



**Study of lahar hazards at Villa la Angostura**

G. Córdoba et al.

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# Secondary lahar hazard assessment for Villa la Angostura, Argentina, using Two-Phase-Titan modelling code during 2011 Cordón Caulle eruption

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

This paper shows the results of secondary lahar modelling in Villa La Angostura town (Neuquén-Argentina) based on the Two-Phase-Titan modelling computer code, which aimed to provide decision makers a useful tool to assess lahar hazard during the 2011 Puyehue-Cordón Caulle Volcanic Complex eruption. Possible occurrence of secondary lahars that could reach the city was analyzed. The performance of the Two-Phase-Titan model using 15 m resolution DEMs developed from optical satellite images and from radar satellite images was evaluated. The output of these modellings showed inconsistencies that, based on field observations, were attributed to bad adjustment of DEMs to real topography. Further testing of results using more accurate radar based 10 m DEM, proved more realistic predictions. The procedure allowed to simulate the path of flows from Florencia, Las Piedritas and Colorado creeks, which are the most influencing streams in Villa La Angostura. The output of the modelling is a valuable tool for city planning and risk management especially considering the glacial geomorphology features of the region, the strong urban development growth and the land occupation tendencies observed in last decade in Villa La Angostura and its surroundings.

## 1 Introduction

After decades of quiescence, the Cordon Caulle volcanic complex in the Chilean Southern Andes began an eruptive process at 14:45 LT on 4 June 2011 (Elissondo et al., 2011) from the new vent named We Pillan (New Crater in Mapuche language) (Collini et al., 2012). This vent is located in the Southern Volcanic Zone (SVZ) at 40.58° and 72.13° W (Lara and Moreno, 2006), and 2240 m a.m.s.l. (above mean sea level). The sub-plinian eruption produced a large plume of gases and pyroclastic material that reached 12 km in height (Fig. 1) which eventually circled the Southern Hemisphere disrupting air traffic on several continents. As typically occurs in mid-latitude Central and South Andean eruptions (Villarosa et al., 2006; Folch et al., 2008; Collini et al., 2012),

**NHESSD**

2, 6373–6395, 2014

### Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



---

**Study of lahar hazards at Villa la Angostura**G. Córdoba et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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.

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 km<sup>2</sup> with at least 10 cm thick ash and 170 km<sup>2</sup> 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)

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



which was developed at SUNY University at Buffalo. For the solids phase, this model is based on the early work of Savage and Hutter (1989), Iverson (1997) and Iverson and Denlinger (2001), who arrived at the insight that very large dense granular flows could be modeled as incompressible continua governed by a Coulomb failure criterion (Coulomb, 1773). The fluid phase uses the typical hydraulic approach (Chow, 1969; Guo, 1995) together with the Colebrook–White equation (Colebrook and White, 1937) for the basal friction. The phases interact through a phenomenological interphase drag and a buoyancy term.

Further, the equations of motion are depth averaged, by assuming that the flow depth is very small in comparison to the runoff. This mean that the resulting equations neglect vertical accelerations in similar way to shallow water approaches. By scaling the problem stating that  $\epsilon = H/L$ , where  $L$  is runout length to the pile front, and neglecting higher-order terms in  $\epsilon$ , the correspondent equilibrium equations become (only  $x$  direction are shown):

### 1. Conservation of Mass:

$$\partial_t \hat{h} + \partial_x \left( \hat{h} (\overline{\varphi v_x} + \overline{\varphi^t u_x}) \right) + \partial_y \left( \hat{h} (\overline{\varphi v_y} + \overline{\varphi^t u_y}) \right) = 0. \quad (1)$$

