Assessing lahar hazards at Cotopaxi volcano (Ecuador) controlled by volcanic eruptions and glacier retreat

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EGU

Motivation & Outline of this study

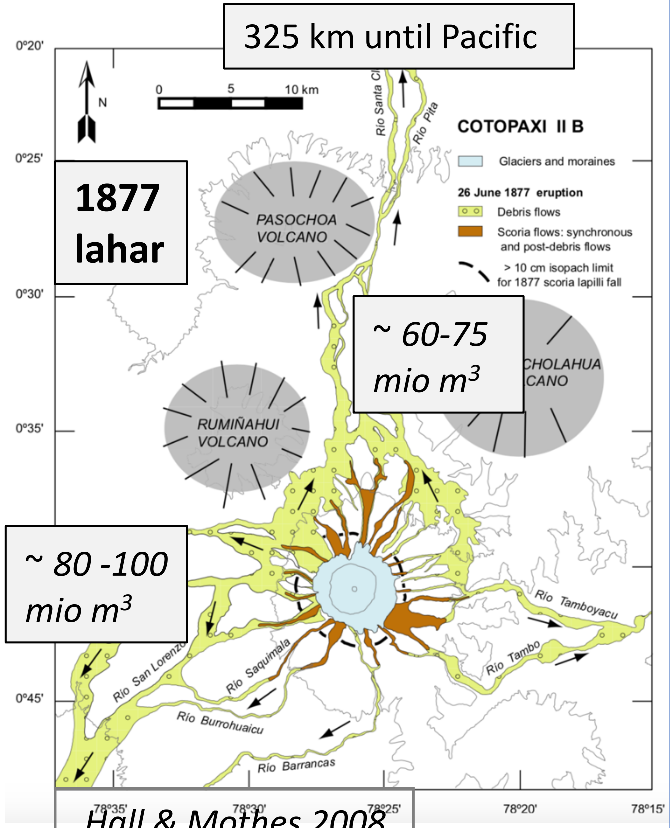
- Cotopaxi is an **active stratovolcano** (5897 m asl) with an extensive, but diminishing **glacier cap**
- It is one of the most dangerous volcanoes worldwide

Lahars at Cotopaxi

Part 1

Large **primary** lahars **triggered by explosive eruptions**.
These lahars travel 100s of km down the main drainages, like during the last destructive lahar event in 1877

