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Timber-framed building damage from tephra fall and lahar: 2015 Calbuco eruption, Chile

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Abstract

Assessing the damage to buildings from volcanic eruptions is an important aspect of volcanic risk assessment and management. However, there is a limited empirical evidence base to draw upon when describing the relation between volcanic hazard intensity and resulting physical damage. The 2015 subplinian eruption of Calbuco volcano, Chile, caused damage to buildings near the volcano because of tephra fall and lahars. Chilean authorities conducted a damage assessment of 961 properties (990 buildings) to inform an assistance programme for property owners affected by the eruption. Property assessments typically contained observations and classification of damage to a house, and in some instances accessory buildings such as sheds, garages, and exterior storage rooms. In this study we used this unique damage data set to adapt damage state frameworks for tephra fall and lahar for classifying and analysing damage observations. We developed data quality indicators to provide transparency for how we accounted for data quality issues. We assigned a tephra and/or lahar damage state to 571 buildings (530 houses and 41 accessory buildings). The 419 buildings for which we did not assign a damage state either had too little information or fell outside of tephra and/or lahar hazard zones. The minimum tephra

thickness isopach band that caused complete collapse was 10 to 15 cm (dry deposit loading ~1 to 1.6 kN m⁻², saturated deposit loading 1.6 to 2.4 kN m⁻²), but most commonly (55% of tephra exposed DS5 houses n=11), this occurred at 15 to 30 cm (dry deposit loading ~1.5 to 3.3 kN m⁻², saturated deposit loading 2.4 to 4.8 kN m⁻²). Lahar damage was typically described as complete (DS5), with 26 houses being swept away or destroyed around the Blanco South River. Our results add to the limited evidence base of post-eruption tephra and lahar impacts to buildings and contribute to volcanic risk and impact assessment.

Keywords: Calbuco, tephra fall, lahar, volcanic hazard, risk assessment, impact assessment, damage assessment, building vulnerability, damage scale

1. Introduction

Assessing the impact of volcanic hazards to buildings is an important focus of volcanic risk assessment globally (Bonadonna et al., 2018; Jenkins et al., 2014; Wilson et al., 2014). Post-eruption volcanic impact assessments studying the effects of volcanic eruptions on buildings are useful as they provide valuable insights of observed damage in a real-world environment (e.g. Spence et al., 1996; Blong, 2003a; Baxter et al., 2005; Jenkins et al., 2013; Jenkins et al., 2015a). However, it can be challenging to collect this information due to safety concerns, ethical considerations, rapid alteration of deposits (e.g. by rain or clean-up), as well as technical and logistical challenges (e.g. lack of relevant experts, cost) (Jenkins et al., 2015a). Consequently, there are few studies that have comprehensively assessed volcanic impacts to buildings during or following volcanic eruptions and there is a relatively poor understanding of how susceptible buildings are to volcanic hazards (Blong, 2003a; Jenkins et al., 2013; Wilson et al., 2014). This hinders the development of more accurate vulnerability models that could be used to assess the likely performance of buildings during future eruptions.

This study analyses the impacts to timber-framed, predominantly residential buildings (houses), from tephra fall and lahars of the April-May 2015 Calbuco eruption, Chile. It adds to the small number of studies in the global literature that comprehensively analyse building damage from volcanic eruptions (e.g., Spence et al., 1996; Blong 2003a; Baxter et al., 2005; Jenkins et al., 2013; Jenkins et al., 2015a; Jenkins et al., 2017). Our analysis relies upon damage observations, classifications and photos by the Chilean Ministerio de Vivienda y Urbanismo (MINVU) during governmental damage assessments between 29 April and 21 October 2015, and our own observations and semi-structured interview data gathered 19 months post-eruption. We develop a fit-for-purpose damage state framework for categorising damage induced by tephra fall and lahars from the 2015 Calbuco eruption. We characterise uncertainty and challenges associated with hazard, asset, and impact data and discuss future research that could help with these challenges.

In the Background section we present an overview of Calbuco volcano and its 2015 eruption, describing relevant characteristics of the emergency response for the eruption. We summarise typical building characteristics of houses near Calbuco volcano. In the Methods section we outline our approach to developing a building damage state framework for volcanic hazards, describe the volcanic and building data used in our analysis, and our approach to assigning damage states. In the Results section we present our findings relating to relationships between hazard intensity and assigned damage states. Finally, in the Discussion section we interpret our results and their implications for damage state framework development, the assignment of damage states, and associated uncertainty with hazard, exposure, and impact data collection.

2. Background

2.1 Calbuco volcano and eruption history

Calbuco volcano (41.33°S, 72.618°W, 1974 m a.s.l.) is a late-Pleistocene to Holocene andesitic volcano located in the Southern Volcanic Zone of Andes mountain range (Stern et al., 2007) between Llanquihue and Chapo lakes to the west side of Liquiñe-Ofqui Fault Zone (López-Escobar et al., 1995). The Southern Volcanic Zone of the Andes (~30 active volcanoes), where Calbuco volcano is situated, results from subduction of the oceanic Nazca plate under the South American plate (Stern et al., 2007; López-Escobar et al., 1995). The volcano has been built over the past 300,000 years, spanning three glacial-interglacial cycles, with andesitic products dominant in the past 100,000 years (Moreno 1974, 1976). At the beginning of the most recent postglacial period, the main cone collapsed generating a large volcanic avalanche, which flowed to the north, resulting in a 3 km³ volume deposit covering 60 km² (Clavero et al., 2008; López-Escobar et al., 1995). An andesitic dome grew inside the collapse amphitheatre; this has since been the site of several viscous lava flows. Typical volcanic hazards for eruptions of Calbuco volcano include tephra fall, lava flows, lahars, and pyroclastic flows (Figure 1; Moreno, 1999; Moreno et al., 2006; Stern et al., 2007). Historical eruptions have impacted agriculture, damaged buildings, and required evacuations (Table 1).

2.2 Land use, infrastructure, and building typology

Ensenada is the closest village to Calbuco volcano (~15 km NE) with 1,169 inhabitants (INE, 2017) and was the most directly affected area in the 2015 eruption, exposed to lahars and tephra fall accumulation. Ensenada is a sparsely populated and spread out community, with most permanent and seasonal residences located along Route 225 (Figure 1). The precise boundary of Ensenada is poorly defined; we use the name to refer to the area between Calbuco and Orsono volcanoes that was affected by the 2015 tephra fall. Puerto Montt, the capital of the 'Los Lagos'

region, is located 30 km SW of Calbuco volcano (pop. 171,000; INE, 2017); Puerto Varas and Alerce are urban areas located 25 km from the volcano with 29,000 and 46,000 inhabitants respectively (INE, 2017). In the areas surrounding Calbuco volcano, settlements are relatively sparsely populated farming and touristic areas, with denser population concentrations to the north and west of the volcano (Figure 1).

Table 1: Description and impacts from recent eruptions of Calbuco volcano, Chile. See Figure 1 for key place names. The Smithsonian Institution Global Volcanism Program has assigned the 1893-1894 eruption a VEI 4, and the 1929 and 1961 eruptions a VEI 3.

Eruption date	Description	Reference
1893-1895	Impacted agriculture (mainly potato farms) and navigation in Llanquihue Lake by tephra accumulation. Pyroclastic flows reached Chapo Lake and Caliente-Hueñuhueñu River and some lahars impacted buildings on the northeast flank, forcing people to evacuate the area.	Petit-Breuilh (2004)
1929	Debris flows impacted the Caliente-Blanco river basin. The melting of ice by lava flows increased the volume of water in Chapo Lake causing flooding of the Chamiza River, damaging buildings, farms and killing several cattle.	Petit-Breuilh & Moreno (1997)
1961	Large lahars reached farms to the north of the volcano. Lava flows also impacted the north flank (6.8 km runout), and to the south (3.5 km runout). A main highway 6 km south of Ensenada was covered with 1-2 m of lahar deposits from Tepú River. The estimated velocity of this lahar was 5-6 m s ⁻¹ .	Klohn (1963); Petit-Breuilh (2004); Castruccio et al. (2014).

Figure 1: Map of the study area, including hazard zoning from Moreno et al. (1999) and population distribution (LandScan, 2009).

2.2.1 Economic Activities

Tourism is the main economic activity around Calbuco volcano with around 200,000 visitors annually in Puerto Montt and surrounding areas (Sernatur, 2018). The Llanquihue Lake basin is a popular tourist destination with ~350,000 visitors per year (Sernatur, 2018). Commerce accounts for 35% of total businesses in the region. Other important regional economic activities are transport-communication (11%), agriculture (11%), and manufacturing (9%) (Ministerio de Economía, 2014). These four economic activities employ 46% of workers in the region (Ministerio de Economía, 2014).

2.2.2 Building characteristics

Buildings around Calbuco volcano are predominantly timber-framed. The Global Earthquake Model (GEM) Level 3 Building Exposure Model for Chile estimates that in rural areas of Puerto Varas and Puerto Montt, ~95% of all buildings are constructed from timber (92% are of timber construction for the whole Los Lagos region) (Santa María et al., 2017). Houses in the study area are typically owner built, 1 or 2 story stand-alone dwellings (Figure 2). Chile has a snow loading code (NCh431-2010) establishing the minimum loads roofs must be designed to withstand depending on the latitude and height above sea level (Instituto Nacional de Normalización (INN), 2010). The minimum snow load in NCH431-2010 for our study area is 0.25 kN m^{-2} (INN, 2010). The Chilean wind load code (NCh432.Of71) requires that structures like those in this study be designed to withstand instantaneous wind speeds consistent with 20 years of wind data at the site (INN, 2000). If this is unavailable, basic pressures of approximately $70 - 106 \text{ kg m}^{-2}$ (equivalent to ~ 0.69 to 1.04 kN m^{-2}) for heights above the ground of between 0 and 10 m, but this is dependent on surface roughness, and requires the review and approval from an inspecting authority (INN, 2000). Houses in the area south of Calbuco volcano (e.g. Blanco South River) are typically older and not as well maintained as those in Ensenada (Figure 3).