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 2. Conservation of Solid Phase Momentum:

$$\begin{aligned}
 \partial_t (\hat{h} \overline{\varphi v^x}) + \partial_x (\hat{h} \overline{\varphi v^x v^x}) + \partial_y (\hat{h} \overline{\varphi v^x v^y}) = & \quad (2) \\
 & - \frac{\epsilon}{2} \left( 1 - \frac{\rho^f}{\rho^s} \right) \partial_x (\alpha_{xx} \hat{h}^2 \overline{\varphi} (-g^z)) \\
 & - \frac{\epsilon}{2} \left( 1 - \frac{\rho^f}{\rho^s} \right) \partial_y (\alpha_{xy} \hat{h}^2 \overline{\varphi} (-g^z)) \\
 & + \left( 1 - \frac{\rho^f}{\rho^s} \right) (-\epsilon \alpha_{xx} \partial_x b - \epsilon \alpha_{xy} \partial_y b + \alpha_{xz}) \\
 & \hat{h} \overline{\varphi} (-g^z) - \frac{\epsilon}{2} \frac{\rho^f}{\rho^s} \overline{\varphi} \partial_x (\hat{h}^2 (-g^z)) \\
 & - \epsilon \frac{\rho^f}{\rho^s} \hat{h} \overline{\varphi} (-g^z) \partial_x b + \left( \frac{\overline{D}}{\rho^s} \right) (\overline{u^x} - \overline{v^x}) + \hat{h} \overline{\varphi} g^x.
 \end{aligned}$$

### 3. Conservation of Fluid Phase Momentum:

$$\begin{aligned}
 \partial_t (\hat{h} \overline{\varphi^f u^x}) + \partial_x (\hat{h} \overline{u^x \varphi^f u^x}) + \partial_y (\hat{h} \overline{\varphi^f u^x u^y}) = & \quad (3) \\
 & - \frac{1}{2} \epsilon \partial_x \hat{h}^2 \overline{\varphi^f} (-g^z) - \left( \frac{\overline{D}}{\rho^s} \right) (\overline{u^x} - \overline{v^x}) \\
 & + \hat{h} \overline{\varphi^f} g^x + \overline{\varphi^f} C_t u^x \|\mathbf{u}\|
 \end{aligned}$$

where  $\overline{\varphi}$  is the solids volumetric concentration, and  $\overline{\varphi^f} = 1 - \overline{\varphi}$ .  $\phi_{\text{int}}$  and  $\phi_{\text{bed}}$  represent basal and internal friction angles,  $\alpha_{xy} = -\text{sgn}(\partial_y v)$ ,  $\alpha_{xx} = k_{\text{ap}}$ ,  $\alpha_{xz} = -v^* \tan(\phi_{\text{bed}}) / \|\mathbf{v}\|$ , where  $k_{\text{ap}}$  relates the normal and tangential stresses.  $\hat{h}$  represents the depth of the



## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



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 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 areas, 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 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 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

# NHESSD

2, 6373–6395, 2014

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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

**Study of lahar hazards at Villa la Angostura**

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is similar to the correspondent prediction done using the 15m DEM. In the case of Florencia creek, the prediction shows that the flow could go through the whole School 186 neighborhood, even reaching the highway.

## 5 Conclusions

5 These results constitute the first scientific tool, produced from quantitative data that has been made available to the authorities in order to make decisions during the course of the emergency.

Although at this point this is not a probabilistic tool, results of the presented modelling provide a good evaluation of secondary lahar susceptibility and have set the basis for  
10 future development of a probabilistic approach.

The output of the modelling is a valuable tool for city planning and risk management especially considering the physical characteristics of Villa La Angostura area, the strong urban development growth and the land occupation tendencies observed in the last decade.

15 In forested areas, the availability of a DEM produced from good radar data is critical in order to get the minimal resolution required for the modelling.

