 µm), very fine skewed (skewness of 1.043 and 0.487 µm) and very platykurtic (~2.2 and 1.6 µm) distributions. All the matrix samples obtained from mixed facies (3A to C) and those from matrix facies (3D and E) display
bimodal and poorly sorted grain size (Fig. 9A; sorting from 22.9 to 28.1 µm), very fine skewed (skewness from −0.08 to 0.09 µm), falling into the sandy gravel textural field (coarse to very coarse sand with mean between 34.4 and 108.6 µm) with platykurtic to very-platykurtic distributions (kurtosis between ~1.3 and 1.7 µm). Clay grain size fraction represents about 0.7 to 2.9 weight % of the matrix.

In contrast to these sediments, PDC samples (OL1 and OL2) correspond to coarse ash and fine lapilli (Fig. 9B), poorly to very well sorted (4.9 to 25.5 µm), coarse to very fine skewed (~0.9 and ~0.4 µm) with platykurtic and mesokurtic distributions (5.2 and 1.4 µm). In general, the VDAD matrix samples show finer mean and higher sorting than other fully sampled volcanic debris avalanche deposits of other stratovolcanoes (Fig. 9C; see Dufresne et al 2021a, b).

Matrix particles of sample 3C correspond to moderately highly altered polylithologic clasts with blocky or irregular shape, subangular to subrounded (Fig. 9D). These particle sizes develop different types of cracks including pull-apart-like fractures (Fig. 9E) but also impact features such as staircase geometries on compact grains (Fig. 9F), scratches, and percussion marks. At larger scales (i.e., tens of cm), these features are also observed as scratches and grooves. On the other hand, the largest particles (1–7 cm) of the OL samples are subangular to subrounded, with poly lithologic
composition, including brown subrounded ash aggregates (accr -
cretionary lapilli, 55%: Fig. 9G), gray porphyritic subangular andesite lava fragments (25%), subrounded clear-brown porphyritic pyro -
clasts (10%), and “fresh” (i.e., with an unaltered surface) dark gray irregular porphyritic pyroclasts (10%: Fig. 9H). The ash aggregates are poorly indurated and lose their compaction easily under stress.

Geochronology and VDAD contact relationships

Downstream the Laja River valley and near the locality of Peluca (Fig. 5), close to the run out limit of the VDAD, the avalanche front consists of mixed facies that overlies > 2 m thick of loose alluvial (lahar) deposits that comprise rounded to subrounded clasts (Fig. 10; gravel, pebbles, and some cobbles), moderately imbricated, which represent older Laja River gravel beds.

We obtained an AMS dating from two minor wood samples lying to the deposit base at El Toro creek (14 km NW from the scar), inside chaotic injections of fluidized wet paleosol; these retrieved an age of 9542–9766 cal. y BP. As mentioned before, the VDAD emplacement dammed the Laja Lake outlet, a new large and voluminous lake that flooded an extensive area toward the east of the Antuco volcano, 200 m above the normal water-line. This huge lake left a silt/clay bed of lacustrine sediments rich in organic material at El Pino River (~ 19 km SE from the volcano), which AMS age gave 5049–5198 cal. y BP. This age establishes that the lake existed by that time and fits very well that the VDAD previously dammed the lake outlet too.

When the VDAD forms the present erosion surface, the top deposit consists of several subrounded metric-sized clasts and blocks, displaying abrasion features such as striations and percussion marks. Otherwise, at Bocatoma Canal Abanico and El Peñón sites (Figs. 5 and 10), there are good exposures of contact relationships of the VDAD with other units. In fact, in the first place, the EA basalts are directly overlaid by the avalanche. Meanwhile, at El Peñón, the VDAD is overlaid by a ~ 5-m-thick dilute PDC (surge) layer, containing juvenile ash and highly vesicular porphyritic, fine-to-medium lapilli-sized basaltic scoria (Fig. 10). These PDCs have been dated downstream the valley of Laja River to 3486–3721 cal. y BP. With a maximum calibrated age of 4152–4407 y BP (Table 1),
and a minimum age of 3525–4018 y BP (Romero et al. 2020), El Pino sub-Plinian pumice tephra fallout identified E of Antuco also fits well with the PDCs to the W, thus probably represent contemporaneous events.