Figure 2: Examples of timber-framed houses typical in Ensenada. All were subject to 10 - 20 cm of tephra during the Calbuco eruption. (Photos from our field work November-December 2016).

Figure 3: Examples of timber-framed houses typical in Blanco South (Photos: MINVU).

2.3 April-May 2015 Calbuco eruption

The 2015 eruption of Calbuco consisted of three major tephra-producing phases: 22 April (18:05 - 19:35), 23 April (00:54 - 07:00), and 30 April (13:08 - 15:00) (Castruccio et al., 2016; Romero et

al., 2016; Van Eaton et al., 2016). There was little prior warning of the eruption: the initial phase began 3 hours after a seismic swarm was recorded (>220 events, $M_L < 2.5$) began (Valderrama et al., 2015) and no prior ground deformation was observed retrospectively with InSAR (Delgado et al., 2017). The first two phases resulted in 12 cm of co-eruptive subsidence 2 km south of the volcano at a source depth of 8-11 km (Delgado et al., 2017). Hundreds of earthquakes were associated with the eruption, the largest reported as M_L 3.8 located to the west of Calbuco at 6.3 km depth on 23 April 2015 (Valderrama et al., 2015; 2016; Matoza et al., 2018). Eruption column heights were 14.5 - 15.5 km a.s.l, 16.9 - 17.3 km a.s.l, and 3 - 4 km a.s.l for phases 1, 2, and 3 respectively (Castruccio et al., 2016; Romero et al., 2016; Van Eaton et al., 2016).

Tephra fall from the eruption was dispersed northeast of Calbuco volcano, with the geographically dispersed community of Ensenada affected by 0.1 to 55 cm of tephra (most of the built-up area was affected by 10-20 cm) (Figure 4; Romero et al., 2016; Van Eaton et al., 2016). Romero et al. (2016) reported modal grainsize of tephra in Ensenada as -2ϕ (4 mm), -1ϕ (2 mm), and 0ϕ (1 mm) for individual tephra layers from the eruption with rare lithics ($\sim 0.2\%$). Based on their tephra sampling estimate, the deposit is 80% light brown pumice and 20% high density poorly vesiculated pumice. This was consistent with our own limited field observations. Romero et al. (2016) report an average dry deposit bulk density of 997.3 kg m^{-3} based on “four fine-grained lapilli samples”. We also collected tephra samples from around Ensenada during field work in December 2016, which yielded higher average bulk density values, and consequently, higher potential tephra loadings (Table 2), although this may reflect compaction of the deposits in the intervening 19 months.

Lahars occurred in the rivers on the southern (Blanco South River and Este River), and northern and northeastern (Blanco Este River, Pescado River, and Tepú River) flanks of Calbuco volcano (Figure 1). The southern sector experienced both syn- and post-eruptive lahars, while the northern sector only experienced post-eruptive rain-triggered lahars. The volume of lahar deposits was 3.9

- $4.3 \times 10^6 \text{ m}^3$ in Blanco South River and $5.5 - 5.7 \times 10^6 \text{ m}^3$ in Blanco East River (Flores, 2016). The Blanco South lahar had a runout of $\sim 12 \text{ km}$ and average velocity of 7.5 m s^{-1} (Bono and Amigo 2015; Flores, 2016). Bono and Amigo (2015) reported a maximum lahar flow velocity for Blanco South River as 25 m s^{-1} .

Table 2: Average tephra bulk density measurements and potential tephra loading from the 2015 Calbuco eruption.

Bulk density	Bulk density (kg m^{-3})	Loading at 0.1 cm (kN m^{-2})	Loading at 1 cm (kN m^{-2})	Loading at 10 cm (kN m^{-2})	Tephra thickness (cm) at minimum snow load code (0.25 kN m^{-2})
Dry (Romero et al., 2016)	997.3	0.01	0.1	0.98	2.6
Dry (this study)	1115	0.01	0.11	1.09	2.3
Wetted (this study)	1134	0.01	0.11	1.11	2.3
Saturated (this study)	1615	0.02	0.16	1.58	1.6

In response to first (and second) phase of the eruption, a 20 km evacuation zone was implemented, based on the risk of potential pyroclastic density currents (Mella et al., 2016; Hayes et al., in review). However, four days after phase 1, property and business owners were permitted access to some areas in Ensenada between 08:00-17:00 to collect belongings and clear ash from roofs to prevent damage (Hayes et al. in review). As more information about the eruption was collected and interpreted and eruptive activity subsided, the evacuation zone was reduced to 10 km 6 weeks after the eruption initiation, allowing much of Ensenada to be reoccupied (Mella et al. 2016; Hayes et al., in review). However, most of the settlements south of the volcano remained evacuated due to limited evacuation routes and persistent lahar risk (Hayes et al. in review). By September 2015, five months after the eruption began, the evacuation zone was reduced to within 2.5 km of the summit of the volcano (Figure 4; Mella et al., 2016; Hayes et al., in review), allowing access to all previously settled areas.

MINVU is the agency responsible for providing government assistance to property owners after disasters in Chile. To determine the level of assistance offered, MINVU undertook an extensive field survey of buildings to assess the level of damage sustained at individual properties. This inspection process was used to determine the extent of damage from the eruption, which in turn determined the amount of financial assistance property owners would receive from the Government for repair or rebuilding of damaged houses.

Figure 4: Overview of the Calbuco 2015 eruption deposits and evacuation zones. Lahar, PDC, and tephra isopach from SERNAGEOMIN.

3. Methods: Assessing post-eruption damage

In natural hazard impact assessment, there are three main approaches to characterising the relation between hazard intensity and resulting physical damage: 1) vulnerability indicators, 2) damage matrices, and 3) fragility or vulnerability functions, including damage ratio functions (Kappes et al., 2012; Wilson et al., 2014). Standard approaches are to quantify the cost of repair / replacement (or a derivative product, damage ratio), or to categorise the damage into building damage states (DS). The former is commonly used in the insurance industry, although in some instances it is mapped from building damage state (e.g., RiskScape; Deligne et al., 2017). Damage states are a type of damage scale that are often used to classify observational post-disaster damage information, ranging from an undamaged to a completely damaged (typically collapsed) state (Blong 2003b). In this study, we use damage states to characterise damage that occurred to buildings from the 2015 Calbuco eruption. Figure 5 outlines the conceptual approach taken in this study and we detail each aspect in the subsections below.

Figure 5: Conceptual approach to developing damage state frameworks and assigning damage states and data quality metrics in this study

3.1 Existing tephra fall damage state frameworks

In this section, we discuss the tephra fall damage state frameworks used to inform our development of the tephra fall damage state framework used in this study. Spence et al. (1996) undertook the first detailed tephra fall damage assessment, developing and applying damage states to damage resulting from the 1991 Pinatubo eruption in the Philippines, focusing on an area 27 km from the volcano which received ~150-200 mm of tephra. Through analysis of photographs, they remotely assessing 51 buildings and developed the first tephra fall damage state scale, drawing on earthquake building damage state scales (Kárník et al., 1983). Concurrently, Blong and McKee (1995) provided detailed descriptions of tephra fall damage characteristics following the 1994 Rabaul eruption in Papua New Guinea, which produced thick

(100 to 950 mm) tephra falls in Rabaul town, ~6-7 km from the vents. They described damage in detail but did not explicitly assign damage states. Blong (2003a) followed up with a survey of 173 Rabaul residential, commercial and industrial buildings (11 different typologies) using field observations and insurance loss data, and categorized damage using a modified version of the Spence et al. (1996) damage states scale. The Blong et al. (2003a) modified damage state considered a wider range of tephra thicknesses and better addressed the economic costs associated with the tephra impact in Rabaul.

Recently there have been further attempts to generate generic building damage assessment frameworks (e.g. Jenkins et al., 2014; Jenkins et al., 2015b) for a range of projects (e.g. MIA-VITA, UNISDR GAR-15) and end-users (e.g. researchers, emergency managers). The lack of empirical observations has been a substantial barrier to their development and validation. This has resulted the use of expert elicitation approaches to develop such frameworks (e.g., Jenkins et al., 2015b). Successful expert elicitation depends on carefully choosing experts, minimizing biased judgements, and the method of reconciling multiple opinions (Cook 1991). Blong et al. (2017a) notes that the lack of empirical information has led to considerable variation in expert judgement, which makes volcanic damage assessment frameworks particularly challenging to develop and validate.

3.2 Existing lahar damage state frameworks

In this section we outline the lahar damage state frameworks used to develop the lahar damage state framework used in this study. There are fewer damage state frameworks for lahar impacts to buildings than there are for tephra fall (Bonadonna et al., 2018). This may be due to lahar hazards being more localised than tephra fall, the higher risk to investigator safety associated with detailed studies of lahar damage, and/or because lahar damage to buildings is often total (e.g. swept away, irreparable, and/or burial) or incremental (Künzler et al., 2012; Pierson et al., 2013; Mead et al., 2017). To supplement the paucity of detailed investigation of lahar impacts to

buildings, we can look to studies of building impacts from similar flow hazards (e.g. debris flow and flood). The DS0-DS4 damage state framework proposed by Jenkins et al. (2015a) considered observations of building damage collected following a lahar at Merapi in 2011, and damage states developed from observations of building impacts from flood and debris flow. Since Jenkins et al. (2015a) published their framework, two additional sets of damage state frameworks have been proposed by Ettinger et al. (2016) and Kang and Kim (2016) for buildings impacted by flash flood and debris flow hazards, respectively. Both studies propose a five-point scale (DS0-DS4) with damage descriptions closely matching those proposed by Jenkins et al. (2015a).

