BABEŞ – BOLYAI UNIVERSITY
Doctoral School of Geography

PhD thesis

Methods for quantitative volcanic hazard assessment in densely populated areas, with emphasis on pyroclastic flows. Case study: El Misti and Arequipa, South-western Peru

~summary~

by: ***Robert Constantinescu***

Supervisor :

Prof. univ. dr. Ioan Aurel Irimuş

~ Cluj - Napoca, 2012 ~

Keywords: volcanic hazards; numerical modeling; probabilistic assessment; El Misti; TITAN2D; BET_VH.

INTRODUCTION

I. Scope: Methods for volcanic hazard assessment

Many cities are built near or on the flanks of active volcanoes exposing population and infrastructure to various volcanic phenomena that may cause human lives loss and disruption of social activity and livelihoods. At the beginning of 21st century, more than half-billion people was estimated to live at risk from volcanic eruptions (Tilling, 2005; Chester et al., 2001) and though there is no recent estimation, this number is believed to have grown due to intense urbanization. Among small urban settlings living in the shade of an potential active volcano, there are also large cities with population approaching or exceeding a million inhabitants like Naples, Italy (near Vesuvius), Ciudad de Mexico, Mexico (near Popocatepetl), Kagoshima, Japan (near Sakura-Jima), Arequipa, Peru (near El Misti).

The goal of this research is to develop and apply a methodology of hazard assessment based on geological records, numerical modeling and probabilistic assessment for pyroclastic flows generated by an eruptive column collapse and volcanic ballistics.

II. Les objectifs de la thèse

The main purpose of this research is twofold: ***(1)*** to use modern computer modeling tools to simulate pyroclastic flows and volcanic ballistics and thus delineate the potential extent of these processes, and ***(2)*** to provide a probabilistic assessment of these hazards, in the form of maps of probabilities for the case study of the city of Arequipa and the nearby El Misti volcano in south-western Peru.

In order to reach these two goals, a series of research steps needs to be fulfilled: **(1)** To identify the hazards, and assess methods used for modeling pyroclastic flows and volcanic ballistics at El Misti volcano. **(2)** To define eruption scenarios for the study area on which the probabilistic assessment will be undertaken, based on the behavior of the volcano and its eruptive history. The eruption scenarios will be describe in accordance with the eruption-scenarios proposed for El Misti by Thouret et al. (1999b), Delaite et al. (2005), Vargas et al. (2010) and Martelli (2011).**(3)** To create a database regarding El Misti's eruptive history and pertinent parameters (i.e. flows volumes, starting locations, friction angles) for modeling. **(4)** To accurately model pyroclastic flows and volcanic ballistics phenomena with the help of TITAN2D and EJECT computer codes. This modeling will be done with parameters extracted from stratigraphical records, exclusion by trial were field data is not available, and data from analogue volcanoes.**(5)** To delineate the potential spatial extent of the volcanic phenomena resulted from computer modeling. Simulations results will be draped on a DEM and compared with past deposits if available. **(6)** To convert the maps of past deposits and those obtained from computer simulations into a binary language in order to facilitate the probabilistic assessment. **(7)** To prepare a database of information from which probabilities may be derived in order to provide a more accurate probabilistic assessment **(8)** Apply the 'Event-Tree' methodology (Newhall and Hoblitt, 2002), within the BET_EF and BET_VH computational tools, in order to obtain the subsequent probabilities of each stage of a volcanic eruption (unrest, eruption, vent opening). The information from geological and stratigraphical records and the results from computer modeling retrieved at previous steps will be used as input in BET_VH in order to obtain the final probability maps for pyroclastic flows and volcanic ballistics. **(9)** As DEMs proved to be important in modeling volcanic hazards (Capra et al., 2010), in a separate section such effects will be studied for small block-and-ash-flows at El Misti simulated with TITAN2D on 20m and 30m resolution DEMs. The DEMs were obtained from Dr. J.C. Thouret, Laboratoire Magmas et Volcans (LMV), University Blaise – Pascal, France. The 30m resolution DEM was made available from previous students and researches at LMV and obtained by combining various elevation data sources like radar interferometry from European Remote Sensing (ERS) satellite with digitalized topographic maps of 1:30,000 and 1:25,000 – scale (e.g. Delaite, 2005). The 20m resolution DEM is a SPOT5 satellite imagery acquired by Dr. J.C. Thouret.