→ Back calculation of 1877 event in order to model future lahars



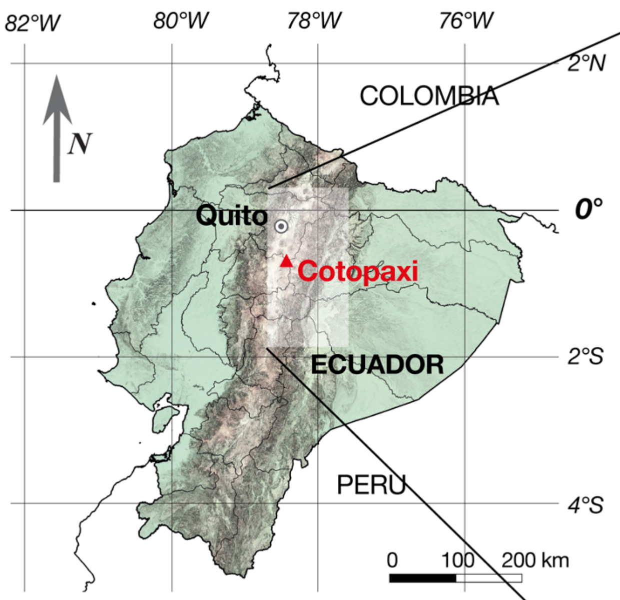
Hall & Mothes 2008

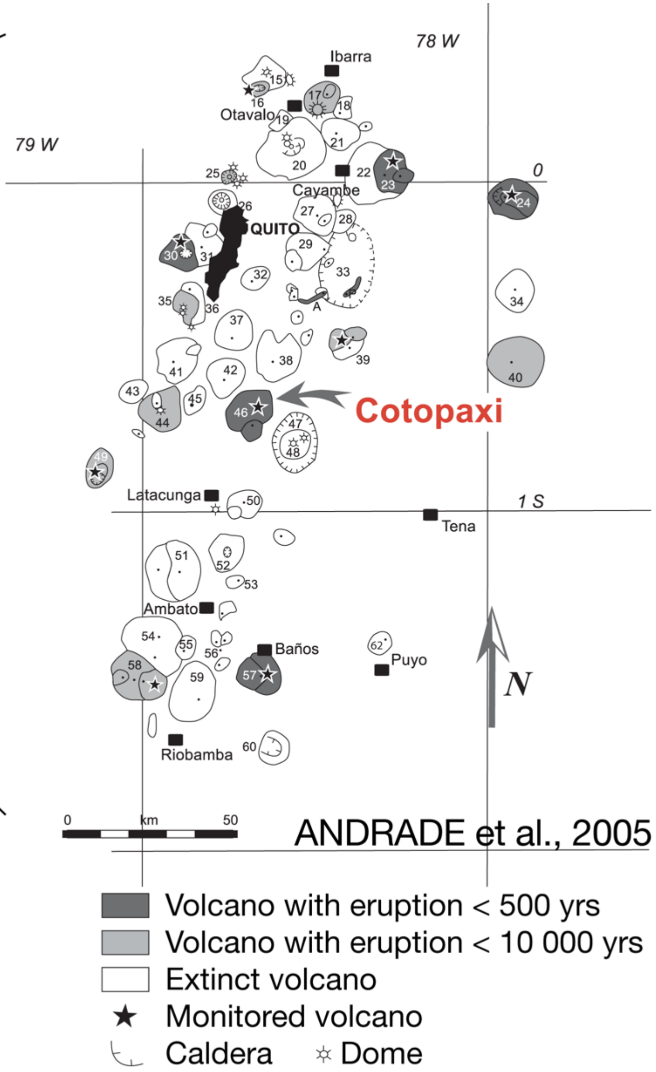
Part 2

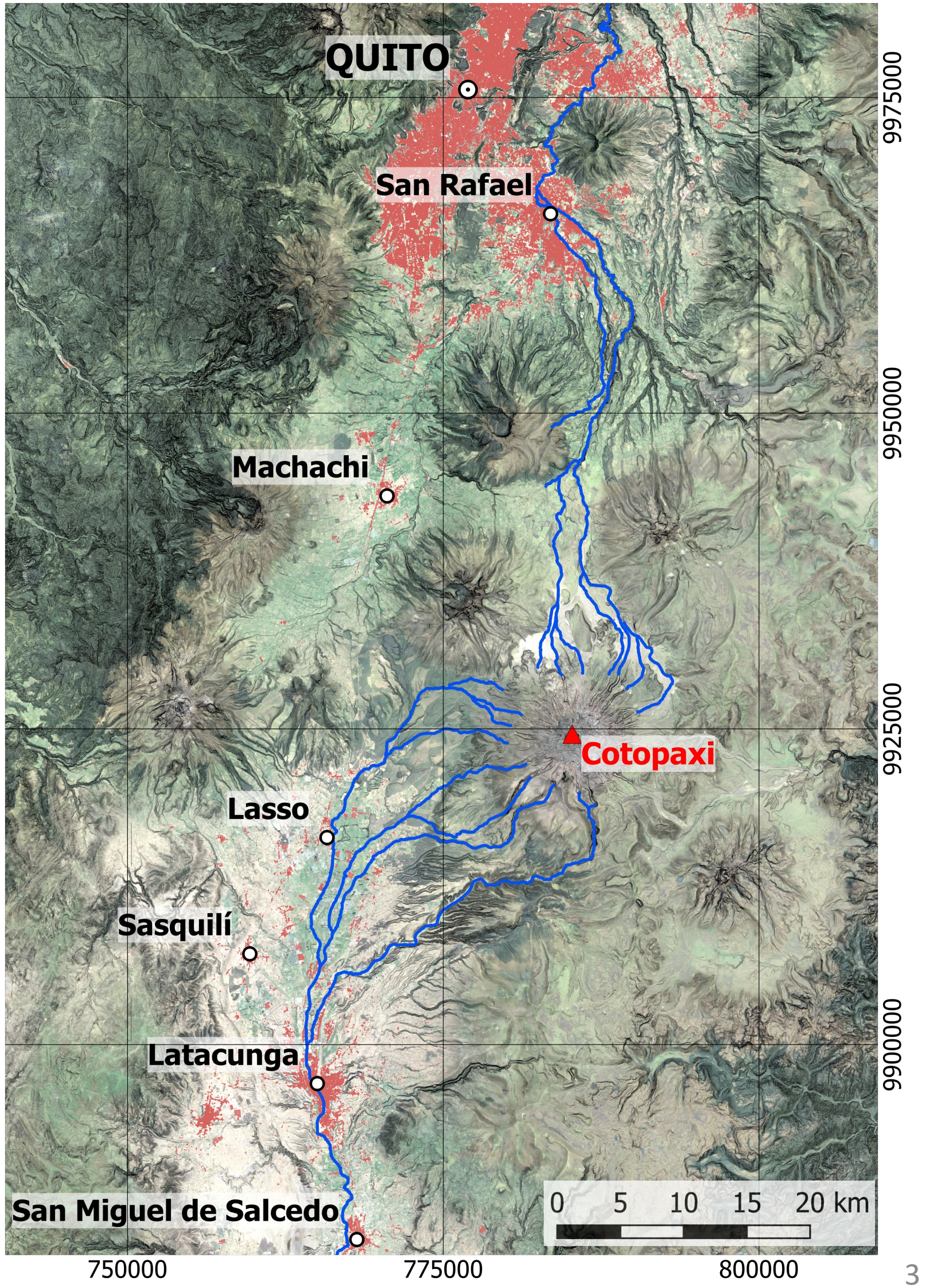
Secondary lahars
Heavy rainfall is considered the common **trigger of secondary lahars**, but can the generation of secondary lahars also be linked to glacier retreat?

Geographical setting

- Located in the Eastern Cordillera of the Andes Mountains
- Sprawling urban centers have developed along the N' and S' drainages (**Inter-Andean-Valley** with > 300,000 inhabitants)