*Author contributions.* A Gustavo Córdoba and Michael Sheridan developed the program TWO-PHASE-TITAN. In addition, G. Córdoba worked in the modeling with Gustavo Villarosa and Debora Beigt. Gustavo Villarosa conducted field work and contributed with the geological background and data interpretation. Debora Beigt cooperated with photo-interpretation and GIS mapping. Jose Viramonte helped in the geologic interpretation. Graciela Salmuni developed the Digital Elevation Models at CONAE.  
20

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## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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- 20

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

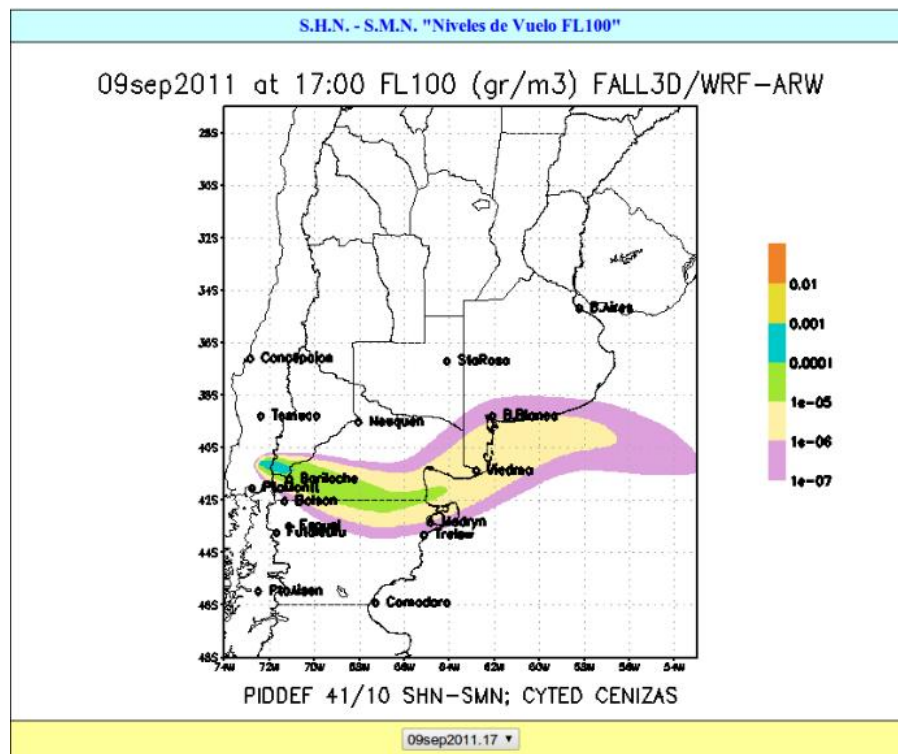
**Table 1.** Calculated total volumes of deposited ash-snow material at each basin, and volumes used in the modeling, as well as the used pile height.

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

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.



**Figure 1.** Fall3D program ash dispersion modeling of the Cordón Caulle complex 2011 eruption. The colored representation shows its subplinian plume dispersion for 9 June (after Collini et al., 2012).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Study of lahar hazards at Villa la Angostura

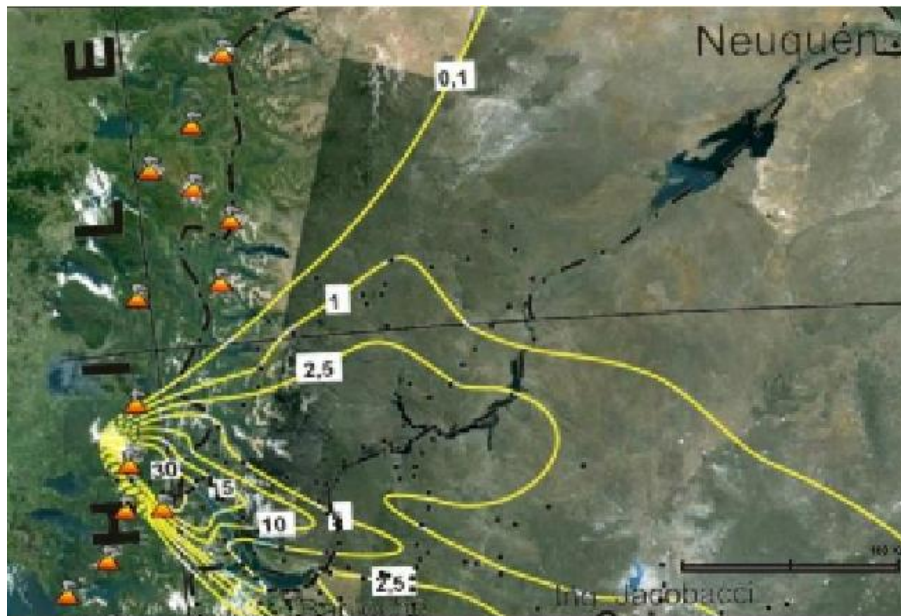
G. Córdoba et al.