Ettinger et al.'s (2016) study drew on damage data from 280 buildings in Arequipa, Peru, affected by the 8 February 2013 flash flood event, and the study considered 12 different building typologies. Kang and Kim's (2016) study investigated damage to 25 buildings in Korea affected by 11 debris flow events between July and August 2011. They developed damage states based on the typically observed damage patterns for two broad building typologies: reinforced concrete and non-reinforced concrete buildings.

3.3 Data and data preparation

3.3.1 Hazard data

We used hazard data from SERNAGEOMIN (tephra isopach, lahar footprint, PDC footprint) and Van Eaton et al. (2016) (tephra isopach). There are discrepancies between the two tephra isopach maps. The underlying field data used for the Van Eaton et al. (2016) isopachs were collected over two periods: 27-30 April 2015 (5-8 days after the eruption began, and before the final phase), and 13-14 July 2015 (~3 months after the eruption began and after the final phase). The underlying field data for the SERNAGEOMIN map was collected 28-30 April 2015. We do not know how interpolation of each map was undertaken. However, we note isopach maps often exhibit differences due to field data uncertainties and/or personal choices and assumptions made by

those constructing them (Klawonn et al., 2014; Bonadonna et al., 2015). For this reason, we aggregated the maximum spatial extents of both tephra isopach maps (1 mm fall deposit) and added a 1 km buffer around this maximum extent to delineate our study area. This ensured that all buildings potentially exposed to tephra were included in our assessment. To consistently compare both isopach maps we have combined some tephra thickness bins as per Table 3. For lahar, we assign a 100 m buffer to the SERNAGEOMIN footprint account for uncertainty in the precise extent of lahar inundation.

Table 3: Tephra thickness bins used in this study and corresponding bins used by SERNAGEOMIN and Van Eaton et al. (2016)

Tephra thickness bins used in this study (cm)	SERNAGEOMIN tephra thickness bins	Van Eaton et al. (2016) tephra thickness bins
0.1 – 1	0.1 – 0.5; 0.5 – 1	0.1 – 1
1 – 10	1 – 2; 2 – 3; 3 – 6; 6 – 10	1 – 2; 2 – 3; 3 – 6; 6 – 10
10 – 20	10 – 15; 15 – 20	10 – 20
20 – 30	20 – 30	20 – 30
30 – 60	30 – 60	30 – 55

3.3.2 Asset and building damage data

The primary damage data source for our study was provided to us by MINVU. These data were collected by MINVU as part of their building damage assessment during and following the Calbuco eruption. Data were collected between 29 April - 21 October 2015, and in some instances includes multiple follow-up visits to some properties. According to MINVU, 8-10 assessors worked in the Blanco River/Lake Chapo area, and many more (unknown quantity) conducted assessments in the Ensenada area. MINVU reported that assessments did not take longer than 30 minutes per house.

We received data in the form of an ESRI shapefile containing 961 points, one for each property surveyed; a property can contain multiple buildings that are either houses or accessory buildings such as sheds, garages, and storage rooms. Where multiple different building types could be identified, we added an additional data entry with the same Observation ID number but with an alphabetical suffix. For example, Observation ID 273 has three instances, the house (Observation ID 273), the greenhouse (Observation ID 273a), and the woodshed (Observation ID 273b). The dataset does not contain highly detailed descriptions of the asset typology (e.g. roof cladding type, roof pitch, floor type) so we relied on broad descriptions of buildings and general classifications of buildings in the study area from GEM (Santa María et al., 2017), validated through field visits and damage photos.

The attribute table provided building owner identifying details, the date of the MINVU building survey, a written description of the building state, and/or numerical indicators developed by MINVU for the level of damage sustained for the entire building (an overall damage classification) (Table 4) and individual building elements (Table 5). The complete data set is available in the Mendeley Data associated with this manuscript. Table 4 provides all available information we have on MINVU damage classifications criteria. We do not know how individual assessors (not identified in the provided data) subjectively considered building elements in Table 5 when assigning the final MINVU damage classification – we do not know how much variation may be due to individual assessor practices and biases.

We exported the attribute table to an Excel spreadsheet, removed building owner identifying details and translated the attribute column headers and building damage written descriptions into English. Guidance was provided from MINVU to clarify some aspects of the data table and collection process.

Table 4: Damage classification used by MINVU during the Calbuco damage assessment. No further descriptions were available for severity of damage.

Damage classification by MINVU	Severity of damage
0	No damage
1	Increasing degrees of damage
2	
3	
4	
5/6	Severe damage
7	Not verifiable

Table 5: Building elements assessed and classified by MINVU during damage assessments after the Calbuco 2015 eruption

Type of building element	Specific building elements classified by MINVU
Structural elements	Piles, beams, structural walls, foundation, mezzanine structure, roof.
Construction completions	Windows, doors, roof cover, wall cover, partition walls, ceiling, deck.
Installations	Fresh water, sewerage, electricity, gas.
Exterior to buildings	Garden fences, perimeter fences, terrain, entry, stairs, gangway, slopes, retaining walls, sanitary networks, spot drain, public power poles.

Secondary data sources utilised in this study were photos, Google StreetView and GoogleEarth imagery. Most photos we used were provided by MINVU, which were taken by assessors during their visits to the property and were coded using a unique identifying number that linked the observation in the MINVU damage data set and the photo. The remaining MINVU photos supplied were taken during a subsequent visit to a property, and frequently following repairs and clean-up.

As a supplementary source of information, we also used photos provided by Ministro Obras Públicas (geolocated), the Puerto Varas municipality, SERNAGEOMIN, our own geolocated photos taken during a visit to the study area 19 months post-eruption, and publicly available media and social media photos we could geolocate. Individual properties were manually linked to the geolocated photos by comparing structures seen in Google Earth aerial imagery with those structures that could be seen in the geolocated photos. Supplementary photos that did not contain geolocated metadata and/or were from publicly available media and social media were located based on common landmarks that we recognised from our geolocated images and Google StreetView.

Publicly available Google StreetView imagery acquired in March 2013 is available in limited parts of the study area; unfortunately, no StreetView imagery was available for Ensenada at the time of our analysis. Publicly available GoogleEarth imagery from both before and after the eruption is available for the entire study area. Pre-eruption imagery was taken in January 2014 and post-eruption imagery was taken immediately following the eruption in April 2015 (upper reaches of Blanco South River and in Ensenada), as well as February 2016 (Ensenada) and October 2016 (Blanco South River).

3.4 Developing suitable damage state frameworks

We employ a six-point damage state framework (DS0 - DS5) for both tephra fall (Table 6) and lahars (Table 7) as this best represented the spread of damage descriptions within the MINVU data set. Both tephra and lahar damage state frameworks were based on existing frameworks (see section 3.1 and 3.2) and then modified to accommodate damage descriptions within the MINVU data set (Figure 6). To identify the necessary modifications, we randomly selected 20 data points and reviewed all available information and agreed on data quality metrics (see section 3.5). Each team member then independently decided on a damage state, which we revealed at the

same time by holding up a sign with a number indicative of the damage state. If the vote was unanimous, a damage state was assigned. If there was a disagreement, each team member described their rationale behind the damage state they chose, and we then re-voted. The mean damage state value after the second round of voting - rounded towards the mode if necessary - was then assigned as the damage state. This group voting process allowed us to refine and clarify language and identify assumptions that were being made when applying the damage state scale. To ensure consistency between both frameworks, we added a damage state to the lahar damage state framework of Jenkins et al. (2015a) so that both frameworks use a six-point scale.

Figure 6: Conceptual overview of our approach taken to develop damage state frameworks and data quality metrics (see section 3.5) used in this work

3.5 Assigning a damage state

We assigned a damage state by manual assignment for a subset of data, and used an automatic assignment from an Excel algorithm based on the MINVU damage classification for all data (Figure 7). The manual assessment considered all available information and group voting as

described in Section 3.4. The auto-assignment was undertaken to consistently interpret the MINVU classifications (both the overall and specific elements) in a timely fashion.

Figure 7: Conceptual diagram of our approach to developing a damage state framework and assigning damage states to observations within the MINVU data set.

Table 6: Damage state framework for cataloguing building damage from the Calbuco 2015 tephra falls. A building is assigned a damage state based on the level that best describes the damage, which may not include all of the listed characteristics.

State	Description	Characteristics	Consequence
DS0	No damage	- No damage caused	
DS1	Minor damage to non-structural elements	- Damage to gutters. - Few tiles dislodged. - Damage to fittings, e.g. air-conditioning units and appliances - Damage to contents - Dents in the roof covering	Minor repairs and cleaning necessary
DS2	Moderate damage but vertical structure and roof supports intact	- As above - Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to up to half of roof covering, e.g. tiles, metal sheet. - Little to no damage to principal roof supports, i.e. rafters or trusses. - Damage to roof overhangs or verandas.	-As above -Interior may require cleaning, repainting, and/or overhaul of electrical systems for habitability and health (e.g. heating and cooking).
DS3	Severe damage to the roof <u>and</u> supports	- As above - Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to over half of roof covering. - Damage to any single principal roof supports and some damage to walls. - Severe damage or partial collapse of roof overhangs or verandas.	-As above -Building likely unsafe for occupancy
DS4	Partial or total collapse of the roof <u>and</u> supports	- As above - Collapse of roof covering and any single principal roof support(s). - At least half of the external walls and/or internal walls deformed or collapsed.	-Building unsafe for occupancy -Potentially irreversible damage and demolition required
DS5	Building collapse	- As above - Collapse of roof, principal roof supports and/or supporting external walls over more than 50% of floor area of building.	-Building unsafe for occupancy -Irreversible damage to most contents and fittings -Demolition required

Table 7: Damage state framework for cataloguing building damage from the Calbuco 2015 lahars. Modified from Jenkins et al. (2015a), with the addition of a new Damage State 1 “Light damage”. A building is assigned a damage state based on the level that best describes the damage, which may not include all of the listed characteristics