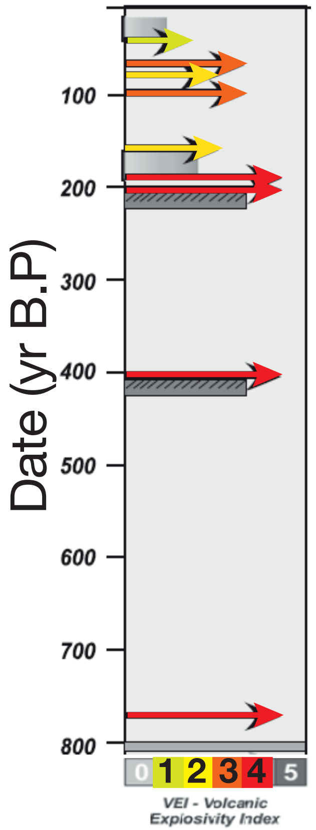




Volcanic history of Cotopaxi

Note: High frequency and magnitude of eruptions

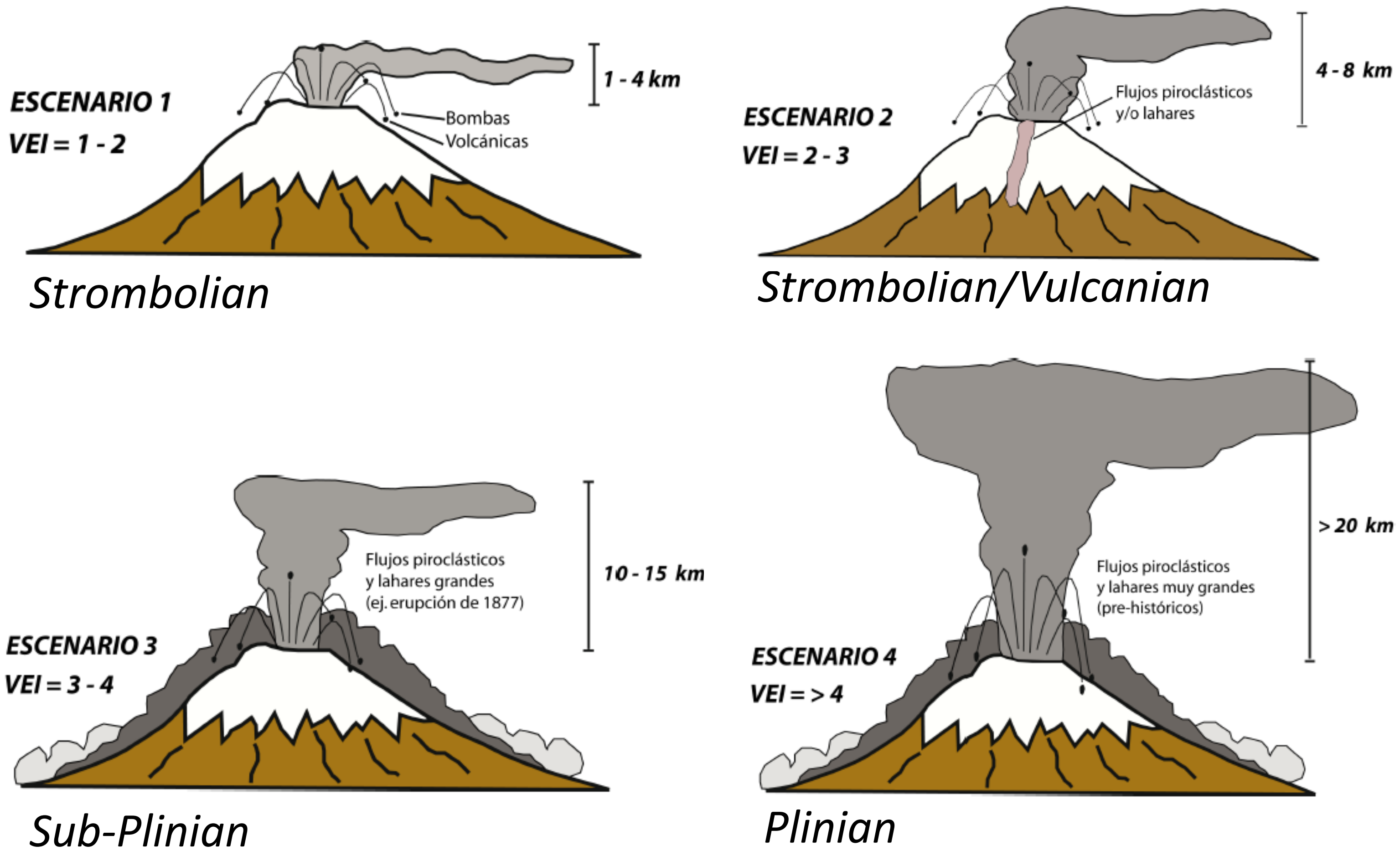
Historical Eruptions



Pistolesi et al. 2011

In the last 800 yrs eruptions rank between VEI 1 – 4 (VEI = Volcanic Explosivity Index)

Potential eruption scenarios



Ordóñez et al., 2013; Andrade et al. 2005

Can we set up a **generic model for large magnitude lahars** at Cotopaxi

- by applying the **Voellmy-Salm rheology**
- covering the lahar path from initiation on the flank to distal reaches
- including a first-order estimation of **erosion and entrainment**?

METHODS: RAMMS Debris Flow model

RAMMS is a physically-based, depth-averaged debris flow model using the Voellmy-Salm rheology

- **Voellmy-Salm friction law:**

$$S = \mu \cdot \rho \cdot H \cdot g \cdot cos(\varphi) + \frac{\rho \cdot g \cdot v^2}{\xi}$$

Frictional Resistance S (Pa) is calculated by

- Coulomb-type friction μ [-]
- Turbulent friction ξ [m/s²]
- Density ρ [kg/m³]
- Flow height H [m]
- Slope angle φ [%]
- g = 9,81 [m/s²]
- Flow velocity v [m/s]

- **Entrainment module:** $\tau = \rho g H \varphi$

Entrainment rate is a function of the local shear stress τ (kPa) acting on the channel bed