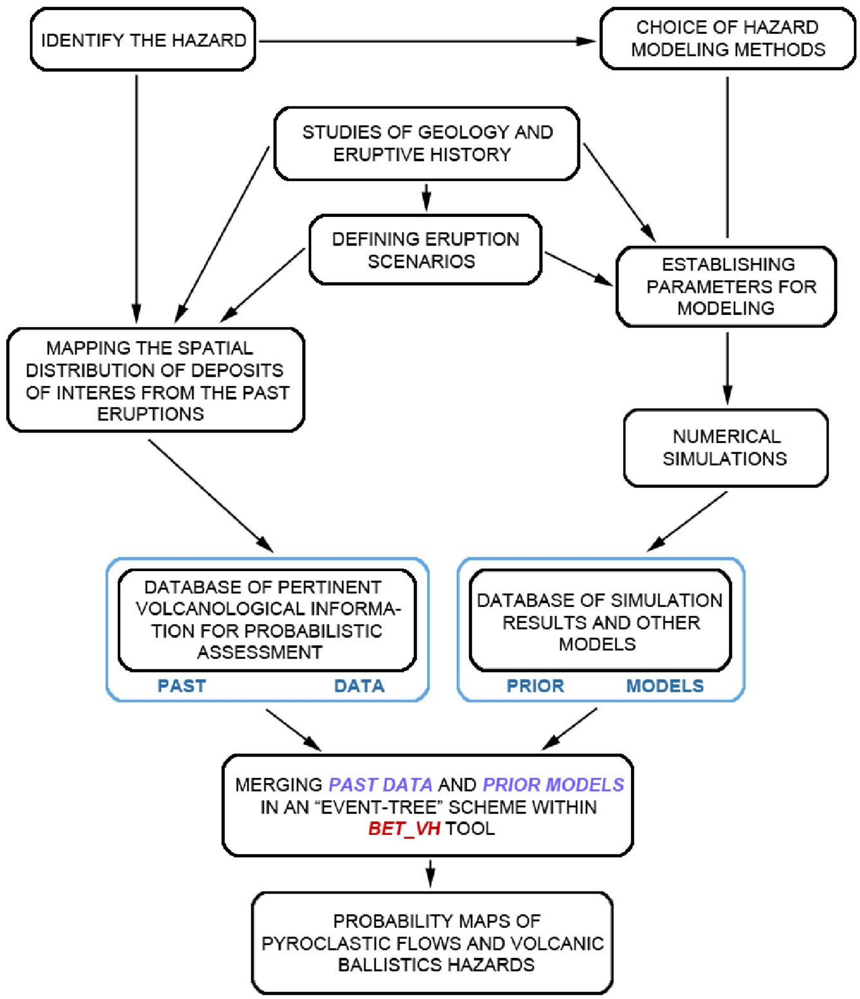

Figure 2. Workflow proposed in order to model pyroclastic flows and volcanic ballistics and follow by the use of all information available (e.g. stratigraphic data; eruption frequency; numerical modeling results) at El Misti for elaborating probabilistic hazard maps.

PART I: Volcanic hazards and their assessment

I. Volcanic hazards

For a specific natural phenomenon to become a natural hazard it is necessary to represent a threat to a community, to people and their livelihoods. If an extreme phenomenon occurs in a non populated area (e.g. Antarctica) and affects no human livelihood, it is just considered as a natural phenomenon, but if the same phenomenon occurs within a populated area and poses a threat, it is considered a ***hazard***

I.1. Direct volcanic hazards

The direct volcanic hazards occur during the eruptive stages, from unrest until the end of an eruption, and they have been separated by type in: - *fall* processes and *flowage* processes.

I.1.1. Fall processes

The *fall processes* are referred to the ejection and deposition of air-borne fragmental volcanic materials from explosive eruptions (Tilling, 2005). They are represented by *tephra fallout and volcanic ballistics.*

I.1.2. Flowage processes

Among dangerous flowage processess we mention : *pyroclastic density currents; lateral directed balst;debris avalanches / flank collapse; primary volcanic debris flows / lahars; Jökulhlaups ; lava flows..*

I.2. Indirect volcanic hazards

Les hasards volcaniques indirects résultent soit à la suite d'un phénomène volcanique direct, soit sous l'emprise de ses effets à long terme, après que l'éruption soit finie. Parmi les plus importants on compte : *Les vagues de tzunami* ; *Les lahars secondaires (secondary lahars) ; Les changements climatiques post-éruptives* (*post-eruptive climate changes) ; La famine etc.*

I.3. Pyroclastic density currents (PDCs)

Pyroclastic density currents as mixtures of volcanic gases and clasts include both *pyroclastic flows* and *pyroclastic surges*.