**Figure 2.** Interlayered ash-snow deposit at the nearby mountains of Villa la Angostura. The total deposited thickness is less than 1 m. The ash corresponds to almost 30% of such a thickness.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)





**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).

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





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

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

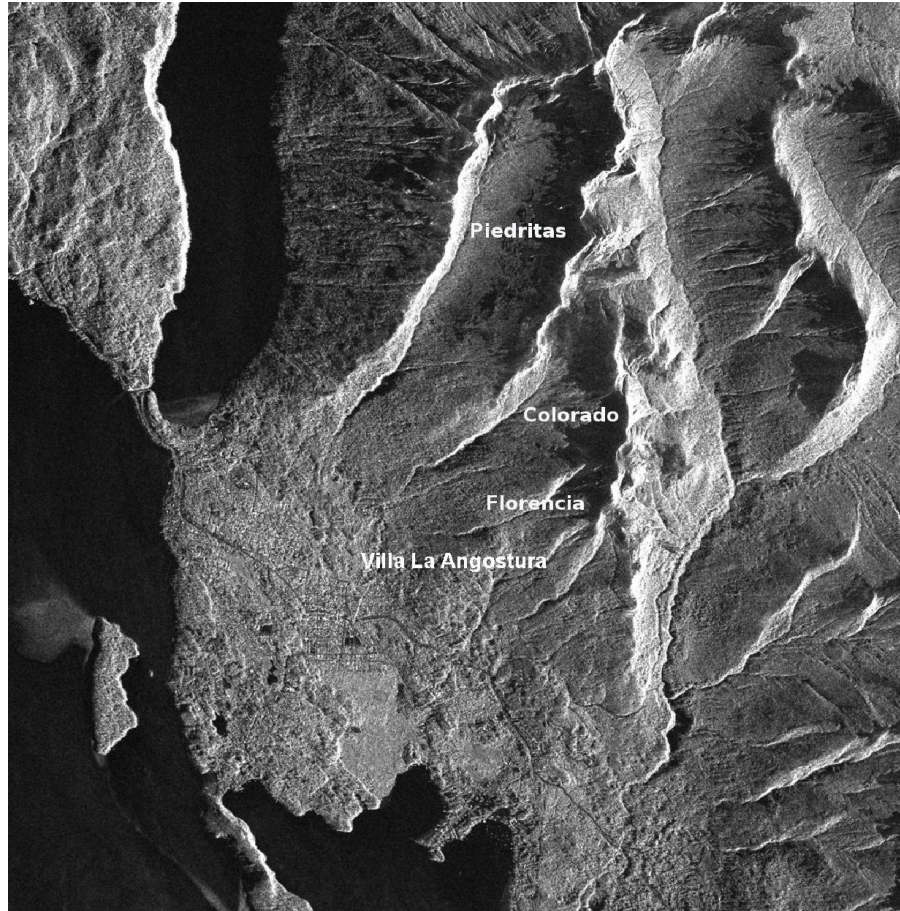
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**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).