State	Description	Characteristics	Consequence
DS0	None		
DS1	Light damage to building exterior only	Cosmetic damage to/ soiling of building exterior. Little to no deposit infiltration into the building	Clean-up required with minimal damage to building contents
DS2	Minor damage to building	Deposit infiltration into building under door and through gaps, e.g. ventilation grills	Damage to building contents
DS3	Moderate to building	Window and door glass failure. Possible weak door and window frame failure	Sediment deposition inside building, substantial damage to contents
DS4	Severe damage to building	Loss of parts of external and/or internal wall and infill panels OR Burial by sediment	Substantial internal deposits; building likely to be unsafe for occupancy OR Irreversible damage
DS5	Complete damage to building	Wall, frame, roof or foundation failure OR Burial by sediment	Building unsafe for occupancy; may have to be demolished OR Irreversible damage or costly clean-up

The auto-assignment of damage states first determined whether the overall MINVU building damage classification was consistent with the classifications made for individual building elements, and that the building was exposed to either tephra or lahar as per the hazard footprints (Figure 8). If these conditions were met, and the MINVU overall classification was 1 or 2, then DS0 or DS1 were assigned respectively. It was unclear how higher MINVU classifications (i.e. all individual elements classified as 3, 4, 5, 6) would integrate into our damage state framework, so these were manually reviewed using written observations of damage from MINVU damage assessors and/or any photographs that were available (Figure 8). If the first set of conditions were not met, building damage was instead auto-assigned based on the MINVU damage classification of the roof and wall structure (Figure 8). If none of these conditions were met, the building was not auto-assigned a damage state. Fb

Figure 8: Conceptual diagram of the approach used to auto-assign damage states.

One co-author (AMM) also worked through the data set and manually assigned a damage state to data points that were exposed to tephra and/or lahar. Manual and auto-assigned damage states were then cross-referenced and checked for consistency. Where there was a difference between the auto-assigned and manually assigned damage state (n=147), three additional team members (JLH, RC, GTW) voted on a damage state and the mode damage state from the four team members and the auto-assigned damage state was assigned. Where there was no auto-assigned damage state, we worked in teams of three or more and used written observations to assign the damage state. Observations where a manual damage state could not be assigned were discarded from further analysis.

We decided to err on the side of a higher damage state when there was ambiguity between two or more states. In this instance, the impact data quality rating for usefulness and detail (see section below) was either A or B.

3.6 Assigning a data quality metric

Our study relies on three different components of information: hazard (e.g., lahar footprint, tephra thickness), asset information (e.g., building type), and impact of the hazard to the asset (e.g., MINVU observations, classifications, photos). Any given observation may contain considerable data quality variations across hazard, asset, and impact information. Consequently, we have developed data quality indicators, described below.

3.6.1 Data quality indicators

We used data quality indicators to characterise the data usefulness/detail, and data completeness (Table 8). We assigned a data quality metric for hazard, asset, and impact for each data point in the MINVU damage data set based on all available information, resulting in a multi-dimensional representation of data quality. Data quality metrics were assigned at the same time as manually assigning the damage state. The lowest data quality was assigned to data points that had either no information or no useful information. For some situations it was possible to infer hazard intensity, asset typology, and/or damage state, but there were either conflicting lines of evidence (e.g. different tephra thicknesses on the two isopach maps) or vague descriptions that meant that we could not confirm the hazard, asset, or damage classification. For the hazard intensity component, the distinction between 'B' (possible to infer hazard intensity, but potentially conflicting information) or 'C' (easy to infer hazard intensity) was whether the tephra information was consistent. A designation of 'C' would be a site where the isopach ranges overlapped, for example, a range of 10 - 20 cm on one isopach and a range of 15 - 20 cm on the other isopach. Our intention here was to demonstrate relative consistency and not precision. Consistency for the

424 asset and impact categories was determined based on similarities between photographs and
425 written descriptions. Inconsistency was determined if a photo suggested a higher or lower damage
426 state or different asset typology should be assigned than what the written description conveyed.

427

428 **Table 8:** Data quality indicators used in our analysis

Data usefulness and detail	Data completeness			
	I <u>Hazard</u> : No information <u>Asset</u> : No information <u>Impact</u> : No information	II <u>Hazard</u> : Photo OR model(s) <u>Asset</u> : Photo OR written description <u>Impact</u> : Written observation	III <u>Hazard</u> : Photo AND model(s) <u>Asset</u> : Photo AND written description <u>Impact</u> : Photo(s) of damage	IV <u>Hazard</u> : Local technical measurements <u>Asset</u> : Local technical information <u>Impact</u> : Written observation AND photo(s) of damage
A <u>Hazard</u> : No useful information <u>Asset</u> : No useful information <u>Impact</u> : No useful information	A-I	A-II	A-III	A-IV
B <u>Hazard</u> : Possible to infer hazard intensity AND/OR IF completeness II-IV, conflicting intensity across data sets <u>Asset</u> : Possible to infer asset type AND/OR IF completeness II-IV, conflicting across data sets <u>Impact</u> : Possible to infer damage state AND/OR IF completeness II-IV, conflicting across data sets	B-I	B-II	B-III	B-IV
C <u>Hazard</u> : Easy to infer hazard intensity AND IF completeness II-IV, consistent across all data sets <u>Asset</u> : Easy to infer asset type AND IF completeness II-IV, consistent across all data sets <u>Impact</u> : Easy to infer damage state AND IF completeness III-IV, consistent across all data sets	C-I	C-II	C-III	C-IV
D <u>Hazard</u> : Undisturbed hazard intensity measurement taken at site <u>Asset</u> : Engineering level quantitative information <u>Impact</u> : Engineering level quantitative information	D-I	D-II	D-III	D-IV

4. Results

Below we summarise our analysis of building damage from the Calbuco 2015 eruption. The complete data set is available in the Mendeley Data associated with this manuscript.

4.1 Hazard exposure to Calbuco 2015 eruption products

Out of 990 data points, 73 data points were outside both tephra and lahar hazard buffers. Reviewing the written descriptions indicated that 46 explicitly stated no damage from the volcano, 22 had written descriptions that were unclear or contained no useful information, 2 indicated damage from earthquakes, and 3 suggested ash accumulation. We are unable to confirm that ash was definitely present at these 3 locations, but they were 3-4 km from the 1 km buffer we used, suggesting ash accumulation was most likely trace. Given that this information lacks confirmation, we excluded them from further analysis. The remaining 917 data points were located within areas exposed to tephra fallout, lahar, both tephra and lahar, or within the 1 km tephra fall or 100 m lahar buffer zone. The exact number of buildings assumed to be exposed to different accumulations of tephra varied depending on whether the SERNAGEOMIN or Van Eaton et al. (2016) isopach map was used, especially in areas south of the volcano (Figures 9-10).

Figure 9: Spatial distribution of damage states. Overlaid by the SERNAGEOMIN tephra isopach. Note: for overlapping points the highest damage state is displayed.

Figure 10: Spatial distribution of assigned damage states. . Overlaid by the Van Eaton et al. (2016) isopach. Note: for overlapping points the highest damage state is displayed.

4.2 Data quality indicators

The distribution of data quality for hazard, asset, and impact information is presented in Figure 11. For the hazard component of the data used in this study we had either photographic evidence or a model for all data points (data quality indicator II), and this information was mostly consistent between different sources (e.g. different tephra isopachs) (data quality indicator C: 77%, n = 761). However, there were some conflicts between hazard data (data quality indicator B: 19%, n = 188). Only 4% (n=41) of data points are complete enough to have both the model and photographic evidence of the hazard (data quality indicator III), and no data points have site specific hazard intensity measurements (data quality indicator IV).

There was very limited information regarding specific asset typology characteristics such as roof pitch or number of stories. Thus, for the purposes of this work we characterised asset typology into two classes: 1) a house, or 2) accessory buildings (e.g. barns, sheds, garages). There was no useful information to determine asset typology in 34% (data quality indicator A: n=338) of the data set. A photo or written description that indicated the asset typology occurred in 57% of the data points (data quality indicator II, n=568), compared with 8% that contained both a photo and a written description (data quality indicator B/C-III, n = 84). However, only for 1 of those data points was it easy to infer asset typology (Data quality indicator C). No data points contained engineering level quantitative information (Data quality indicator D).

Of the complete damage data set (990 observations), 42% of data points had no useful information (data quality indicator A, n=413). For observations that had only a written description, it was possible to assign a damage state for 33% of data points (data quality indicator B-II, n=326), and easy to infer a damage state for 24% of data points (data quality indicator C-II, n=235). There were only 4 data points that did not have a written description but did have a photograph where it was possible or easy to infer a damage state (data quality indicator B/C-III). There were 12

474 observations that had both a written description and a photo of the damage (data quality indicator
475 B/C-IV).

476 To summarise, hazard had the highest data quality, with most data points having a data quality
477 indicator of C-II, compared to asset and impact data quality, which mostly fell within the B-II
478 indicator field.

Figure 11: Data quality for hazard, asset, and impact information used in this study. The codes are described in Table 8.

4.3 Damage states summary

4.3.1 Buildings exposed only to tephra fall

More houses were assumed to be exposed only to tephra fall using the Van Eaton et al. (2016) tephra isopachs compared to the SERNAGEOMIN isopachs (Table 9). Both yield similar numbers of houses when comparing tephra thickness equal to or in excess of 10 cm (279 for Van Eaton et al. (2016) and 267 for SERNAGEOMIN). A total of 417 houses were classified as exposed to tephra when including the 1 km tephra buffer zone that encompassed the extent of both isopach maps.

