

the dominant regional winds directed the ash clouds over the Andes and caused abundant ash fallout across the Argentinean provinces of Río Negro, Neuquén and Chubut, affecting the more proximal areas in Chile as well. Large quantities of ash fell in the nearby regions until the end of July, causing major problems in villages and cities of the Patagonian Andes and permanent closure of airports. Villa la Angostura, one of the most touristic areas of Patagonia, located near the Argentine-Chilean border and at short distance from the new vent, was one of the most affected cities.

As a consequence of these ash fall events, thick deposits of tephra and snow accumulated during the winter covered extensive areas surrounding Villa La Angostura. This resulted in a lahar hazard for the town, as the snow began to melt during the spring and summer seasons. This paper analyzes the hazard posed by the snow-ash deposits that could contribute to secondary lahar formation potentially affecting Villa la Angostura.

2 Volcanic event and deposits

On 27 April 2011 the Chilean OVDAS-SERNAGEOMIN institute (OVDAS-SERNAGEOMIN, 2011a) reported that a swarm of volcano-tectonic earthquakes, centered on the Cordón Caulle fissure zone, were detected. These earthquakes continued to increase in magnitude and frequency until Saturday 4 June, when the eruption sequence began (OVDAS-SERNAGEOMIN, 2011b). At 13:00 LT, an earthquake followed by a strong blast surprised neighbors at Villa La Angostura, 45 km East-South-East of the vent, and a 5 km-wide ash and gas plume rose to more than 12 km height (Fig. 1). Then, coarse ash fall occurred soon after in the villa and by 16:30 LT the plume reached San Carlos de Bariloche, located 100 km SE of the vent producing a dense coarse ash seized pyroclastic fall. A sampling network was set up to collect direct fall tephra from the beginning of the eruption, covering a transect from Paso Puyehue, at the Chile-Argentina border, Villa La Angostura, Bariloche and to the steppe as far as Ingeniero Jacobacci in Río Negro province.

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Over 400 thickness data were plotted to make an isopach map (Fig. 3). The most relevant characteristic of the first pulses of the eruption that comes up clearly from the map is a distribution pattern showing three main deposition axes that correspond to the dispersion directions of the main plumes at 90, 110 and 130. Deposited materials during the period June–October 2011, affected more than 1450 km² with at least 10 cm thick ash and 170 km² were covered by more than 30 cm thick tephra.

Direct tephra fall in the basins of the streams draining towards Villa La Angostura accumulated more than 15 cm thick deposits along the dispersion axis. The unconsolidated ash deposits were remobilized by precipitations and wind and many fall pulses were covered by snow soon after the deposition. This was especially frequent in the upper sections of the fluvial basins at altitudes over 1000 m a.s.l. In those environments, characterized according to their glacial origin by high slope valley walls, mobilization of tephra towards the valley floor occurred rather quickly, accumulating reworked materials 2 or 3 times thicker than the original deposits.

By the end of the spring most snow disappeared, the pyroclastic material contained in the snow pack was almost completely transported to the floor of the valley and the finer fractions were intensely reworked by wind. As a result, thicknesses varied significantly compared to the original deposit, particularly in the heads of these U shaped valleys. The resulting isopach map using data collected up to November 2012 shows these variations, as shown in Fig. 4.

3 Lahar hazard assessment

In order to provide the decision makers with a reliable tool of possible lahars from Florencia, Piedritas and Colorado creeks, we chose the modeling method, which accounts for the current topography and uses geological data as initial conditions.