Pyroclastic surges are dilute suspension currents in which particles are carried in turbulent suspension and in a thin bed – load layer (Druitt, 1998); they have high mobility and speed and can easily outrun topographic barriers. Field studies and observations of historic eruptions suggest that there are at least three types: base surges (Valentine and Fisher, 2000), ground and ash-cloud surges (Nakada, 2000). *Pyroclastic flows* are high- density mixtures of hot lava blocks, ash, pumice and volcanic gas (Nakada, 2000), which typically generate poorly-sorted deposits (Druitt, 1998). Driven by gravity, pyroclastic flows tend to be channeled into valleys. Large scale pyroclastic flows associated with caldera-forming ash flows can move distances of more than 100 km (Nakada, 2000). PFs associated with lava dome collapses are called *block-and-ash-flows*; pyroclastic flows formed by column collapse are called *scoria flows* or *pumice / ash flows* depending if they have moderate or high vesicular components (Druitt, 1998). The travel distance of a PDC is strongly influenced by the volume and mass of the flow and the height at which the collapse occurs.

II. Methods for volcanic hazards assessment

Given the different degrees of exposure of some communities to the proximal volcanic phenomena (e.g. ballistics, pyroclastic density currents) and the more distal ones (e.g. tephra fall, lahars), volcanic hazard assessments have been undertaken as early as in the 1970's. A volcanic hazard and risk management strategy must nowadays be based on a multi disciplinary approach that will include volcanological aspects along with social and economical characteristics in the area of interest. Risk management for volcanic hazards involves partnerships between volcanologists and a wide variety of community stakeholders (Blong, 2000). Historic records of past eruptions are the first source of information to be acquired as background for volcanic-hazard studies (Crandell et al., 1984).

II.1. Deterministic maps

La plus connue démarche est de créer des cartes des hasards basées sur l'histoire éruptive du volcan. Les cartes de hasard volcanique reproduisent d'habitude l'extension actuelle ou potentielle des phénomènes volcaniques qui se produisent par « écoulement » (des écoulements pyroclastiques, lahar, coulées de lave), mais aussi la distribution potentielle de tephra (Haynes et al. 2007).

II.2. Eruption scenario based maps

More comprehensive and detailed hazard analyses are based on eruptive scenarios in which the extent of the volcanic products is assessed either for a specific eruptive size or a specific chosen eruptive scenario. Most often, the eruption scenarios are defined based on most common eruption types in the past activity of the volcano and their related hazards. Scenario-based maps also combine statistical approaches that will commonly result in calculation of recurrence time of a specific type of eruption.

II.3. Mathematical methods

II.3.1. Statistical and semiempirical methods

Even though stratigraphical–based hazard-zone maps provided a good base for volcanic risk management, recent developments in volcanology and computing technology yielded the need for more accurate hazard maps and hazard analyses based on mathematical models approach. Different semi-empirical and statistical methods have been developed and applied for individual volcanic hazard assessment.

II.3.2. Probabilistic methods

Probabilistic assessment of volcanic hazards has been proposed over the past two decades in order to provide a more quantitative, short and long-term forecasts of eruptions and subsequent phenomena. An **Event Tree** is essentially a representation of events in which branches are logical steps from a general prior event through increasingly specific subsequent events to final outcomes (Newhall and Hoblitt, 2002).

II.3.3. Computer modeling of volcanic hazards

Computer modeling of volcanic hazards have been developed along with development of computational infrastructure and technology. Such computer models are based on assumptions about physical laws that govern a volcanic phenomenon and allow modeling based on basic parameters (e.g. wind direction for tephra modeling, bed friction angles for PDCs modeling). Usually, computer modeling focuses on a single phenomenon (e.g. tephra fall, volcanic ballistics) or for a class of volcanic phenomena (volcanic mass flow such PDCs, lahars, debris avalanches).