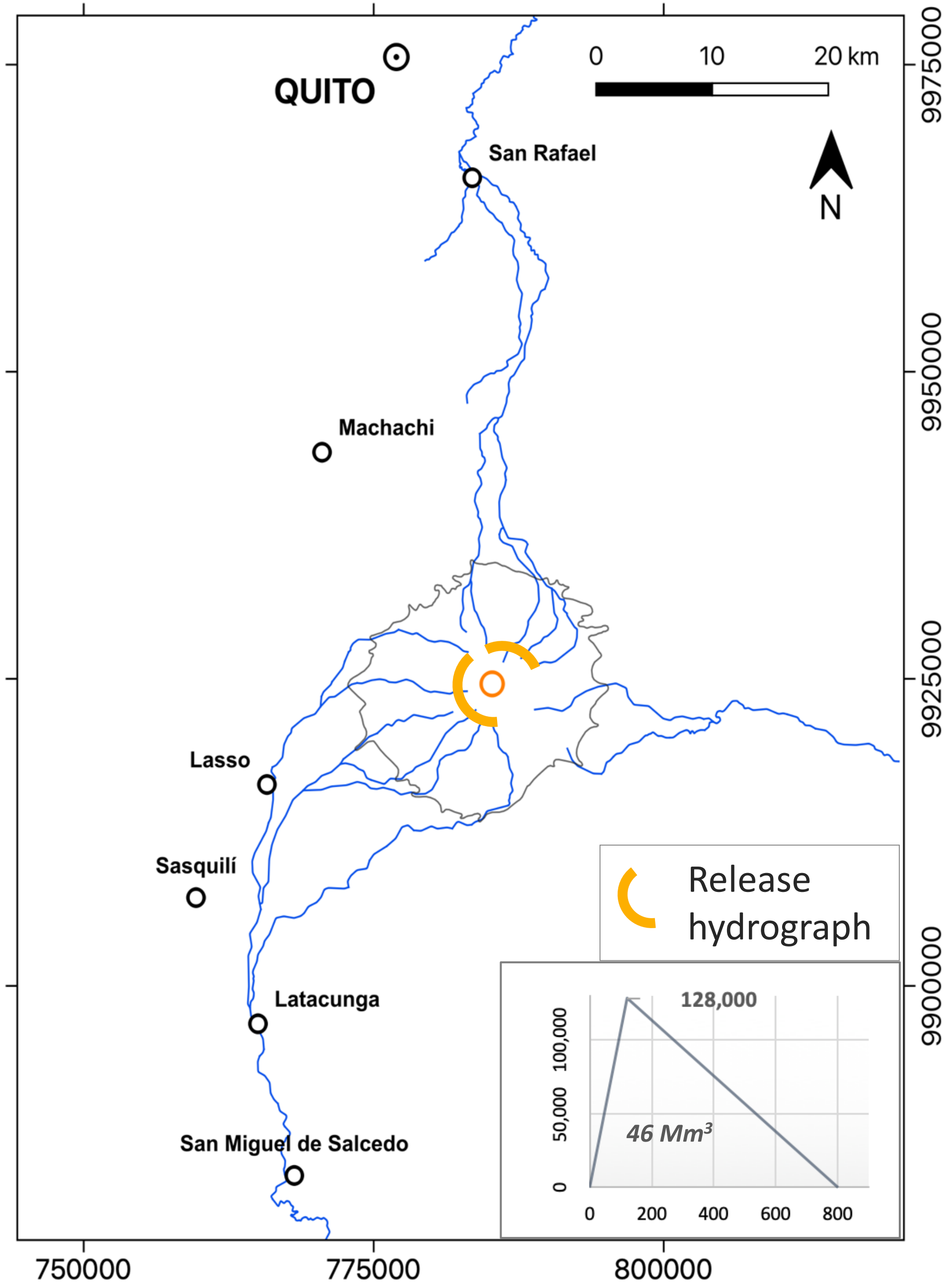
Erosion potential	Erosion rate [m/s]	Pot. erosion depth [m/kPa]	Yield stress [kPa]
Default (Illgraben)	0.025	0.1	1.0
High	0.05	0.2	0.5
Low/Limited	0.013	0.05	1.5

METHODS: Premises of the model

- 10m resolution
- Model area includes major cities close to the volcano, extends ~60 km downstream from the crater in N & S direction
- Erosion parametrization based on geology & topography: Examples for erosion potentials

default *high* *low/limited*

- Release with 3-point-hydrograph, estimated based on empirical formula for near-source peak discharges of granular debris flows (Mizuyama et al., 1992)