Due to the two phase characteristics of debris flows, the chosen model must be a model that accounts for the two phase behavior of lahars (Iverson, 1997). In this case we used the Two-Phase-Titan model (Córdoba et al., 2010; Sheridan et al., 2011)

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flow, \vec{v}^x and \vec{v}^y the solids velocity field, \vec{u}^x and \vec{u}^y the fluid velocity field, ρ^s and ρ^f the solids and fluid densities. ϵ is the ratio flow depth to flow length, g is the gravity, C_f is the friction factor, and D is the interphase drag coefficient. The solids and fluid momentum equations in y direction have a similar form. Note that if $\overline{\varphi^f} \rightarrow 1$ Eq. (3) becomes the

5 typical shallow water approach of hydraulics (Chow, 1969).
The model has the additional advantage of saving computer power, because it is a pseudo-3-D approach, which is also due to its mesh adapting capabilities. Through the extended use of this program in real scale problems, it has shown its reliability and robustness. Thus, in this work we use Two-Phase-Titan as the computational tool to

10 study and forecast the lahar hazard in Villa la Angostura.

Initial conditions

We analyzed the lahar hazard at Villa La Angostura from three creeks whose streams flow directly toward the urban area of the town. As can be seen in Fig. 5 they are Las Piedritas creek, which have a catchment area of 7.75 km^2 , Colorado creek, with

15 a catchment area of 3.8 km^2 and Florencia creek, with a catchment area of 1.3 km^2 (Baumann et al., 2011). The program Two-Phase-Titan needs the location of the piles, their initial volumes, the pile height and initial concentration of solids as initial conditions.

In order to set the initial volumetric fraction of solids, we used the snow and ash

20 deposits from the eruption. Figure 2 shows several interlayered ash-snow deposits from the Cordón Cauille eruption. They show that almost 30% of them are composed by the deposited ash. Thus, we use as initial solids volumetric concentration $\varphi_s = 0.3$ for all the initial piles.

The needed data to set the initial volumes was taken from the Elissondo et al. (2011)

25 report, which analyzes the deposits of the ash fall from the 4 July 2011 eruption of Cordón Cauille volcanic complex on the nearby mountains. From the estimated deposited material at each basin done by Elissondo et al. (2011) and the depth of the

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deposits shown in Baumann et al. (2011), we set the initial volume for the piles located at Las Piedritas, Colorado and Florencia creeks. Two cases were analyzed for each creek, a high and a medium volume. As it is of low probability for all the deposited material to become a lahar in large catchments, we assumed different fractions of the

5 total deposited volume as initial height and medium volumes. In the case of Las Piedritas basin, we assumed as high initial volume the 50% of the total deposited material, and the quarter of all the deposited material as a medium volume. In case of medium size catchment areas like Colorado, 75% of the deposited material is assumed as high volume. Finally, we assume that from the material deposited on small catchment ar-

10 eas, 90% could become part of the lahar. Another initial condition is the pile height. In this paper we use the reported material deposited depth, which are less than 1 m in all the basins (Elissondo et al., 2011; Baumann et al., 2011). However, we increased this values by a security factor, in order to account for the uncertainties not accounted for. Table 1 summarizes the high and medium volumes, as well as the pile height used as

15 initial conditions in our modeling.
The location of the initial piles where chosen at long distances from each outlet basin. In the case of Las Piedritas, we tested several initial locations. One from the farthest place on the basin, others from the lateral walls. All of them resulted in almost the same pile height and flow velocity at the basin outlet. The basin of Colorado receives the Florencia-North stream as well. Thus, we locate piles both at the top of the Colorado basin and at the top of the Florencia-North stream. In the case of Florencia-South, the initial pile was located at the top of its basin.

An additional pile was located at the top of the La Ponderosa basin, just to test if lahars could reach the town. However, there is no collected data about the deposited

25 ash volumes. We assumed the same volumes as in Florencia creek due to the size of this basin is similar.

4 Results

In order to run Two-Phase-Titan, a Digital Elevation Model (DEM) is needed. The National Commission of Space Activities of Argentina (CONAE) initially provided us with two 15 m resolution DEM. One of them developed from optical satellite images and the second one from radar satellite images.