At El Peñón, PDCs are covered by high-energy alluvial deposits (lahars) with similar fractions of subrounded to subangular volcanic clasts within a moderately consolidated coarse sandy matrix. On top of the alluvial deposits, two remarkable ~ 5-m-thick columnar basaltic andesite lavas are observed and correspond to the first post-collapse Antuco basal flows. A paleosol sandwiched between the PDC and the alluvial deposit reported age of 3342–3449 cal. y BP (Table 1), while a paleosol lying between the VDAD and these alluvial deposits yields 2746–2867 cal. y BP; however, PDCs have been eroded or have no lateral continuity in that site (800 m NW from BCA in Fig. 5).

Alluvial deposits stratigraphically overlying the Antuco VDAD at Los Cipreses plain form a 3- to 5-m-thick layer, carrying boulders up to 12 m in diameter, covering the whole area. The same stratigraphic relation takes place at El Chacay and Las Lagunillas, where the alluvial deposit reaches up to 30 m thick. Also, these deposits can be tracked far W from the volcano through the Laja and Itata Rivers; in Santa Juana, 140 km W from Antuco, where they form abandoned terraces of massive, clast-bearing basaltic volcanic sand containing charcoal with an age of 1697–1757 cal. y BP.

Discussion
Characteristics of the pre-collapse edifice and instability factors

The topography of the pre-collapse edifice remains has been used to establish its height to ca. 3300 m asl, which in turn means a landslide volume ≥ 4.3 km³. In this sense, the size of the pre-collapse volcano may have been an inherent factor to promote its gravitational failure. It does not mean that the pre-collapse cone was built rapidly, as suggested to be an important instability factor for other mafic stratovolcanoes (e.g., Romero et al. 2021b): the eruptive fluxes estimated by Martínez et al. (2018) for the evolution of Antuco do not report significantly larger increases in the eruption rate from the EA stage (0.28–0.34 km³·kyr⁻¹) to the LA stage (0.27–0.54 km³·kyr⁻¹), and the cumulative volumes of the LA stage are comparatively insignificant (3–6 km³) against those of the EA stage (55–65 km³). Hence, the edifice total height (ca. 2200 m above its substratum) and its steep-sided upper flanks (> 36°) may have induced sufficient gravitational instability to the upper half of the stratovolcano to promote its lateral collapse.
On the other hand, the existence of hydrothermally altered rocks within the VDAD is diagnostic of the edifice being affected by hot fluid circulation producing weakening and promoting instability (e.g., Roverato et al. 2021). Most of the materials which comprise the VDAD are highly weathered and hydrothermally altered, including clays and Fe oxides. Laboratory evidence (e.g., del Potro and Hürlimann 2009; Pola et al. 2014) suggests that the influence of T and pH related to hydrothermal processes causes a drop in the shear strength of basaltic rocks between −45 and −85%.

**Triggering factors**

It is always challenging to determine the specific triggering factor that led a volcano to collapse, especially when there are no direct observations available. However, we have not found unquestionable pre- or syn-collapse pyroclastic deposits, nor as indubitable juvenile fragments contained within the matrix, nor interbedded within the avalanche. Thus, we discard a magmatic eruption as the triggering mechanism. Hence, it may constitute a “Bandai-type collapse” (Sekiya and Kikuchi 1889; Nakamura 1978), the last described as originated by “phreatic eruptions.” The lack of juvenile magma within the VDAD can be interpreted as it was deep beneath the summit at the time of the collapse (e.g., Belousov et al. 2007; Siebert and Roverato 2021).

On the other hand, seismicity may also trigger a catastrophic landslide, as in Mt Saint Helens on May 18th, 1980 (Washington, USA), which occurred after an $M_w ~ 5$ earthquake (Malone et al. 1981). These earthquakes may be especially important when volcanoes lie directly above active tectonic faults (e.g., McLeod and Pittari 2021). At Antuco, Arancibia et al. (2009) pointed to an extensive pre-Andean NW–SE strike-slip fault affecting the crust beneath the volcano, and hence influencing the lateral collapse. However, this structure is fairly parallel to the direction of the collapse. Contrarily, a well-defined dyke and normal fault pattern extends SW–NE, from Sierra Velluda to Antuco, parallel to the Antuco scar (Moreno et al. 1984; Melnick et al. 2006a, b; Albornoz 2019). Normal faults beneath volcanoes produce unstable flanks which are normal to sigma 1, to the dyke injections strike, and which affect the cone flanks that are in extension (Mathieu et al. 2011). Despite any syn-collapse earthquake being preserved, some of these exten-