Table 9: Comparison of the number of houses assumed subjected to tephra using different tephra isopachs

Tephra thickness band	SERNAGEOMIN	Van Eaton et al. (2016)
0.1 - 1 cm	11	38
1 - 10 cm	49	79
10 – 20 cm	211	159
20 – 30 cm	41	96
30 – 60 cm	15	24
Total	327	396

Regardless of the tephra isopach map used, the relationship between damage state and tephra thickness is complicated (Figure 12). Half of all houses exposed to low tephra thickness (0.1 - 1 cm) were classified as DS0. Buildings exposed to over 10 cm of tephra were rarely classified as DS0. Relatively few houses were classified as DS4-DS5 regardless of the tephra isopach or thickness band, indicating lack of widespread structural failure. All houses classified as DS5 were subjected to over 10 cm of tephra. A

small proportion of houses that were exposed to 0.1 - 1 cm of tephra were classified as DS4.

Figure 12: Percentage of houses classified by damage state and tephra thickness using two different isopach maps.

In some cases, damage to accessory buildings was described (n=42). We classified damage to these structures separate from houses as we suspect these structures may not be built to the same standard as houses, which were systematically evaluated by MINVU assessors during the damage assessment. Damage to accessory structures was mostly classified as DS5 (n = 10), but as their structure types were not systematically reported in the MINVU data set, there may be a reporting bias towards heavily damaged structures for these asset types.

4.3.2 Houses exposed only to lahar

Only seven of the 31 houses that were within the lahar zone but not exposed to tephra fall (according to Van Eaton et al. (2016) isopachs) had damage classified as greater than or equal to DS1, compared to 46 of the 95 houses using the SERNAGEOMIN tephra isopach map (Figure 13). Most houses (~80%) only exposed to lahars as per the SERNAGEOMIN isopach map are

classified as either DS0 or DS5. Substantially less houses were classified DS5 when using the Van Eaton et al. (2016) isopach than were the SERNAGEOMIN isopach, indicative of the broader tephra distribution in the Van Eaton et al. (2016) map that covered heavily affected lahar areas.

Figure 13: Distribution of damage states for houses exposed to only lahar. Note: tephra buffer is 1 km around the tephra extent of both isopach maps (see section 3.3.1)

All but one of the houses that were assigned DS5 and not exposed to tephra fall (according to the SERNAGEOMIN isopachs) were located completely within a lahar zone (i.e. 0 m from lahar). The one house that did not was located 61 m from a lahar zone. The description of damage for this data point suggests that there was a presence of ash (although it also falls outside of our 1 km tephra buffer zone), and that it was a cabin in construction with total loss suffered due to a flood of the river.

For the seven data points assigned DS1 and not exposed to tephra fall (according to the SERNAGEOMIN isopachs), five suggest that tephra fall may have been involved with the damage. Three of these five fall outside of the Van Eaton et al. (2016) isopach map, but within the 1 km buffer zone. The other two fall within the 0.1 - 1 cm band of the Van Eaton et al. (2016) tephra isopachs. This suggests that either the data points are mislocated or that the maximum

extent of tephra fall (including potential remobilisation) is poorly constrained. Photographs, Google satellite imagery, and the written descriptions for the two houses suggest the data points are correctly located, but due to the amount of time elapsed between the eruption and the date the photographs were taken (9 months) it is not possible to conclusively determine the presence of tephra.

4.3.3 Houses exposed to both tephra and lahar

Damage for houses exposed to both tephra fall and lahars indicates dominance towards DS0 and DS5 (Figure 14). For the four DS1 assigned houses, the description of damage cannot clearly be attributable to coming from solely lahars or tephra. For the five houses assigned DS2, only two instances described damage attributable to tephra fallout. The remaining three instances describe river sediment inside the house, humidity issues due to the flood waters, deformed doors, broken pipes, and low damage to floor coverings and walls. We assigned DS3 to only one house that was affected by tephra (0.1 – 1 cm) and lahar, which was reported as having damage to the floor and beams, and damage (severity not reported) to the roof. We assigned DS4 to five houses exposed to tephra (1 – 10 cm) and lahar, which had either photos or written descriptions indicating lahar sediment ingress, and damage to exterior walls indicative of lahar damage. We classified six houses as DS5 that fall within the 0.1 - 1 cm tephra thickness bands of Van Eaton (2016)'s isopach map. For each of these data points, the dominant cause of damage was associated with lahar. The damage descriptions suggest that the house was swept away and/or aerial/ground-based photos show damage clearly caused by lahar activity.

Figure 14: Houses exposed to both tephra and lahars at classified damage states. Note: tephra exposure based on Van Eaton et al. (2015) isopachs. No houses were exposed to both tephra and lahars when using the SERNAGEOMIN tephra isopach.

4.3.4 Other descriptions of damage

Although most of the building damage appears to be a result of either tephra fall or lahar, 30 damage observations describe earthquake, land movement, fire/burning, roof perforation, and/or subsidence related impacts. This reflects the multi-peril nature of volcanic eruptions. Subsidence, deformation of walls/windows/doors, and cracks in houses were inferred by assessors as being a result of either earthquakes associated with the eruption or “land movement”. There were 14 observations that describe an influx of vermin (rats or mice), which was a concern of public health officials following the eruption (Hayes et al., in review). One observation (Observation ID 947) described burn marks on the roof cover of a building exposed to 0.1 - 1 cm of tephra approximately 11 km from the vent. Observation ID 767 described a large “stone” perforating a roof located approximately 7.5 km from the volcano (also down axis of tephra deposition), but there is no indication of the size or mass of the stone. Observation ID 154 described damage that was not repairable, including potentially due to rain water accumulation. It is ambiguous if damage relating

to rain water is a compounding effect following damage from the lahars, tephra fall, or whether this is an entirely separate circumstance.

5. Discussion

5.1 Hazard information for damage assessments

One of the major challenges of post-eruption impact assessment is collecting and using accurate hazard data. There can be a reliance on externally collected hazard information that has been collected for purposes unrelated to damage or impact assessment. The consensual document from the 1st IAVCEI-GVM Workshop “From Volcanic Hazard to Risk Assessment” highlighted the importance of understanding vulnerability parameters to ensure that appropriate and useful hazard data are collected (Bonadonna et al., 2018). Our approach here relies upon tephra thickness and bulk density data collected at varying times after the eruption by different research groups, and serves as a useful illustration of the challenges involved with relating hazard data with damage observations. Individual thickness measurements can vary considerably due to local thickness variations (Bonadonna et al., 2015), human factors (Engwell et al., 2015) and post-eruption compaction and preservation issues (Blong et al., 2017b). Measurements are typically interpolated and communicated through tephra isopach maps. As seen in the two maps used in our work, different approaches to contouring tephra thickness data can result in considerable variations in the final isopach map. This presents a challenge when attempting to compare hazard intensity with highly localised impact observations. We also note the variability between the average bulk density measurement reported in Romero et al. (2016), and those we measured (Table 2). Our average dry and wet deposit bulk density was approximately 10% higher than the dry deposit bulk density value reported in Romero et al. (2016). The saturated deposit bulk density we report is 38% higher than the average dry bulk density reported in Romero et al. (2016). This variability has an influence on potential tephra loading exerted on buildings and as a consequence

increases the uncertainty regarding identifying a potential loading threshold that initiates roof collapse. An important aspect of future impact assessments is to consider all of these issues; ideally, damage assessments should be carried out as soon after impact as is possible and should include site-specific measurements of the hazard intensity (e.g. thickness and load) for each damage data point. However, we recognise that this is very rarely possible due to time constraints, availability of expertise, data collection priorities and safe access to the impacted area (Jenkins et al., 2015b).

For safety, ethical, and logistical reasons, damage assessments are typically undertaken once an event has finished. For volcanic processes, the hazard intensity can increase over time (e.g., tephra deposit thickness increases from further tephra falls or remobilisation, and/or is wetted which increases density), including after catastrophic failure of a structure. This makes it challenging to establish the precise hazard intensity where a given level of damage occurred. Blong (2003a) highlighted this issue when describing damage to structures from the Rabaul 1994 eruption. In some situations Blong (2003a) was able to use stratigraphic concepts to infer potential collapse thresholds below the final tephra loading measurement. However, these interpretations can take considerable time, which can be highly limited when conducting damage assessments, and require close, and potentially unsafe, inspection of a damaged building. Therefore, a balance must be struck between obtaining detailed building damage descriptions and ensuring that a large enough and representative sample of buildings are studied. Further, some buildings in Rabaul did not collapse until weeks after the load was applied to the roof (Blong, 2003a), which suggests that obtaining a precise threshold of collapse is not only associated with the hazard intensity, but also how long it is subjected to that hazard intensity. As we were reliant on a data set collected by others for different purposes, we were unable to do similarly detailed analysis as described in Blong and McKee (1995) or Blong (2003a). This is an important consideration when interpreting our results and for future post-eruption impact assessments. An additional source of uncertainty

regarding tephra load on roofs is the possibility for rainfall to wet the deposits, potentially increasing their load by up to 100% depending on deposit characteristics such as porosity (Macedonio and Costa, 2012). Increased tephra load due to rainfall was a concern for building owners and was one of the reasons for allowing temporary access to Ensenada to clear tephra from roofs four days following the eruption and before any rainfall occurred (Hayes et al. in review). However, the area has a high incidence of holiday homes and absentee ownership, meaning that some properties may not have been cleaned before rainfall. In fact, tephra could be observed on a few building roofs during our field visit in December 2016. It is not possible for us to establish the buildings in the data set that had roofs cleared of tephra prior to any rainfall.

Remobilisation was not reported to be a major issue in or around Ensenada, which authorities (e.g. emergency managers) considered to be due to the relatively coarse grain size of the tephra deposit (Hayes et al. in review). As such, post-event remobilisation was unlikely to have considerably affected areas outside of the 1 km buffer zone used in this work. This was not the case farther afield in Argentina, where several communities experienced remobilisation issues (Reckziegel et al., 2016). Thus, it was appropriate to exclude from analysis properties that were outside of the hazard zones for our study of relatively proximal communities. However, for other data sets this assumption may not hold; where our methodology is applied, damage from remobilisation may need to be considered.