In order to test the DEMs, we used the initial data set for Florencia creek. Orange contours in Fig. 6, shows the predictions of Two-Phase-Titan using the DEM based on optical sensors, and the red contours shows the prediction using the DEM build from radar sensors. The Google-Earth image shows a widespread forest that hides the Florencia stream from view. The optic DEM reproduces this effect showing the terrain flatter than it actually is. For this reason the model predicts that the lahar will be highly spread from the beginning. By contrast, using the radar sensor based DEM, the flow follows the actual natural channel hidden by the trees. In addition, the limit of the forest may be seen by the model as an abrupt change in the topography. This is the case of some locations in Villa la Angostura, where patches of more than 30 m high forest have been cleared to allow human settlements. Thus, the program predicts a diversion of the flow where such a barrier is reached (see the arrow in Fig. 6), while the flow just follows the natural channel in the prediction done by the program using the radar based model.

Therefore, the optic sensor based terrain model was replaced by the more accurate radar sensor based DEM. As explained above, we use two initial conditions. One with high volumes and the second one with medium volumes (see values in Table 1). Figure 7 shows the prediction of Two-Phase-Titan for the medium volumes. In this case, none of the flows reach the urban area. Nevertheless water treatment facilities and scattered living houses could be inundated. For the volume used in La Ponderosa creek, Two-Phase-Titan predicts that the flow could inundate the main road and structures built near it. It is outstanding to see that the flow from Piedritas creek inundates

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part of a planned urban expansion zone. However, the flow is diverted in an almost 90° angle seemingly by a topographic barrier.

In the case of high volumes, the urban area is shown to be reached from the flows from Florencia creek (see Fig. 8). We should pay special attention to the possibility that the school named School 186 might become affected, as shown by the circle filled in blue. Based on such prediction of the program, we advised the local governmental authorities of the city to take appropriate decisions about that possibility. Then, the Mayor ordered to temporary relocate the kids to another school located in a safer place. In the cases of Colorado and La Ponderosa, the runout of the flow is almost the same as the medium volume case. Nevertheless, they show a trend to inundate in a more expanded way, showing bigger inundation areas than in the case of medium volumes. Fortunately, increase in the inundation area occurs in less populated areas.

In the case of Las Piedritas creek, we located the initial pile at the highest place of the basin. The flow shows a meandering behavior until it reaches the middle of the basin. From that point, its behavioral characteristics become similar to the case of medium volumes but with more depth at each point. Then, despite of the high volume used, the program shows that the flow could be diverted in the same way as it was in the medium volume case. With a personal visit to the place where the diversion happens, we found that there is no such topographic barrier. Instead, there is a narrow opening in the hills. Thus, the prediction of Two-Phase-Titan about the path followed by the flow was mistaken, probably because the 15 m DEM was flattening the representation of the terrain.

We decided to test if by using a more accurate DEM, the prediction would become more realistic. Then the CONAE, developed a 10 m resolution DEM, which was used to repeat the medium volume predictions. Figure 9 shows a Google-Earth image of Villa la Angostura with the medium size modeled lahars using that DEM. The initial piles were located at the top of the basins of Las Piedritas, Colorado and Florencia creeks. In this case the flow from Las Piedritas followed the narrow path, predicting that the flow could reach the beginning of the urban area. The prediction for Colorado creek

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Table 1. Calculated total volumes of deposited ash-snow material at each basin, and volumes used in the modeling, as well as the used pile height.

Creek	Total volume (m)	Large volumes (m)	Medium volumes (m)	Pile height (m)
Piedritas	600 000	300 000	150 000	1
Colorado	270 000	200 000	70 000	1
Florencia	55 500	50 000	20 000	1.5