METHODS: Sensitivity analysis and calibration

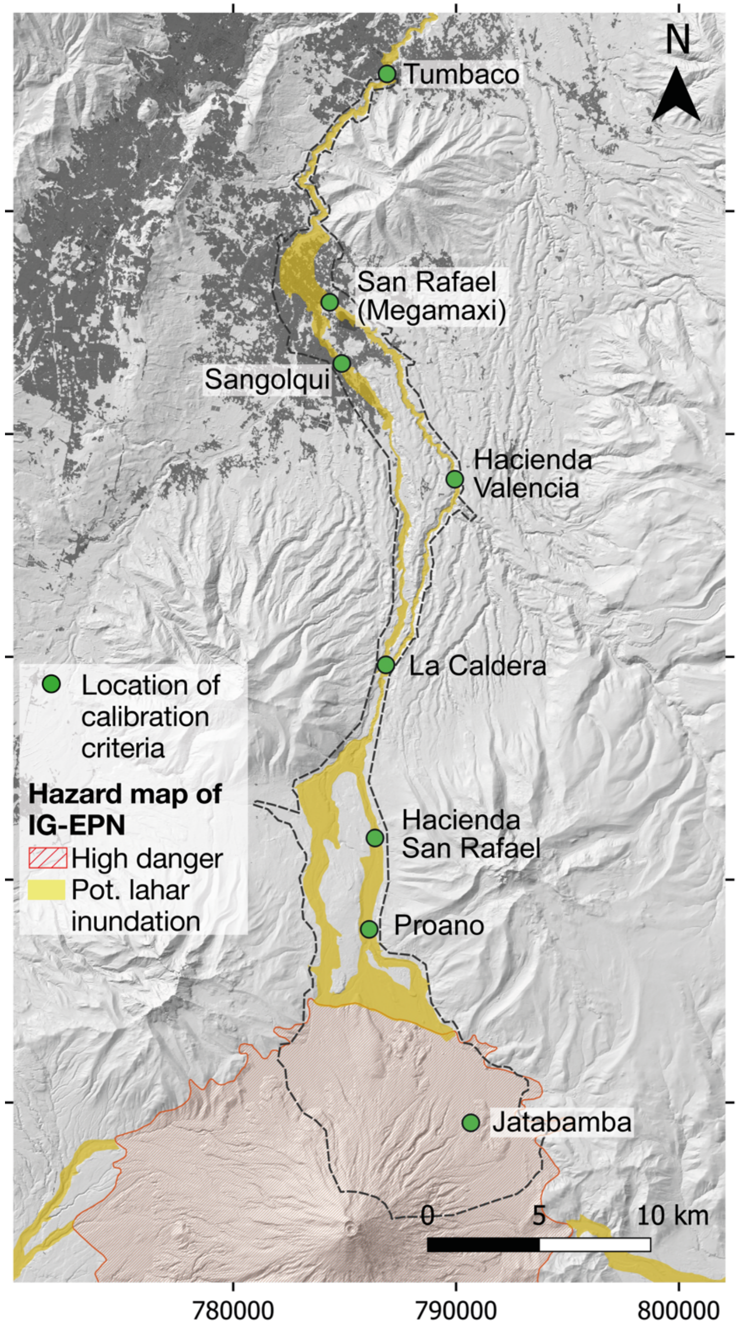
Back-calculation of the 1877 lahar for calibration of the model

- The friction coefficients μ and ξ dominate flow behaviour

  -> sensitivity analysis to various model outcomes

  represented by

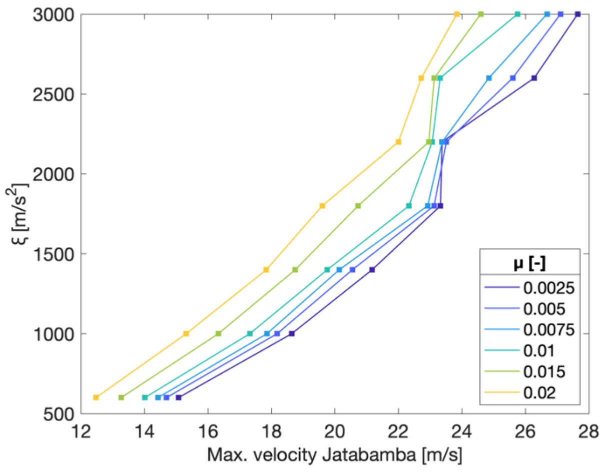
- **14 calibration criteria** act as simulation constraints
  - ➢ **Strict criteria:** Must-have for any lahar model representing the 1877 event (e.g. run-up at La Caldera)
  - ➢ **Additional criteria:** Data with less reliability, including eyewitness estimates on arrival times, and published estimates on flow discharge, velocity, height derived from field investigations

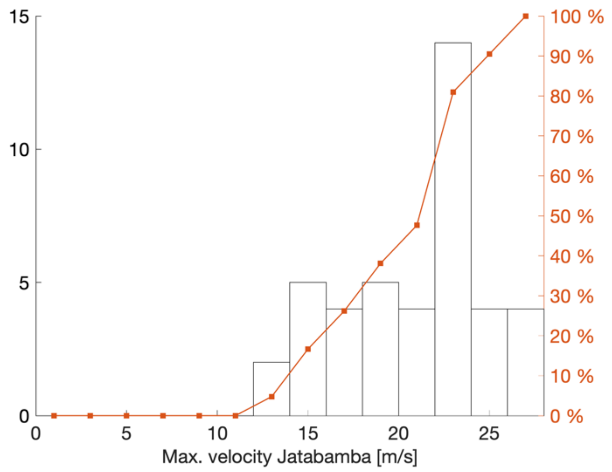


RESULTS: Sensitvity analysis and calibration

The model outcomes for each calibration criteria are compared against the target value

E.g. **Flow velocity at Jatabamba (18 m/s)**





ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	15.1	14.7	14.4	14.0	13.3	12.5
1000	18.6	18.2	17.9	17.3	16.3	15.3
1400	21.2	20.6	20.1	19.8	18.8	17.8
1800	23.3	23.1	22.9	22.3	20.7	19.6
2200	23.4	23.5	23.4	23.1	23.0	22.0
2600	26.3	25.6	24.9	23.3	23.1	22.7
3000	27.6	27.1	26.7	25.8	24.6	23.8

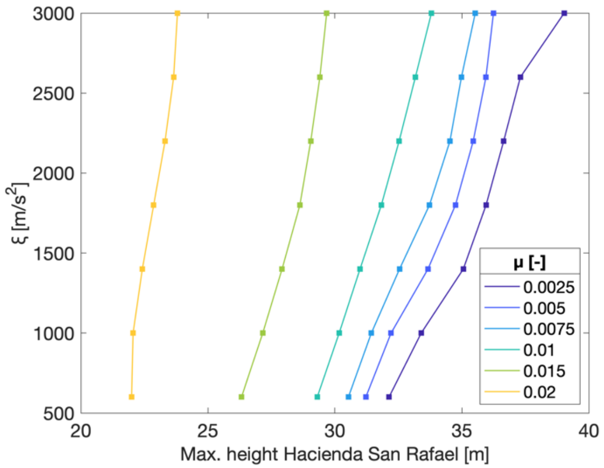
ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	-16	-18	-20	-22	-26	-31
1000	4	1	-1	-4	-9	-15
1400	18	14	12	10	4	-1
1800	30	28	27	24	15	9
2200	30	31	30	28	28	22
2600	46	42	38	30	29	26
3000	54	51	48	43	37	32