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

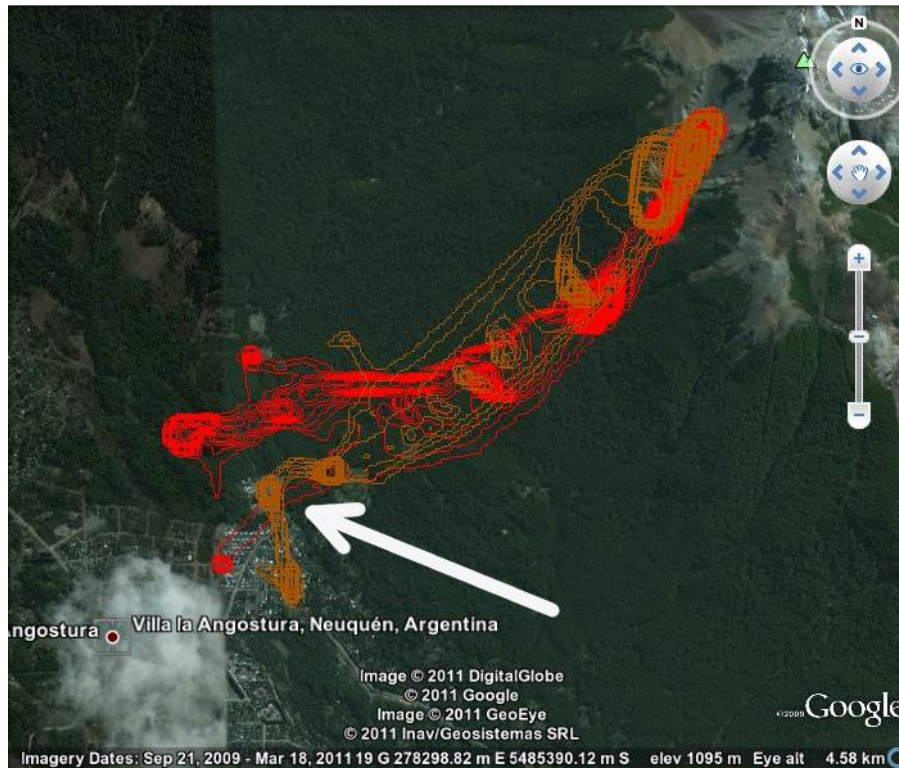
Full Screen / Esc

Printer-friendly Version

Interactive Discussion







**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.

# NHESD

2, 6373–6395, 2014

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

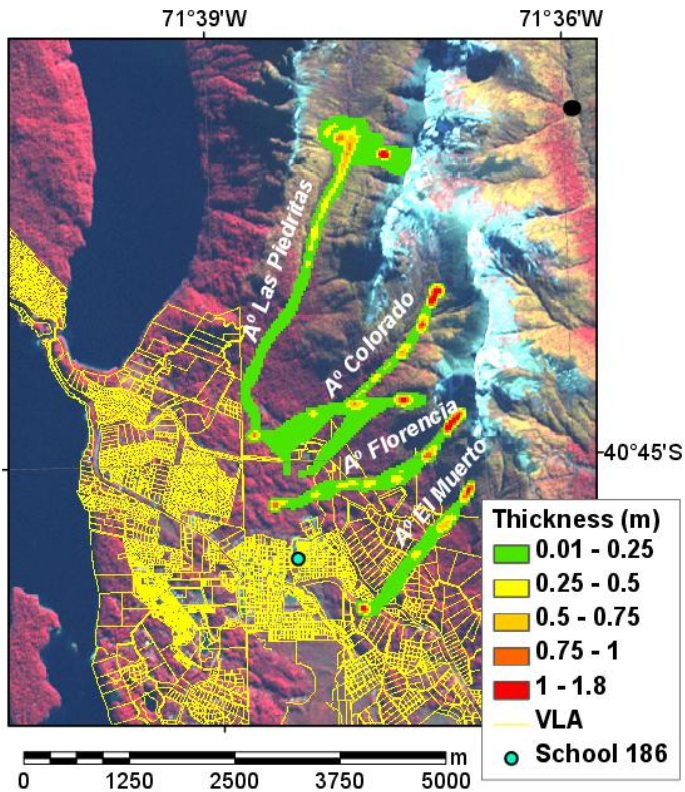
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