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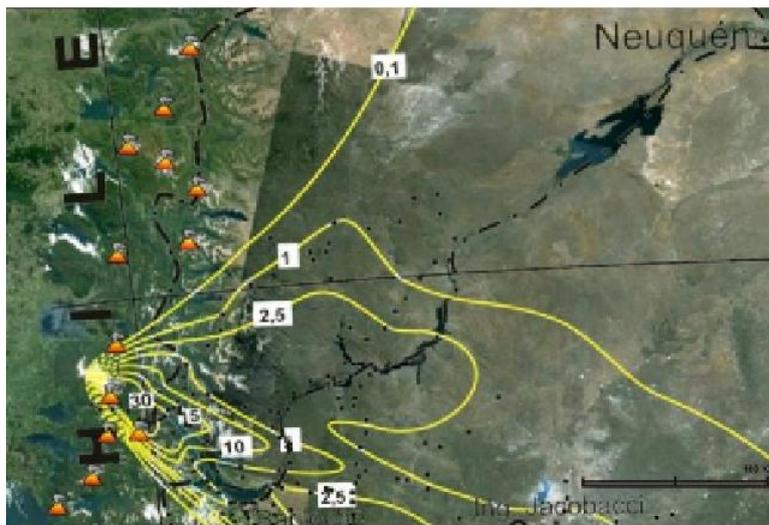


Figure 3. Isopach and affected area by the end of October 2. The yellow lines are the isopach contours. The dots are the sampling sites (after Villarosa and Outes, 2013).

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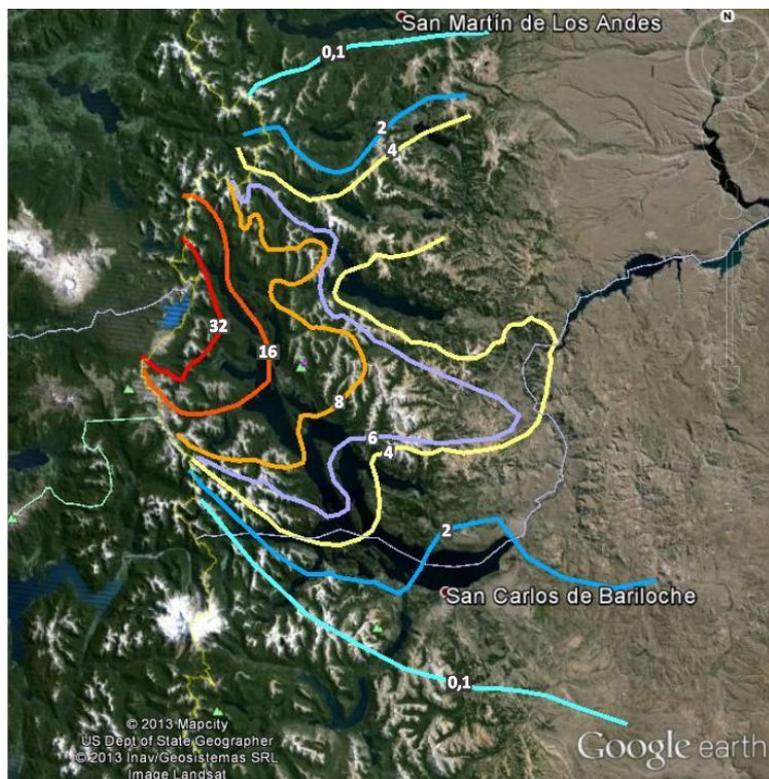


Figure 4. Distribution of tephra deposits modified by erosion and remobilization by November 2012, thicknesses expressed in centimeters (after Villarosa and Outes, 2013).