**Avalanche emplacement and dynamics**

The Antuco VDAD has different characteristics according to the degree of valley confinement: at the surroundings of the volcanic edifice (i.e., up to 5.7 km W-NW from the current summit, where the valley width reaches c. 6 km), the deposits shows (1) the existence of normally faulted (horst-and-graben style), coherent toere megablocks, as in Cerro Cóndor, and (2) strike-slip faults to the valley margins when the avalanche becomes increasingly confined (e.g., Shea and de Vries 2008), favoring the increasing number of primarily small hummocks in these regions (e.g., Pauagua et al. 2014). On the other hand, as the valley stretches at > 6 km from the volcano, we documented (1) the existence of basal facies of highly disintegrated materials, found at the flow margins and representing high-shear zones within a laminar boundary layer; (2) the less-deforming mixed facies found at the central parts of the VDAD, in some cases still preserving loghologic domains; and (3) reverse grading of some metric clasts within the avalanche. These longitudinal transformations have been observed in other similar VDADs by Voight et al (1983) and Takarada et al. (1999) and suggest combined kinematics involving a translational slide and a plug flow during the debris avalanche transport and deposition. This combined model is called multiple shear zones (Pauagua et al. 2021). Whereas the translational slide is typical of an unconfined landscape and is governed by large listric normal faults converging at the sliding plane, the plug flow consists of a less deformed plug layer and a highly deformed laminar boundary localized at the base or the confined flow margins (Pauagua et al. 2021). As observed in Antuco, the confined avalanche results in long run out distances (e.g., Tost et al. 2014; tens of km from the source) but also substantial thickening of the flow (e.g., McLeod and Pittari 2021).

The debris avalanche velocity can be obtained considering the friction loss (Eq. 1) and using the potential energy (Eq. 2) of the avalanche run-up on the topography, following the approach of Naranjo and Francis (1987):

$$F = 100 \left[1 - \left(\frac{h}{H}\right)^{0.5}\right]$$

$$v = 10 \times \sqrt{\frac{2 \cdot g \cdot h}{100 - F}}$$

Then, $g = 9.8 \text{ m s}^{-2}$ and $v = 102.2 \text{ m s}^{-1}$. This velocity is higher than the dry debris avalanches of Parinacota and Socompa volcanoes in northern Chile (60 and 80 m s$^{-1}$; Naranjo and Francis 1987; Clavero et al. 2002) but lower than the 2006 non-volcanic wet avalanche of Mt. Can-abag in Philippines (120–130 m s$^{-1}$; Catane et al. 2007). Considering this velocity, the avalanche could have reached its total run out in just 4 min. However, further observations are required to establish the flow deceleration with distance.

During transport, underlying sediment incorporation is expected especially in the confined segment of the flow (e.g., Tost et al. 2014); however, Antuco VDAD is not particularly rich in these components. Moreover, considering the difference between the originally collapsed cone (i.e., 4.3 km$^3$) and the resulting bulk avalanche volume (6.4 km$^3$) may be explained by volumetric expansion, either by the edifice disintegration and/or by the degree of water involvement during the avalanche which expands...
the clay-rich matrix. The mobility of VDAs can be highly influenced by water, allowing their transformation into lahars or debris flows (e.g., Scott et al. 2001; Roverato et al. 2011; Delcamp et al. 2017; Paguican et al. 2021). Delcamp et al. (2016) estimate that a 4-km³ cone can fill its 30% with water in a climate characterized by ~1000 mm year⁻¹ (see Delcamp et al. 2016). The sector collapse of Antuco was deep-seated, dissecting most of the summit region, and probably disrupting a large part of its aquifer. Sudden dilation of the landslide front in the first moments of its transport would have allowed the trapped water to quickly migrate outward where it would precede the avalanche as a flood (Delcamp et al. 2016). VDADs directly transformed to cohesive debris flows have shown matrix-dominated facies with high clay contents of the source material (mainly produced by edifice hydrothermal alteration), bimodal grain-size distributions, clay contents to >3%, and a semi-indurated or indurated matrix (e.g., Scott et al. 2001; Dufresne et al. 2021a, b; Roverato et al. 2021 and references therein). Despite it was challenging to decipher the longitudinal transformation of the Antuco VDAD beyond the front of the deposit due to erosion, all these properties are observed in the distal front of the deposit. Then, we suggest that water was considerably involved in the avalanche mobility and dynamics during its emplacement.