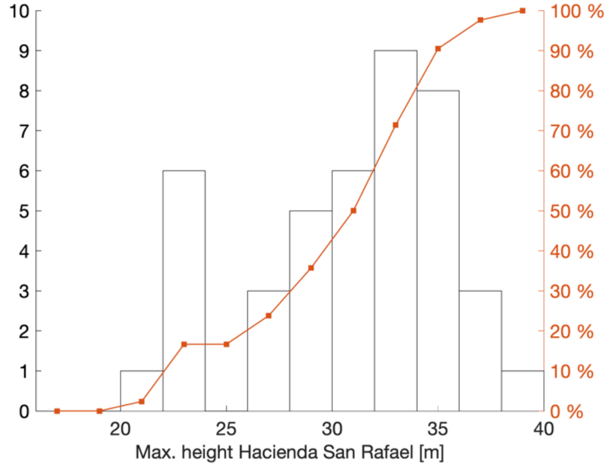
Model outcome

Model performance: Deviation [%] from target value

RESULTS: Sensitivity analysis and calibration

E.g. **Stage height at Hacienda San Rafael (27 m)**

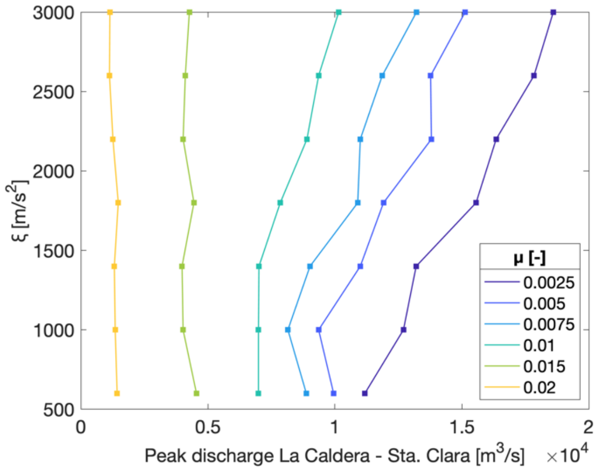


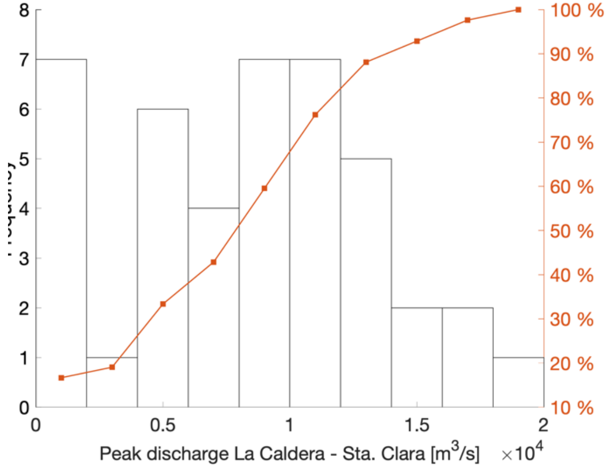


ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	32.1	31.2	30.5	29.3	26.3	22.0
1000	33.4	32.2	31.4	30.2	27.2	22.1
1400	35.1	33.7	32.5	31.0	27.9	22.4
1800	36.0	34.7	33.7	31.8	28.6	22.9
2200	36.6	35.4	34.5	32.5	29.1	23.3
2600	37.3	35.9	35.0	33.2	29.4	23.7
3000	39.0	36.2	35.5	33.8	29.7	23.8

ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	19	16	13	9	-3	-19
1000	24	19	16	12	1	-18
1400	30	25	21	15	3	-17
1800	33	29	25	18	6	-15
2200	36	31	28	20	8	-14
2600	38	33	30	23	9	-12
3000	45	34	32	25	10	-12

E.g. **Discharge at La Caldera - runup to Sta. Clara (14,000 m³/s)**



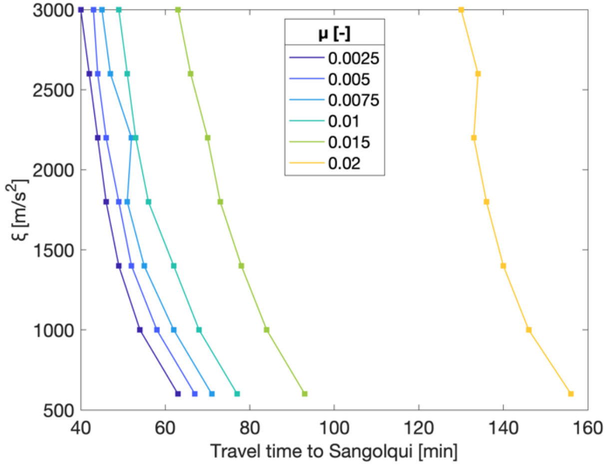


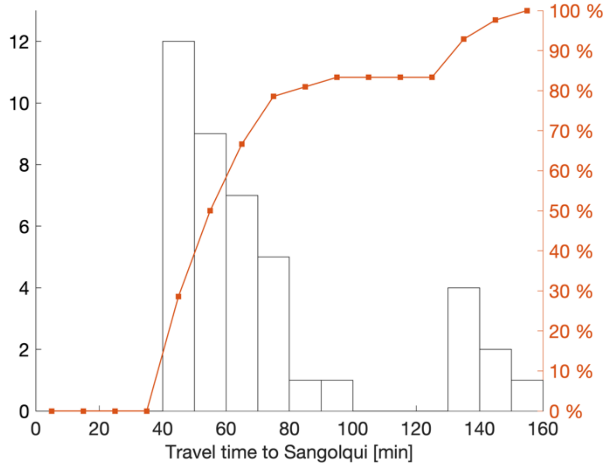
ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	11180	9950	8875	6990	4550	1426
1000	12700	9360	8150	6990	4023	1350
1400	13200	11000	9020	7010	3982	1316
1800	15560	11915	10900	7850	4450	1470
2200	16350	13800	11000	8900	4025	1260
2600	17840	13770	11865	9360	4110	1125
3000	18600	15130	13215	10150	4270	1140

ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	-20	-29	-37	-50	-68	-90
1000	-9	-33	-42	-50	-71	-90
1400	-6	-21	-36	-50	-72	-91
1800	11	-15	-22	-44	-68	-90
2200	17	-1	-21	-36	-71	-91
2600	27	-2	-15	-33	-71	-92
3000	33	8	-6	-28	-70	-92

RESULTS: Sensitivity analysis and calibration

E.g. **Travel time to Sangolquí (< 60 min)**





ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	63	67	71	77	93	156
1000	54	58	62	68	84	146
1400	49	52	55	62	78	140
1800	46	49	51	56	73	136
2200	44	46	52	53	70	133
2600	42	44	47	51	66	134
3000	40	43	45	49	63	130

ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015	0.02
600	5	12	18	28	55	160
1000	0	0	3	13	40	143
1400	0	0	0	3	30	133
1800	0	0	0	0	22	127
2200	0	0	0	0	17	122
2600	0	0	0	0	10	123
3000	0	0	0	0	5	117

Consideration of differences between modelled *(m_i)* and target value *(t_i)* for all *n* calibration criteria *(i)* in order to find best-fit μ/ ξ-combinations:

$$\phi = \frac{\sum_{i=1}^{n}\left(\frac{m_i - t_i}{t_i}\cdot 100\right)}{n}$$

ξ [m/s^2] \ μ [-]	0.0025	0.005	0.0075	0.01	0.015
600	28	30	32	36	53
1000	23	24	26	29	46
1400	24	23	24	27	41
1800	27	26	25	25	39
2200	28	26	26	25	38
2600	33	27	27	26	36
3000	37	29	28	28	34

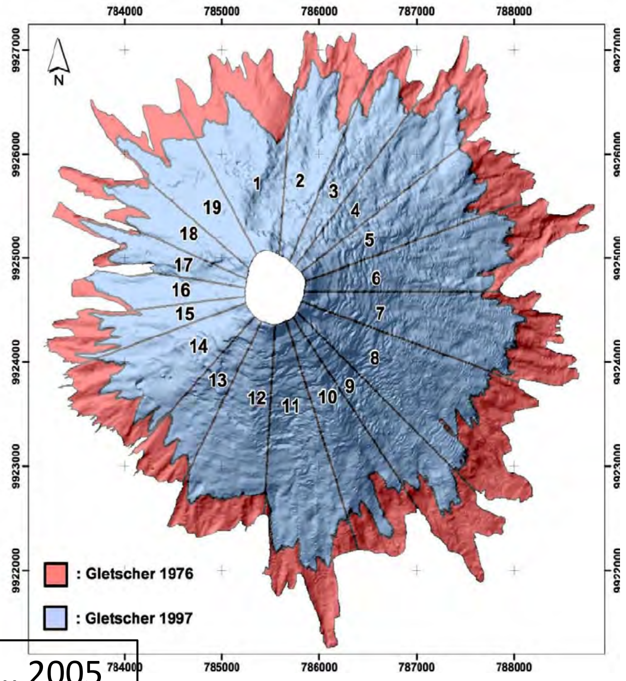
μ = 0.005 and $\xi = 1400\ \frac{m}{s^2}$ used for simulation of future lahar scenarios

Modelling results to be submitted to ESP&L

Is there process-based link between the rapid glacier retreat and observed secondary lahars without any clear trigger at Cotopaxi?

Glacier retreat at Cotopaxi

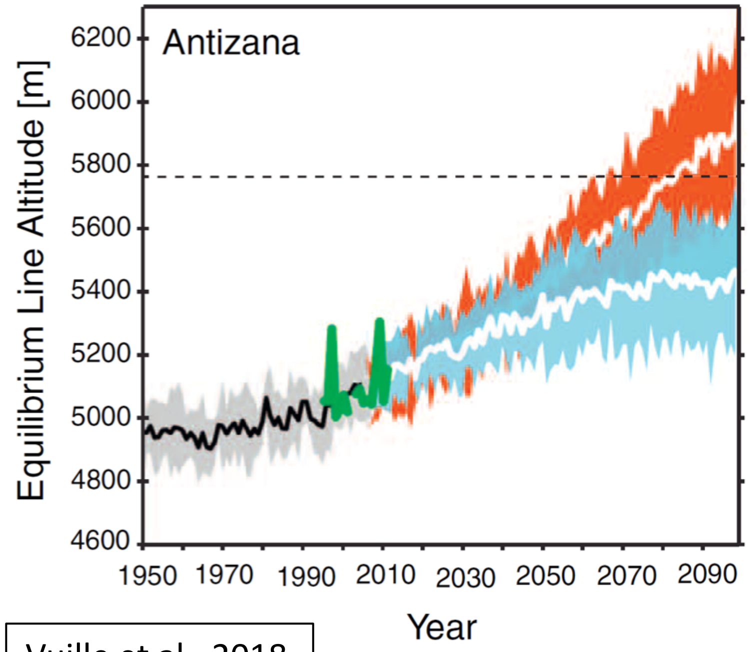
Between 1976 and 2015 the glacier surface decreased from 21.8 km^2 to 11.6 km^2 by ~ 50% (Caceres, 2017)