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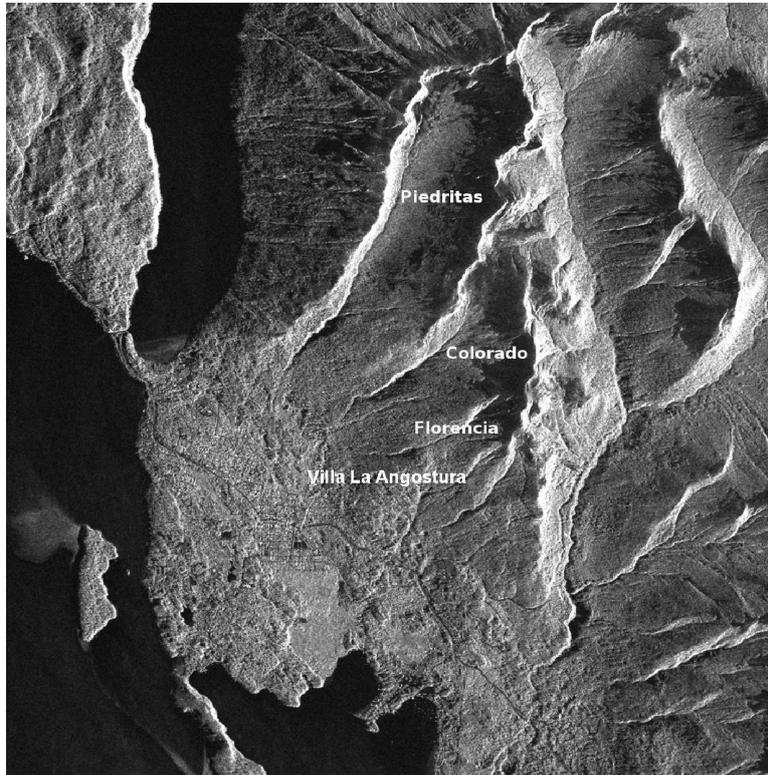


Figure 5. Satellite view of the area of Villa la Angostura, showing the three streams that enter the urban part of the town (image courtesy of Comisión Nacional de Actividades Espaciales, CONAE).

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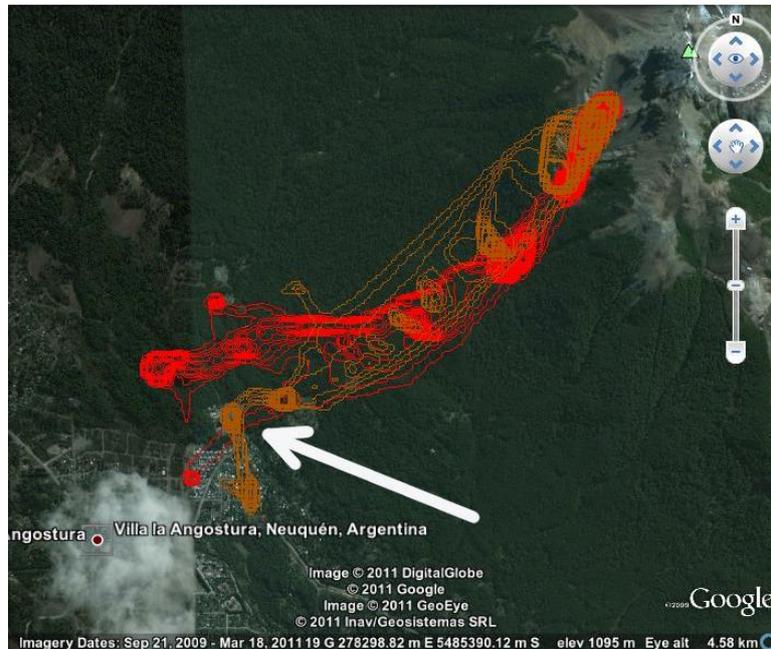


Figure 6. Two-Phase-Titan predictions using two DEMs on a Google-Earth image. The orange contours shows the prediction of the lahar inundation using the DEM based on optical sensors. The red contours shows the prediction of the lahar inundation using a DEM developed from radar sensors. The white arrow points to a beginning of the forest that seems to divert the flow, because it is seen by the optic sensor based DEM as a wall.