II.3.3.1. Tephra fall and volcanic balistics modeling

Hurts (1994) created ASHFALL computer code to predict the thickness of ash deposits from a volcanic eruption. Hurst and Smith (2004) used ASHFALL code for a probabilistic assessment of ash fallout in New Zealand. Computer modeling and probabilistic assessment given a single or a range of scenarios for tephra fallout can be done with TEPHRA and TEPHRA 2 codes (Fig. 9 a). The assumption of the codes is to create a physical model of tephra dispersal and sedimentation and a probabilistic assessment to identify a range of input parameters and provide hazard curves and maps (Bonadonna et al., 2005, Connor and Connor, 2006, Biass and Bonadonna, 2012). *EJECT* is a computer code created by Mastin (2001) and helps to compute trajectories and traveled distances of volcanic bombs, by using several key parameters as block diameter and density, initial velocity, ejection angle, atmospheric features and tailwinds.

II.3.3.2. Volcanic mass flow modeling

For volcanic mass flows modeling we shall mention those that have provided good results - ENERGY CONE (Malin and Sheridan, 1982), FLOW2D and FLOW3D (Sheridan and Macias, 1992; Sheridan et al., 2000), VOLCFLOW, PDAC2D, LAHARZ, PYROFLOW, TITAN2D (Tab. 4).

II.3.3.3. Lava flows modeling

FLOWGO is a numerical model proposed by Harris and Rowland (2001) to describe the area inundated by the down-flow of channel-contained lava. The model integrates thermo-rheological characteristics of the lava flows with environmental factors (gravity, slope) and channel dimensions (Harris and Rowland, 2001; Rowland et al., 2005).

II.4. Combined methods

New studies tried to incorporate a multi – hazard assessment based on combination of geological maps with eruption-scenarios within a probabilistic framework, like those of Alberico et al. (2011) and Magill and Blong (2005a).

III. Case study : El Misti and the city of Arequipa

III.1. El Misti and Andean Central Volcanic Zone

The Andes represent the longest continental mountain range in the world, stretching about 7000 km along the western coast of South America. They were formed by the subduction of Nazca oceanic plate with South American continental plate the convergence still advancing today with 63 mm / yr in the Central Andean margin (e.g. Norabuena et al., 1998; Kendrick et al., 2003; Mamani et al., 2008). The volcanoes of Central Volcanic Zone (Fig. 11) are represented by 44 major active volcanic centers and 18 minor centers and / or fields (de Silva and Francis, 1989a,b, 1991; Stern, 2004). In Peru there are at least nine potentially volcanic centers (Fig. 11), of which four have erupted since the Spanish conquest (Bullard, 1962; de Silva and Francis, 1990; Legros, 1998, 2001). The four major active volcanic centers are presented below from North to South: Sabancaya, El Misti, Ubinas and Huaynaputina. Along these volcanoes, Bullard (1962), de Silva and Francis (1990), Legros (1998, 2001) are considering as potentially active the following: - *Coropuna, Yucumane,* *Tutupaca* and *Ticsani*. A phreatic event ~ 1900 A.D. is debatable if attributed to Yucumane or Tutupaca (de Silva and Francis, 1990).

El Misti (5822 masl) stratocone, along with Chachani and Pichu – Pichu, represent a local group of volcanoes located on the western edge of Cordillera Occidental of Southern Peru, dominating the tectonic depression where the city of Arequipa lies (Fig. 12 a,b). The morphology of the cone favors the volcanic flowage processes towards south where debris flows and avalanche deposits are found, and north – west in the Rio Chili canyon. The present geomorphologic features have implications in hazard assessment of the volcanic mass flows because their distribution and runout distances are depending on the high vertical drop and the guiding channels. There are no barriers that may block the volcanic flows. Most of the channels have straight course, some of them presenting sudden changes in course direction and lower rims that may allow overflow.