Age of the collapse and impacts

The upper Laja River valley bedrock consists mainly of highly folded Oligocene–Miocene strata (Curamallín Formation) and some Miocene granites (Thiele et al. 1998). The oldest Pleistocene glaciations carved the ancestral valley where the ca. 500–300 ka BP Sierra Velluda volcano edifice was built (Martínez et al. 2018). The younger glaciations eroded these basement rocks, and the upper Laja River valley was invaded by the intra-post glacial Antuco volcano lavas (Thiele et al. 1998). Thus, at the bottom of the eroded valley, EA basalts locally outcrop. Our AMS dating was collected from chaotic injections of fluidized wet paleosol that retrieved an age of 9542–9766 cal. y BP and is consistent with that reported by Moreno et al. for a pre-collapse tree trunk. However, the small brush branch found by Lohmar (2000) to the VDAD base, near Abanico village, yielded an AMS age of 6290 ± 60 y BP, whose calibrated age is 6,949–7,261 cal. y BP (Table 1 and Fig. 4). This age should be more precise as it may represent younger vegetation of the Laja River valley before the avalanche, so it is likely representative of the maximum VDAD age.

At the time of the lateral collapse, the NW Patagonia (40°–44°S; south of Antuco) had a colder-and-wetter climate by 7.6 to 5.3 ky BP (Moreno and Vide16a 2016); this condition lasted until at least 4 ky BP, characterized by increased precipitation between October and August, forcing glaciers to expand and leading to a mid–Holocene Neoglaciation (Davies et al. 2020 and references therein). North of Antuco (~30°S), wetter conditions prevailed from 5.5 to 4.1 cal ky BP before the beginning of a dryer period (Tiner et al. 2018). The field evidence consisting of paleo coastal lines and the existence of lacustrine sediments reaching 1580 to 1600 m asl in the area of El Pino River with ages of ~5.1 cal ky BP are features that evidence the existence of a widespread lake in the past, after the sector collapse, as a result of the Laja Lake blockage by de VDAD. The current lake may host up to 6 km³ of water when reaching 1400 m asl (maximum water line during the 1980s), covering ~100 km². The lake level rise to 1580–1600 m asl implies a lake surface of ~290 km² and a volume of ≥21–23 km³. This volume is estimated by modeling the hydrologic data provided by Dirección General de Aguas (DGA; https://sniia.mop.gob.cl) and also using the volumetric data of Fernández (2018) (Supplementary Material 3), while GIS-based estimates made by Moreno and Mella (2018) indicate as much as 50 km³. This large lake may have lasted several thousand years as indicated by the lacustrine sediments dated in this work (between 5049 and 5198 and 3212 and 3399 cal. y BP).

Volcanic landslides may suddenly release the pressure from hydrothermal systems (e.g., Nakamura 1978; Moriya 1980; Procter et al. 2014) or either shallow magma in an explosive fashion (e.g., Voight et al. 1981; Belousov and Belousova 1996; Belousov et al. 2020). The existence of dilute PDCs lying on top of the avalanche suggests the depressurization of the shallow magma system may have rapidly triggered magma ascent and eruption (lateral blast?) soon after the collapse. The low amount of fresh (i.e., juvenile) pyroclastic fragments (~10%) contrasting with higher amounts (~35%) of non-fresh volcanic particles together with ash aggregates is diagnostic of hydrovolcanic interactions, probably phreatomagmatic eruptions (e.g., Romero et al. 2021a, b). These eruptions ceased at 3486–3721 cal. y BP according to our radiocarbon dating. Simultaneously, between 4.4 and 3.5 ky BP EL Pino sub-Plinian tephras fallout affected the eastern side of the volcano (Romero et al. 2020), thus indicating a dominant explosive behavior of Antuco soon after the lateral collapse. Further volcanic activity was characterized by a high effusive flux (0.65–0.94 km³ kyr⁻¹), about twice that of the pre-collapse stage (see Martínez et al. 2018), allowing the rapid cone regeneration in a few thousand years.

We have recognized remarkable coarse, high-energy alluvial deposits toward the W–NW, some of them as far as 185 km from the volcano (Thiele et al. 1998; Moreno and Mella 2018). These deposits were previously identified as originated by the Laja Lake outbursts, caused by the VDAD blockage failure. Our evidence fully supports this interpretation; these flooding events deeply eroded the pre-collapse lavas, the VDAD, and the post-collapse PDC deposits carving deep grooves and channels (Moreno et al. 1984; Thiele et al. 1998; Lohmar 2000; Moreno et al. 2000, 2018a; Romero et al. 2021a, b). The distally correlated equivalent deposits, which cover the Laja and Itata river basins, have been described by Carling (2013) as containing laminated basaltic coarse sands, locally showing ripple or low-amplitude dune bedding, alternate with ochre-colored volcanic ash layers. Occasionally, they show scattered sub-rounded and angular clasts (usually < 50 mm; rarely > 1.5 m) forming stringers at bedding planes. These are interpreted as a type of freshwater megaflood-diluted lahars. Moreover, basaltic sands are also found along 200 km in the coast, near the ocean entries of both the Biobío (Laja River is a tributary of Biobío) and Itata rivers. Our radiocarbon dating provides for the first time a geochronologic framework for these events, which occurred in several pulses between 3.4 and 1.7 ka BP. A further detailed assessment is required to better provide a lateral transformation of these deposits and to constrain the nature and catastrophic impact of these flows.