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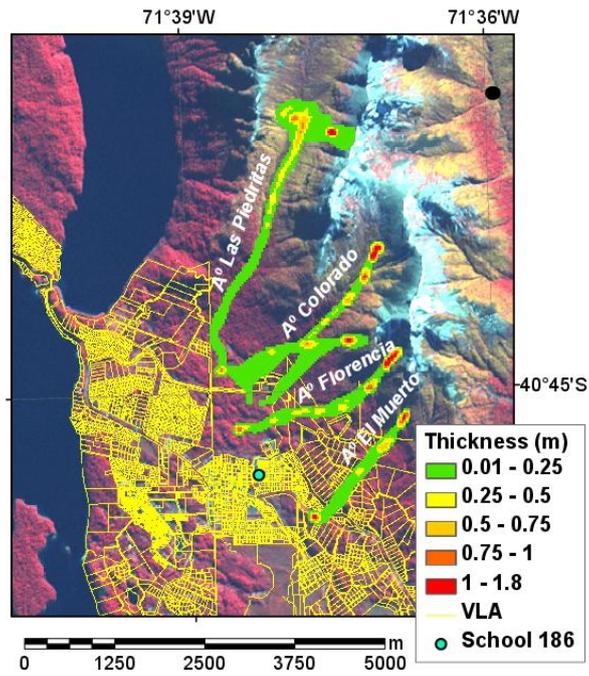


Figure 7. Predictions of Two-Phase-Titan for medium size volumes.

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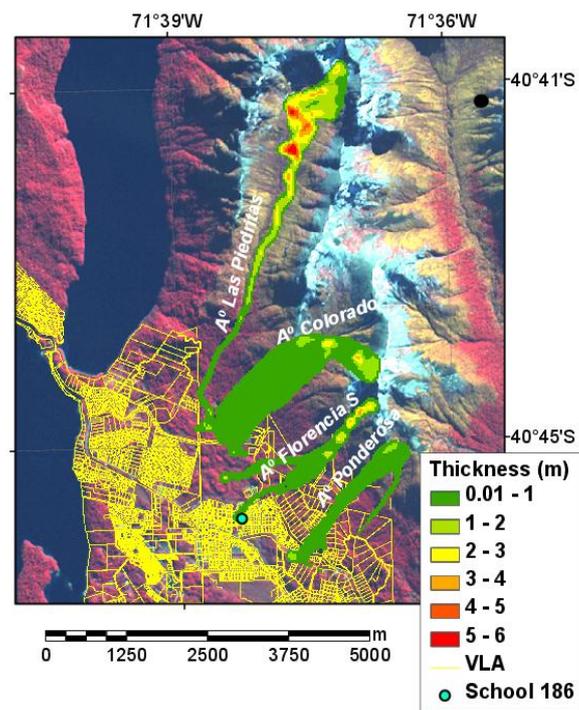


Figure 8. Predictions of Two-Phase-Titan for large size volumes.

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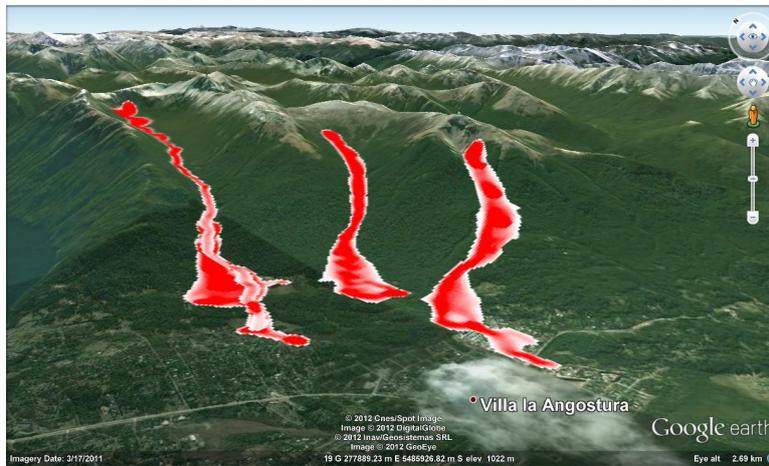


Figure 9. Prediction of Two-Phase-Titan using the 10 m resolution DEM built by the CONAE.