III.2. The city of Arequipa

Arequipa (Fig. 13; Fig. 14 a) is the second largest city in Peru with a population estimated at 835859 people in 2011 (INEI, Instituto Nacional de Estadística e Informática, Perú). From 1960 when the population was roughly 86.000 people, Arequipa experienced a rapid population growth (Thouret et al. 2001), due to social conditions that forced people from the country side to move to the urban areas. Nowadays Arequipa is quickly expending and the lack of urban planning laws has caused an uncontrolled development of the suburbs on El Misti's slopes. The proximity to the volcano makes the city exposed to various volcanic phenomena as geological evidence showed: - tephra fallout, pyroclastic density currents, lahars, debris avalanches (e.g. Thouret et al, 1996, 1999a, 2001; Legros, 2001; Delaite, 2005; Vargas et al., 20101; Martelli, 2011). An important feature that makes the city highly exposed to volcanic mass flows is the H / L ratio: - the vertical drop is cc. 3500 m in about 17 km horizontal distance (Fig. 14 b).

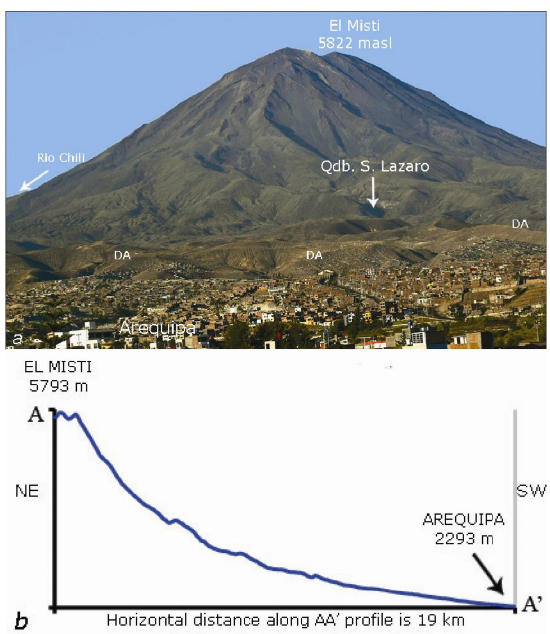

Figure 1. a) View from SW of Arequipa city and El Misti volcano. The cone is carved by a channels and ravines and here, Quebrada San Lazaro is the most prominent channel. Quebrada San Lazaro cuts past debris avalanche deposits (DA) where some of the city's suburbs are built *(image from* **http://www.trekearth.com***)*. **b)** Topographic profile along AA' direction represented in figure 13 showing the vertical drop between El Misti's summit and the city center.

PART II: Analyses and results for pyroclastic density currents and volcanic ballistics zard assessment at El Misti Volcano and in the city of Arequipa

II.1. Methods and rationale

For the purpose of the present study, the pyroclastic flows and volcanic ballistics hazard assessment will be carried out within an event – tree scheme proposed by Newhall and Hoblitt (2002). Probabilistic computations and the resulting probability maps will be obtained by merging all the data available into a BET_VH framework (Marzocchi et al., 2010) that is based on the event – tree logic and provides near real – time probabilities. In order to compute the probabilities as accurately as possible and decrease the uncertainty in the computation, besides the available geological data, computer modeling will be carried out with TITAN2D code for pyroclastic flows and with EJECT code for volcanic ballistics. The obtained maps will be converted in a binary language and merged in a BET_VH scheme.

II.2. Hazard based studie at El Misti

All previous research at Misti, from geologic studies (e.g. Thouret et al., 2001), petrologic (e.g. Ruprecht et al., 2007), stratigraphic (Legros, 2011) and more recent physical volcanology-based study of the c.2030 yr B.P. eruption (Cobeñas et al., 2012) emphasized on the danger that the volcano poses to the city of Arequipa and offered a well documented baseline for volcanic hazard and risk assessment studies. The phenomena that will pose the highest risks to Arequipa are the volcanic mass flows i.e. *pyroclastic density currents and lahars*, due to the high H / L ratio and the proximity of the city.

II.2.1. Eruption scenarios for El Misti

Hazard – based studies at Misti comprised a statistical approach using magnitude vs. frequency data in order to create hazard – zone maps based on eruptive-scenarios (Thouret et al., 1999a, 2001; Delaite et al., 2005; Vargas et al., 2010; Martelli, 2011). The eruptive-scenarios have been extensively discussed by Thouret et al. (1999a), Delaite et al. (2005), Martelli (2011) and a revised version is in progress by Sandri et al. (2012 in prep.). Giving the fact that the hazard assessment proposed in the present study is based on these eruptive-scenarios, here a brief description of each scenario will be provided: - 1) A ***small*** VEI 2 event; 2) A ***medium*** VEI 3 event; 3) A ***large*** scale event, VEI >3**.**