It is difficult to determine lahar hazard intensity during post-event impact assessment. Common lahar hazard intensity measures include flow velocity (m s^{-1}), thickness (m) and pressure (kPa), all of which are spatially heterogenous and difficult to measure in the field. Successive lahars can occur post-eruption and cause compounding impacts to exposed buildings. In this work we were unable to find lahar hazard intensity data beyond an estimated average flow velocity of 7.5 m s^{-1} with a potential maximum of 25 m s^{-1} for the Blanco South River (Bono and Amigo 2015; Flores, 2016). The number of individual lahar events preceding the damage observations made by

MINVU is unknown. For this reason, we concentrated on identifying buildings that were subjected to lahar(s) as a result of the eruption. However, even this is not simple as lahar extent was mapped from satellite imagery after the event, meaning the precise extent is unknown (e.g. flood waters with minimal sediment could have affected some areas). For this reason, we applied a 100 m buffer to mapped lahar extents to ensure we captured all buildings potentially subjected to lahar. Consequently, the conclusions that can be drawn from our analysis are limited to general trends.

5.2 Asset information for damage assessment

High quality, high resolution, and complete asset data sets are rare across the world because they are expensive to develop and maintain. If accurate asset typology assessments are not made during field evaluations it can be challenging to make comparisons between observed impacts and hazard intensity. Houses in our study area are predominantly timber-framed with metal sheet roofs, which simplified the analysis. However, there is considerable variability in sub-typologies (e.g. roof pitch), construction quality, and building age recorded in the MINVU data set. Although there are occasional references to particularly old or poorly maintained houses, building age does not appear to have been systematically recorded by MINVU assessors, which meant we were unable to conduct further analysis on this characteristic.

5.3 Impact information for damage assessment

The recording of impact or damage information in the data set used in this study was variable, which limits the conclusions that can be drawn from the data and subsequent analysis. Ambiguity in the damage descriptions, incomplete information, inconsistent use of terminology, and reporting bias towards severe forms of damage are all potential sources of error in our analysis. An example of an incomplete and vague damage description associated with our analysis can be seen by considering damage observation 704: “The kitchen roof collapsed”. Presented with only this information our group would have assigned DS2 under the assumption that the kitchen is likely to

be less than or equal to 50% of the total roof area of a house in the study area, and there is no reporting of damage to principle roof supports. However, upon investigating a photograph of the damage it became apparent that DS4 was appropriate due to clear evidence that a principle roof support beam failed (Figure 15).

Damage described is possibly biased towards the most identifiable damage. For buildings exposed to multiple hazardous processes it can become a challenge to delineate which process caused each damage type. Further, DS1 may not be readily described as it might not necessarily be considered important by damage assessors. Therefore, DS1 might be assigned as DS0 by damage assessors. This demonstrates the importance of understanding the purpose of any damage assessment survey (e.g. life safety, habitability, insurance assessment).

Figure 15: Photo that correlates to damage observation 704 of the MINVU data set. This building falls within the 15-20 cm tephra fall band. Note: clear evidence for failure of principle roof support beam.

The MINVU data set contained several observations that appear to describe damage that exceeds what might typically be expected for the hazard intensity. This could be an issue with

683 asset classification (e.g. very poor-quality building not captured in the description or photos),
684 vague impact description resulting in an overestimation of damage state (e.g. “damage in the
685 roof”), or inaccurate geolocation of the data point in the field resulting in an incorrect classification
686 of hazard intensity in our analysis.

687 Our assignment of damage state was based on when the observation was made, which may post-
688 date initial repair undertaken by the property owner. For example, Observation ID 931 reports that
689 the property owners had begun repairing their property. This highlights the perishability of impact
690 data following eruptions: it is important that dates are clearly recorded with damage observations
691 and ideally an indication of whether there is evidence of repairs complete or underway.

692 Damage that fell outside the scope of the tephra and lahar damage state frameworks in this work
693 was reported in the MINVU damage data set. For example, water damage that occurred after
694 partial roof collapse may have added to the losses experienced by the occupier of that property.
695 There were also several references to infestation of vermin post-eruption. These types of
696 compounding effects are rarely considered as part of volcanic impact or risk assessments but
697 hazard cascades and compounding effects have been identified as future research requirements
698 in volcanic risk assessment (Bonadonna et al., 2018).

699 A consistent data recording framework was recommended as a necessary development at the 1st
700 IAVCEI-GVM workshop “From Volcanic Hazard to Risk Assessment” (Bonadonna et al., 2018) to
701 remove subjective terminology and ensure that information is recorded in a consistent and
702 systematic manner. The examples described above and our attempts to manage data quality
703 issues in this study highlight the importance of clear, accurate, and comprehensive records of
704 damage observations for future post-eruption impact assessments.

5.5 Considerations for damage states of timber framed houses

An important consideration for volcanic risk assessment is the likelihood of roof collapse due to tephra loading. Our analysis of the MINVU damage data set indicates partial roof collapse of houses may have occurred under dry deposit loadings as low as 0.2 kN m^{-2} (0.6 to 1 kN m^{-2} using Van Eaton isopachs), which is close to the minimum basic snow loading standard of 0.25 kN m^{-2} . These instances were rare, and possibly due to old and poorly maintained buildings, but we cannot rule out that the damage state assigned was a result of our conservative interpretation of damage descriptions. Most typically, partial roof collapse (or greater damage) of houses initiated under minimum loadings of 1.5 to 3.3 kN m^{-2} (dry deposit) or 2.4 to 4.8 kN m^{-2} (saturated deposit), comparable with observations for similar structures made by Blong (2003a) for Rabaul (2 to over 7.5 kN m^{-2}), analytical results from Pomonis (1997) for roofs on Montserrat (1.8 to 3.3 kN m^{-2}), estimates made by Spence et al. (2005) for analogous European buildings (1.8 to 5.5 kN m^{-2}) and for globally similar types in the 2015 Global Assessment of Risk (0.9 to 5.9 kN m^{-2} ; Jenkins et al. 2015b). Interestingly, 75 houses in the MINVU damage data set were subjected to loads in excess of 1 to 2 kN m^{-2} and were not assigned a damage state in excess of DS1. The highest loadings that houses in the MINVU damage data set were subjected to were 2.9 to 5.9 kN m^{-2} (dry deposit) or 4.8 to 9.5 (saturated deposit) ($n=15$), with a third ($n=5$) suffering DS4 or DS5 damage. These houses were all timber-framed with metal sheet roofs, and so not buildings where failure would be unexpected (e.g., reinforced concrete roofs).

Focus of damage states frameworks has often centred on structural performance (e.g. failure of roof support beams). However, defining the difference between DS0 and DS1 is important, as DS1 is usually anticipated as the onset of insurance loss from volcanic tephra fall (Blong et al., 2017c). DS1 is mostly reserved for light non-structural damage (e.g. gutter collapse), but some damage state frameworks identify 'clean-up required' as an indicator of DS1. A potential reason for this would be insurance policies that include payment for the costs of clean-up (Hayes et al.,

2015). This raises the question of the meaning of 'clean-up required' and whether a more precise definition is necessary. For example, if trace tephra fall has occurred, is it appropriate to categorize it in same damage state as a building that suffers damage to roof covers and gutter failure in addition to a more substantial property clean-up? In our Calbuco study, this would mean that all houses exposed to tephra fall and classified as DS0 would need to be upgraded to DS1. In this case, there would be no 'DS0' assignment given hazard exposure, rendering DS0 redundant. The Blong (2003a) damage index included a DS0, but it was not used in their survey as all buildings were exposed to considerable accumulations of tephra. Spence et al. (1996) survey used a DS0 but made no mention of clean-up being required for any of the damage categories used. Thus, the integration of clean-up requirements within residential damage/loss frameworks requires further work. If clean-up is to be included as an indicator of DS1, clear definitions are required as to why it is being used and what 'clean-up required' means.

6. Conclusions

The April-May 2015 eruption of Calbuco volcano produced tephra falls and lahars that affected buildings around the volcano. Houses located in and near Ensenada were exposed to up to 30 to 60 cm of tephra deposition (dry deposit loading: 2.9 to 6.6 kN m⁻², saturated deposit loading: 4.8 to 9.5 kN m⁻²). Houses near rivers draining the volcano were exposed to lahars in the aftermath of the eruption. Of a total data set containing 990 damage observations of various building types, we were able to classify building damage for 570. We found that total collapse of houses (DS5) occurred at a minimum tephra thickness of 10 to 20 cm (dry deposit loading: 1.0 to 2.2 kN m⁻², saturated deposit loading: 1.6 to 3.2 kN m⁻²), but there was evidence that partial roof collapse may have occurred to some houses exposed to 2 cm tephra thickness (dry deposit loading: 0.2 kN m⁻², saturated deposit loading: 0.3 kN m⁻²). Damage from lahars was typically characterised as complete (DS5).

Our study demonstrates challenging data quality issues that must be overcome for robust analysis of post-eruption building damage, particularly when reliant on secondary data sources. Most of the data used here were considered to have low indices for data usefulness, detail and completeness. Co-locating hazard intensity and damage observations would reduce much of the uncertainty derived from relating damage to broad measures of hazard intensity. Robust assessment and documentation practices and consistent use of terminology are particularly important to reduce the potential for errors.