Jordan et al., 2005

Rise of Equilibrium Line Altitude (ELA)

Projected rise of the ELA of ~200 m in the next 50 years (example of neighbouring Antizana volcano)



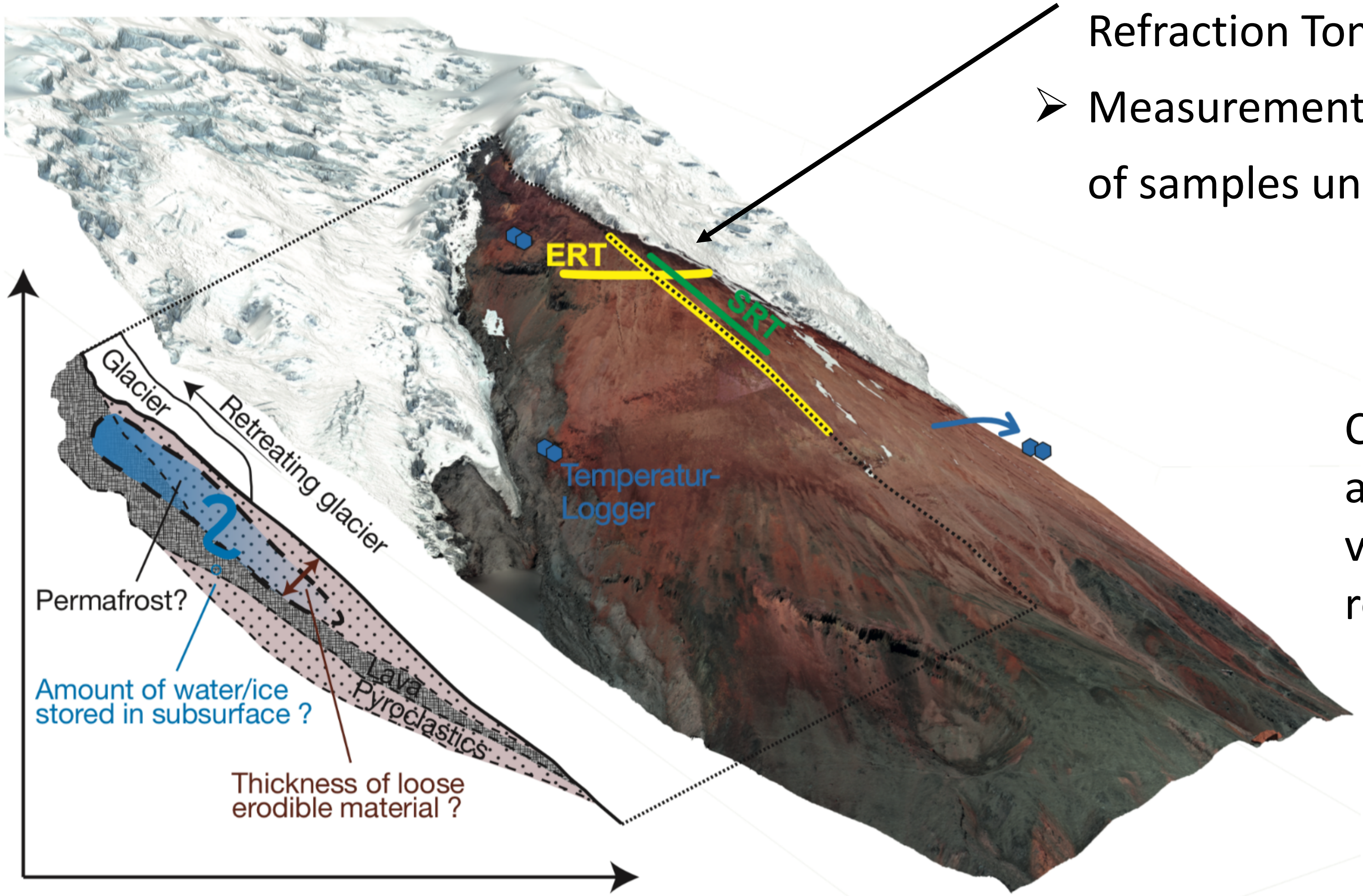
Vuille et al., 2018

Conceptual mechanical model – work in progress

Field work near the glacier margin between 5000 – 5300 m asl in the last year

- **Near surface temperatures**

Installation of 6 temperature loggers



- **Changes in material strength**

➢ Electrical Resistivity Tomography (ERT) and Seismic Refraction Tomography (SRT) surveys

➢ Measurements will be calibrated with laboratory tests of samples under un-/frozen conditions

Combination of ERT & SRT in a 4-phase model to estimate volumetric fractions of air, rock, water and ice.

Conclusions

- We can **well reproduce large lahars with the debris flow model RAMMS**, including **key flow features** such as material entrainment on the flank, run-ups and flow bifurcation
- Spatially distributed calibration criteria comprising different types of calibration metrics are prerequisite for realistic modelling of large syneruptive lahars
- Calibration of frictional parameters yields **very low values for Coulomb type friction μ (0.005)** and **high values for turbulent friction ξ (1400 m/s^2)**

- The role of rapid glacier retreat at Cotopaxi on potential permafrost degradation and the formation of secondary lahars is unknown and needs further investigations

FUNDING:

RIESGOS

https://www.riesgos.de/en/

Federal Ministry of Education and Research

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