The complex chain of coupled volcanic-landscape phenomena presented here represents one of the most dramatic ways in which stratovolcanoes may transform their surroundings. First, the collapse itself may have not presented any precursory activity as it was apparently not preceded by any volcanic activity (even more if it
was triggered by an earthquake as discussed above), unless it experienced phreatic explosions along the SW-NE fracture, a mechanism of landslide triggering that cannot be excluded. Indeed, many phreatic explosions initiate with really weak precursory activity from days to minutes before the eruption (e.g., Christenson et al. 2010; Kato et al. 2015; Caudron et al. 2018). On the other hand, the extremely rapid debris avalanche (∼100 m s⁻¹) resulted in the total burial of the Laja valley, under debris up to hundreds of meters thick, probably in just 4 min. In the distal areas, the water released by the landslide may have led to the immediate formation of large lahars that flooded the lower lands. The subsequent explosive volcanic activity, most likely in the shape of a blast, should have caused enormous devastation in areas not reached by the primary impacts of the debris avalanche. In this scenario, fairly similar to that of Mt. Saint Helens 1980 eruption (e.g., Voight et al. 1981), it is fundamental to monitor large "long-dormant" stratovolcanoes which already show evidence of edifice instability (e.g., large volumes, critical heights, and steep slopes, together with evidence of generalized hydrothermal activity, increasing landslides, frequent seismicity or active faults in their basement, and signals of slow deformation of the flanks, among others). The post-collapse chain of events involving multi-hazards, such as modified eruptive behavior, formation of natural dams prone to failure, or dramatic erosive and flooding process, should be incorporated in volcanic hazard maps of recently collapsed or already gravitationally unstable volcanoes and/or near a critical height. In such cases, Antuco is an excellent case study to forecast these scenarios. These thematic maps ought to include the zoning of different volcanic processes and their corresponding timescales or recurrence intervals. In addition, for volcanoes that have recently collapsed, changes related to their plumbing system, product composition, and evolving eruptive styles should be considered in the volcanic hazard assessment and risk management plans.

Conclusions
In this contribution, we have mapped the Antuco volcanic debris avalanche deposit (VDAD), describing its characteristic facies, and interpreting its emplacement dynamics the instability factors affecting the former cone. We determined that the catastrophic lateral collapse which occurred ca. 7.1 ka BP reduced the total height of the volcano by at least 900 m. The resulting ~6.4 km³ VDAD flowed downstream the Laja River at ~100 m s⁻¹, up to 25 km distance; initially, it behaved as a translational slide and then as a plug flow when it became confined in the valley. Our textural and compositional evidence suggests that this flow may have incorporated enough water to longitudinally transform into a cohesive debris flow in the distal areas. We point to a gravitationally unstable edifice, near its critical angle of repose, and the extensive hydrothermal alteration within the edifice as the main causes of volcano instability. Additionally, the existence of active NE-SW-trending faults below the edifice, some of them probably causing $M_w \sim 5$, may have triggered the final failure of the volcano. The unloading of the shallow hydrothermal/magmatic system suddenly initiated hydrovolcanic eruptions, which ceased about 3.4 cal ky BP, when the activity allowed effusive eruptions able to rapidly reconstruct the collapsed cone. Simultaneously, the VDAD blocked the natural outlet of the Laja Lake, which rose its level attaining an unprecedented volume ≥ 21 to 23 km³ at ~3.1 cal ky BP. The sudden outburst of water trapped in the large ancestral lake, between 3.4 cal. ky and 1.7 ky BP, formed massive high-energy alluvial events reaching at least ~ 200 km downstream. This excellent example demonstrates the complex chain of events related to the destruction of stratovolcanoes and claims for the geologist's attention on their related catastrophic hazards.

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Author contribution
JER: conceptualization, visualization, methodology, investigation, formal analysis, data curation, and writing – original draft review and editing. HM: conceptualization, visualization, methodology, investigation, formal analysis, data curation, and writing – original draft review and editing. MP: methodology, investigation, writing – original draft review and editing. MB: funding acquisition, writing – original draft review and editing. DG: formal analysis, data curation, funding acquisition.

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Declarations
Conflict of interest  The authors declare no competing interests.

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