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References

- Baxter, P.J., Boyle, R., Cole, P., Neri, A., Spence, R., Zucarro G. 2005. The impacts of pyroclastic surges on buildings at the eruption of the Soufrière Hills volcano, Montserrat. *Bulletin of Volcanology*. 67, 4, 292-313. <https://doi.org/10.1007/s00445-004-0365-7>
- Blong, R., 2003a. Building damage in Rabaul, Papua New Guinea, 1994. *Bulletin of Volcanology*. 65, 1, 43-54. <https://doi.org/10.1007/s00445-002-0238-x>
- Blong, R., 2003b. A review of damage intensity scales. *Natural Hazards* 29: 57-75. <https://doi.org/10.1023/A:1022960414329>.
- Blong, R., McKee, C., 1995. The Rabaul eruption 1994: Destruction of a town. *Natural Hazard Research Centre, Macquarie University, Sydney*, 52 pp.
- Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K., Kandlbauer, J., 2017a. Estimating building vulnerability to volcanic ash fall for insurance and other purposes. *Journal of Applied Volcanology*. 6:2. <https://doi.org/10.1186/s13617-017-0054-9>
- Blong, R., Enright, N., Grasso, P., 2017b. Preservation of thin tephra. *Journal of Applied Volcanology*. 6:10. <https://doi.org/10.1186/s13617-017-0059-4>
- Blong, R., Tillyard, C., Attard, G., 2017c. Insurance and a Volcanic Crisis—A Tale of One (Big) Eruption, Two Insurers, and Innumerable Insureds. In C.J. Fearnley, D.K. Bird, K. Haynes, W.G. McGuire, G. Jolly (editors), *Observing the Volcano World Volcano Crisis Communication. Advances in Volcanology (An Official Book Series of the International Association of Volcanology and Chemistry of the Earth's Interior – IAVCEI, Barcelona, Spain)*. Springer, Cham. https://doi.org/10.1007/11157_2016_42
- Bonadonna, C., Biass, S., Costa, A., 2015. Physical characterization of explosive volcanic eruptions based on tephra deposits: Propagation of uncertainties and sensitivity analysis. *Journal of Volcanology and Geothermal Research*. 296, 80-100. <https://doi.org/10.1016/j.jvolgeores.2015.03.009>
- Bonadonna, C., Biass, S., Calder, E.S., Frischknecht, C., Gregg, C.E., Jenkins, S., Loughlin, S.C., Menoni, S., Takarada, S., Wilson, T., 2018. "1st IAVCEI/GVM Workshop: "From Volcanic Hazard to Risk Assessment", Geneva, 27-29 June 2018," <https://vhub.org/resources/4498>.
- Bono, L., Amigo, Á., 2015. Modelamiento de los lahares ocurridos en el volcán Calbuco 2015 con el software RAMMS. *Congreso Geológico Chileno, No. XIV, La Serena, Chile*.
- Castruccio, A., Clavero, J., Rivera, A., 2014. Comparative study of lahars generated by the 1961 and 1971 eruptions of Calbuco and Villarrica volcanoes, Southern Andes of Chile. *Journal of Volcanology and Geothermal Research*. 190, 3-4, 297-311. <https://doi.org/10.1016/j.jvolgeores.2009.12.005>

813 Castruccio, A., Clevario, J., Segura, A., Samaniego, P., Roche, O., Le Pennec, J-L.,
814 Droguett, B., 2016. Eruptive parameters and dynamics of the April 2015 sub-
815 Plinian eruptions of Calbuco volcano (southern Chile), *Bulletin of Volcanology*.
816 78, 62. <https://doi.org/10.1007/s00445-016-1058-8>.

817 Clavero, J., Godoy, E., Arancibia, G., Rojas, C., Moreno, H., 2008. Multiple Holocene
818 sector collapses at Calbuco volcano, Southern Andes. Abstracts, Poster Session
819 III, IAVCEI General Assembly, Reykjavik, Iceland, p. 41.

820 Cooke, R.M., 1991. *Experts in Uncertainty: Opinion and Subjective Probability in*
821 *Science*, Oxford University Press, New York.

822 Delgado, F., Pritchard, M.E., Ebmeier, S., González, P., Lara, L., 2017. Recent unrest
823 (2002–2015) imaged by space geodesy at the highest risk Chilean volcanoes:
824 Villarrica, Llaima, and Calbuco (Southern Andes). *Journal of Volcanology and*
825 *Geothermal Research*. 344, 270-288.
826 <https://doi.org/10.1016/j.jvolgeores.2017.05.020>

827 Deligne, N.I., Horspool, N., Canessa, S., Matcham, I., Williams, G.T., Wilson, G., Wilson,
828 T.M., 2017. Evaluating the impacts of volcanic eruptions using RiskScape.
829 *Journal of Applied Volcanology*. 6:18. <https://doi.org/10.1186/s13617-017-0069-2>

830 Ettinger, S., Mounaud, L., Magill, C., Yao-Lafourcade, A.F., Thouret, J.C., Manville, V.,
831 Negulescu, C., Zuccaro, G., De Gregorio, D., Nardone, S., Uchuchoque, J.A.L.,
832 Arguedas, A., Macedo, L., and Manrique Llerena, N., 2016, Building vulnerability
833 to hydro-geomorphic hazards: Estimating damage probability from qualitative
834 vulnerability assessment using logistic regression: *Journal of Hydrology*. 541,
835 563–581. <https://doi.org/10.1016/j.jhydrol.2015.04.017>.

836 Flores F., 2016. Dynamics of 2015 Villarrica and Calbuco lahar flows. *Cities on*
837 *Volcanoes* 9, Puerto Varas, Chile.

838 Hayes, J.L., Wilson, T.M., Magill, C., 2015. Tephra fall clean-up in urban environments.
839 *Journal of Volcanology and Geothermal Research*. 304, 359-377.
840 <https://doi.org/10.1016/j.jvolgeores.2015.09.014>

841 Hayes, J.L., Deligne, N.I., Bertin L., Calderon, R., Wardman, J.B., Wilson T.M., Leonard,
842 G.S., Stewart, C., Wallace, K.L., Baxter, P., in review. Impacts of the 2015
843 eruption of Calbuco volcano on Chilean infrastructure, utilities, agriculture, and
844 health . Lower Hutt (NZ): GNS Science

845 INE., 2017. Instituto Nacional de Estadísticas; Censo nacional de población y vivienda
846 [National Institute of Statistics; National census of population and housing].
847 Santiago.

848 INN., 2000. Norma Chilena NCh432.Of71. Cálculo de la acción del viento sobre las
849 construcciones, [Chilean normative NCh432.Of71. Calculation of the action of
850 wind on structures]. Santiago, Chile.

851 INN., 2010. Norma Chilena NCh431-2010. Diseño estructural - Sobrecargas de nieve. El
852 Instituto Nacional de Normalización. [Chilean normative NCh431-2010. Structural
853 design - Overload of snow. National Institute of Normalization]. Santiago, Chile.

- Jenkins, S.F., Komorowski, J.-C., Baxter, P.J., Spence, R., Picquout, A., Lavigne, F., Surono., 2013. The Merapi 2010 eruption: An interdisciplinary impact assessment methodology for studying pyroclastic density current dynamics, *Journal of Volcanology and Geothermal Research*. 261, 316-329. <https://doi.org/10.1016/j.jvolgeores.2013.02.012>.
- Jenkins, S.F., Spence R.J.S., Fonseca, J.F.B.D., Solidum, R.U., Wilson, T.M., 2014. The Merapi 2010 eruption: An interdisciplinary impact assessment methodology for studying pyroclastic density current dynamics, *Journal of Volcanology and Geothermal Research*. 276, 105-120. <https://doi.org/10.1016/j.jvolgeores.2014.03.002>.
- Jenkins, S.F., Phillips, J.C., Price, R., Feloy, K., Baxter, P.J., Hadmoko, D.S., de Blizar, E., 2015a. Developing building-damage scales for lahars : application to Merapi volcano, Indonesia. *Bulletin of Volcanology*. 77:75. <https://doi.org/10.1007/s00445-015-0961-8>.
- Jenkins, S.F., Wilson, T.M., Magill, C.R., Miller, V., Stewart, C., Blong, R., Marzocchi, W., Boulton, M., Bonadonna, C., Costa, A., 2015b. Volcanic ash fall hazard and risk. Chapter 3. In: S.C. Loughlin, R.S.J. Sparks, S.K. Brown, S.F. Jenkins and C. Vye-Brown (Editors), *Global Volcanic Hazards and Risk*. Cambridge University Press, pp. 173. Open Access: cambridge.org/volcano.
- Jenkins, S.F., Day, S.J., Faria, B.V.E., Fonseca, J.F.B.D., 2017. Damage from lava flows: insights from the 2014–2015 eruption of Fogo, Cape Verde. *Journal of Applied Volcanology* 6:6. <https://doi.org/10.1186/s13617-017-0057-6>
- Kang, H., Kim, Y., 2016. The physical vulnerability of different types of building structure to debris flow events. *Natural Hazards*. 80, 1475–1493. <https://doi.org/10.1007/s11069-015-2032-z>.
- Kappes, M.S., Keiler, M., Kappes, M.S., von Elverfeldt, K., Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. *Natural Hazards*. 64, 2, 1925-1958. <https://doi.org/10.1007/s11069-012-0294-2>
- Krnk, V., Schenkova, Z., Schenk, V., 1983. Vulnerability and the MSK scale. *Engineering Geology*. 20, 1-2, 161-168. [https://doi.org/10.1016/0013-7952\(84\)90051-6](https://doi.org/10.1016/0013-7952(84)90051-6)
- Klawonn, M., Houghton, B.F., Swanson, D.A., Fagents, S.A., Wessel, P., Wolfe, C.J., 2014. Constraining explosive volcanism: Subjective choices during estimates of eruption magnitude. *Bulletin of Volcanology*, 76,2,1–6. <https://doi.org/10.1007/s00445-013-0793-3>
- Klohn, E. (1963). The February 1961 eruption of Calbuco volcano. *Bulletin of the Seismological Society of America*. 53, 6, 1435-1436.
- Knzler, M., Huggel, C., Ramrez, J.M., 2012. A risk analysis for floods and lahars: Case study in the Cordillera Central of Colombia, *Natural Hazards*. 64, 1, 767–796. <https://doi.org/10.1007/s11069-012-0271-9>.