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

**Study of lahar hazards at Villa la Angostura**

G. Córdoba et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

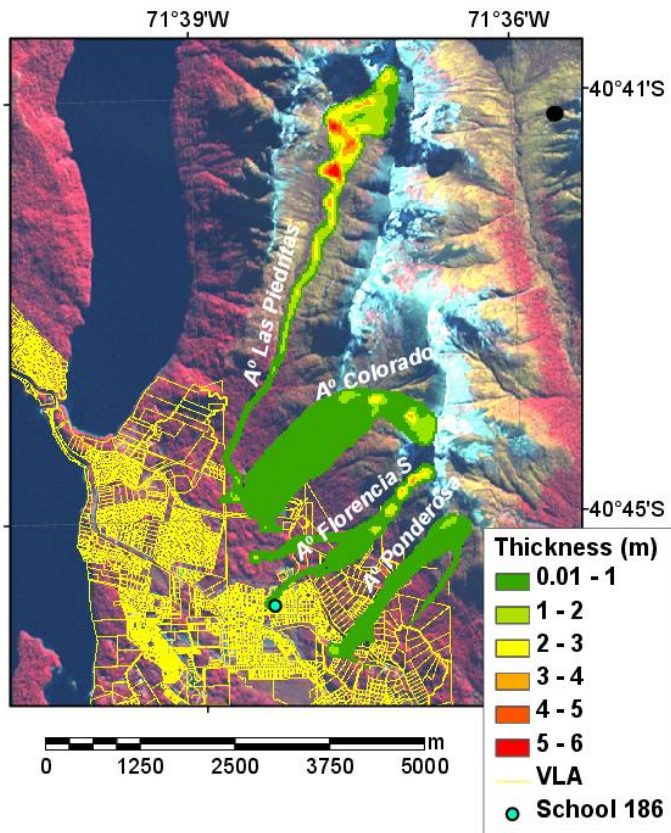
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





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

**Study of lahar hazards at Villa la Angostura**

G. Córdoba et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

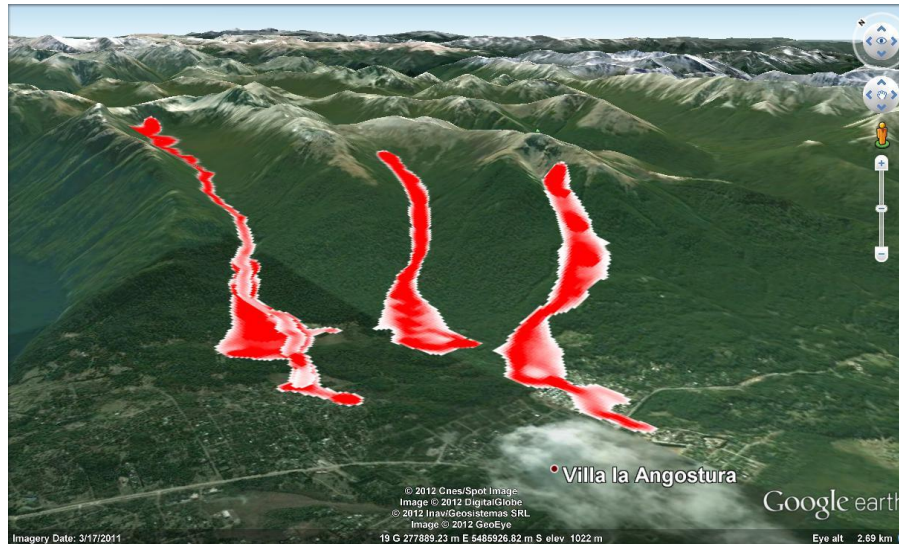


# NHESSD

2, 6373–6395, 2014

## Study of lahar hazards at Villa la Angostura

G. Córdoba et al.



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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