894 LandScan 2009™ High Resolution Global Population Data Set copyrighted by UT-
895 Battelle, LLC, operator of Oak Ridge National Laboratory under Contract No. DE-
896 AC05-00OR22725 with the United States Department of Energy.

897 López-Escobar, L., Parada, M.A., Hickey-Vargas, R., Frey, F.A., Kempton, P.D.,
898 Moreno, H., 1995. Calbuco Volcano and minor eruptive centers distributed along
899 the Liquiñe-Ofqui Fault Zone, Chile (41° 42°S): contrasting origin of andesitic and
900 basaltic magma in the Southern Volcanic Zone of the Andes. Contributions to
901 Mineralogy and Petrology. 119, 4, 345–361. <https://doi.org/10.1007/BF00286934>

902 Macedonio, G., Costa, A., 2012. Brief Communication "Rain effect on the load of tephra
903 deposits". Natural Hazards and Earth System Sciences, 12, 1229-1233.
904 <https://doi.org/10.5194/nhess-12-1229-2012>

905 Matoza, R.S., Fee D., Green D.N., Le Pichon, A., Vergoz, J., Haney, M.M., Mikesell,
906 T.D., Franco, L., Valderrama, O.A., Kelley, M.R., McKee, K., Ceranna, L., 2018.
907 Local, Regional, and Remote Seismo-acoustic Observations of the April 2015
908 VEI 4 Eruption of Calbuco Volcano, Chile. Journal of Geophysical Research:
909 Solid Earth, 123, 5, 3814-3827. <https://doi.org/10.1002/2017JB015182>

910 Mead, S.R., Magill, C., Lemiale, V., Thouret, J-C., Prakash, M., 2017. Examining the
911 impact of lahars on buildings using numerical modelling, Natural Hazards and
912 Earth System Sciences, 17, 703–719. [https://doi.org/10.5194/nhess-17-703-](https://doi.org/10.5194/nhess-17-703-2017)
913 2017.

914 Mella, M., Verges, A., Moreno, H., Bertin, D., Basualto, D., Garrido, N., Quiroz, D., 2016.
915 Volcanic processes (products) map of Calbuco eruption 2015: beyond the
916 scientific use. Cities on Volcanoes 9, Puerto Varas, Chile

917 Ministerio de economía., 2014. X Región de Los Lagos. División de Política Comercial e
918 Industrial. [X Region of Los Lagos. Division of Commercial and Industrial Policy].
919 Ministerio de economía Fomento y Turismo. [Accessed 2018 July 10].
920 [http://www.economia.gob.cl/wp-content/uploads/2014/05/X-Región-de-los-](http://www.economia.gob.cl/wp-content/uploads/2014/05/X-Región-de-los-Lagos.pdf)
921 [Lagos.pdf](http://www.economia.gob.cl/wp-content/uploads/2014/05/X-Región-de-los-Lagos.pdf)

922 Moreno, H., 1974. Airplane flight over active volcanoes of central-south Chile.
923 International Symposium on Andean and Antarctic Volcanology Problems,
924 International Association of Volcanology and Chemistry of the Earth Interior
925 (IAVCEI), Departamento de Geología, Universidad de Chile, Guide Book, No. D-3,
926 56p.

927 Moreno, H., 1976. The Upper Cenozoic volcanism in the Andes of Southern Chile (from
928 40°00 to 41°30' S.L.). In Gonzalez-Furran O, Proceedings of the Symposium on
929 Andean and Antarctic Volcanology Problems, International Association of
930 Volcanology and Chemistry of the Earth Interior (IAVCEI), 143-171.

931 Moreno, H., 1999. Mapa de Peligros del volcán Calbuco, Región de Los Lagos. Servicio
932 Nacional de Geología y Minería, Documentos de trabajo, No 12, 1 mapa escala
933 1:75.000.[Calbuco volcano hazard map, Los Lagos Region. National Geology
934 and Mining Service (SERNAGEOMIN), Work documents, No12, 1 map scale
935 1:75.000] Santiago.

936 Moreno, H., Naranjo, J., Clavero, J., 2006. Generación de lahares calientes en el volcán
937 Calbuco, Andes del Sur de Chile (41,3°S). *XI Congreso Geológico Chileno*.
938 [Generation of hot lahars in Calbuco volcano, Andes of Southern Chile (41,3°S).
939 *XI Chilean Geological Congress*.]Antofagasta, Chile.

940 Petit-Breuilh, M.E. Moreno, H., 1997. La erupción de 1893-1895 del volcán Calbuco
941 (41.3°S) y sus efectos ambientales. *In* Congreso Geológico Chileno, No. 8,
942 Actas, Vol. 1, p. 780-784. [The 1893-1895 Calbuco volcano eruption (41,3°S). *In*
943 Chilean Geological Congress, No. 8, Actas, Vol. 1, p. 780-784]. Antofagasta,
944 Chile.

945 Petit-Breuilh, M.E., 2004. La Historia Eruptiva de los Volcanes Hispanoamericanos
946 (siglos XVI al XX). Serie Casa de los Volcanes N°8. Servicio de Publicaciones
947 del Excelentísimo Cabildo Insular de Lanzarote, Huelva, España (431 pp.).

948 Pierson, T.C., Major, J.J., Amigo, Á., Moreno, H., 2013. Acute sedimentation response
949 to rainfall following the explosive phase of the 2008-2009 eruption of Chaitén
950 volcano, Chile: Bulletin of Volcanology. 75, 1-17. [https://doi.org/10.1007/s00445-](https://doi.org/10.1007/s00445-013-0723-4)
951 [013-0723-4](https://doi.org/10.1007/s00445-013-0723-4).

952 Pomonis, A., 1997. Soufriere Hills volcanic eruption: a risk assessment to buildings from
953 volcanic block impacts and tephra fall loading. Cambridge Architectural Research
954 Ltd Internal Rep.

955 Reckziegel, F., Bustos, E., Mingari, L., Báez, W., Villarosa, G., Folch, A., Collini, E.,
956 Viramonte, J., Romero, J., Osóres, S., 2016. Forecasting volcanic ash dispersal
957 and coeval resuspension during the April-May 2015 Calbuco eruption. Journal of
958 Volcanology and Geothermal Research. 321, 44-57.
959 <https://doi.org/10.1016/j.jvolgeores.2016.04.033>

960 Romero, J.E., Morgavi, D., Arzilli, F., Daga, R., Caselli A., Reckziegel, F., Viramonte, J.,
961 Díaz-Alvarado, Polacci, M., Burton, M., Perugini, D., 2016. Eruption dynamics of
962 the 22–23 April 2015 Calbuco Volcano (Southern Chile): Analyses of tephra fall
963 deposits, Journal of Volcanology and Geothermal Research. 317, 15-29.
964 <https://doi.org/10.1016/j.jvolgeores.2016.02.027>

965 Santa María, H., Hube, M.A., Rivera, F., Yepes-Estrada, C., Valcárcel, J.A., 2017.
966 Development of national and local exposure models of residential structures in
967 Chile. Natural Hazards. 86, Supplement 1, 55-79. [https://doi.org/10.1007/s11069-](https://doi.org/10.1007/s11069-016-2518-3)
968 [016-2518-3](https://doi.org/10.1007/s11069-016-2518-3)

969 Sernatur., 2018. Llegadas a establecimientos de alojamiento turístico, por mes, según
970 región, destino turístico y residencia. Serie 2014-2015-2016. [Arrivals to tourist
971 accommodation establishments, per month, by region, tourist destination and
972 residence. Serie 2014-2015-2016]. ([https://www.sernatur.cl/establecimientos-](https://www.sernatur.cl/establecimientos-de-alojamiento-turistico/)
973 [de-alojamiento-turistico/](https://www.sernatur.cl/establecimientos-de-alojamiento-turistico/))

974 Spence, R., Pomonis, A., Baxter, P., Coburn, A., White, M., Dayrit, M., Field
975 Epidemiology Training Program Team., 1996. Building damage caused by the
976 Mount Pinatubo eruption of June 15, 1991. In: C.G. Newhall and R.S.
977 Punongbayan (Editors), Fire and Mud: eruptions and lahars of Mount Pinatubo,

978 Philippines. Philippines Institute of Volcanology and Seismology, University of
979 Washington Press, Seattle, pp. 1055-1061.

980 Stern, C.R., Moreno, H., Lopez-Escobar, L., Clavero, J.E., Lara, L.E., Naranjo, J.A.,
981 Parada, M.A., Skewes, M.A., 2007. Chilean volcanoes. In: Moreno T, Gibbons
982 W. editors. The Geology of Chile. The Geological Society, London.

983 Valderrama, O., Franco, L., Gil-Cruz, F., 2015. Erupción intempestiva del volcán
984 Calbuco, Abril 2015. Congreso Geológico Chileno, No. XIV, La Serena, Chile

985 Valderrama, O., Cardona, C., Gil-Cruz, F., 2016. Subplinian eruption of Calbuco volcano
986 (Chile), April 22th, an example of VEI-4 explosive eruption with few precursor
987 signals, Cities on Volcanoes 9, Puerto Varas, Chile

988 Van Eaton, A.R., Amigo, A., Bertin, D., Mastin, L.G., Giacosa, R.E., González, J.,
989 Valderrama, O., Fontijn, K., Behnke, S.A., 2016. Volcanic lightning and plume
990 behavior reveal evolving hazards during the April 2015 eruption of Calbuco
991 volcano, Chile. Geophysical Research Letters. 43, 7, 3563–3571.
992 <https://doi.org/10.1002/2016GL068076>.

993 Wilson, G., Wilson, T.M., Deligne, N.I., Cole, J.W., 2014. Volcanic hazard impacts to
994 critical infrastructure: A review. Journal of Volcanology and Geothermal
995 Research. 286, 148-182. <https://doi.org/10.1016/j.jvolgeores.2014.08.030>

996