II.2.2. Selection of volcanic hazards for the present case study

Studies of Thouret et al. (1999a, 2001), Legros (2001), Delaite et al. (2005), Cobeñas et al. (2012) showed that pyroclastic density currents are frequent phenomena in El Misti's past eruption and many, associated with large eruptions, have reached areas where the city of Arequipa is built today. The geologic studies and the previous created scenario – based hazard-zone maps provide a good baseline for a more detailed pyroclastic density currents (pyroclastic flows and surges) assessment. Despite the fact that in Misti's case, phenomena like tephra fall or a possible flank failure represent bigger threats, in the present study the ***ballistics (BA)*** are considered for hazard assessment because they cannot be easily neglected especially in Rio Chili canyon where the military school and hydro power – plants facilities lie within striking distance.

II.2.3. *Pyroclastic flows* and *pyroclastic surges*

Given their different composition as shown in Part I of this study, the flow dynamics is different at flows and surges and thus modeling has to take into account different parameters. Numerical computer codes that are more suitable for simulations of pyroclastic surges are not yet available. Several authors are trying to solve such inconveniences through codes like VOLCFLOW and PDAC2D but these features were not available at the time of the present study. Hence the reasons for which pyroclastic flows have been considered for this study. Another reason for considering pyroclastic flows is reflected in the stratigraphical record. According to Thouret et al. (2001), pyroclastic flows records are better preserved as they are channeled in the valleys of the Quebradas and Rio Chili, whereas pyroclastic surges deposits are found in thin layers and very widespread, unconfined and thus more difficult to identify, interpret and map. Pyroclastic surge deposits were found as far as 13 km on the radial valleys around El Misti and in general they are attributed to: (i) dry pumice-rich, ground surges linked to past Plinian eruptions (ii) ash-cloud surges associated to block-and-ash flows and to pumice-rich flows, (iii) base surges produced by phreatomagmatic and vulcanian eruptions.

II.3. Methods proposed for PFs and BA hazards assessment at El Misti

II.3.1. Computer modeling methods

II.3.1.1. Pyroclastic flows (PFs)

The **TITAN2D** (Fig. 15) program is based upon a depth-averaged model for an incompressible Coulomb continuum, a “shallow – water” granular flow. TITAN2D combines numerical simulations of a flow with digital elevation data of natural terrain supported through a Geographical Information System (GIS) interface (TITAN2D User Guide, 2007). The mathematical model is extensively described in Patra et al. (2005) and Pitman et al. (2003). It assumes an initial ellipsoidal - pile of material that flows over a DEM of the natural terrain. This material is subject to the momentum created by the gravity pull and the friction within particles and the roughed topography. The governing equations are based on a frictional Coulomb – type term and the resulted system of equations is solved with a parallel adaptive mesh, a Godunov solver (Pitman et al., 2003; Patra et al., 2005).

II.3.1.2. Volcanic balistics (BA)

A ballistic object traveling through atmosphere is subject to several forces that dictate its trajectory and velocity, i.e. gravity and air drag (Fig.17). ***EJECT*** (Fig. 18) is a computer code created by Mastin (2001), which helps to computes trajectories and traveled distances of volcanic bombs. The governing equations on which the code is based are those proposed by Wilson (1972) later developed by Fagents and Wilson (1993). These equations have into consideration the elementary forces acting on a ballistic block (e.g. gravity, air drag) and they differ from the other mathematical models by considering the variations of the Reynolds number and the reduce air drag near the vent. The code ignores though other forces as lift, Coriolis force and gravitational – force variations which have applicability rather in military ballistic studies rather than volcanology studies (Mastin, 2001).

II.3.2. Probabilistic methods for hazard assessment

For the present study a long – term hazard assessment for PFs and BA is proposed with the help of BET_VH – *Bayesian Event Tree for Volcanic Hazard* (Marzocchi et al., 2010). Bayesian approach allows the quantification of the influence of natural variability, in terms of eruption sizes and associated eruptive phenomena, on the final hazard estimates (Selva et al., 2010).

II.3.2.1. BET_EF

The use of Bayesian approach allows the estimation of the uncertainties associated to hazards: (i) *aleatoric,* that are due to the intrinsic randomness of the eruptive process and its related hazardous phenomena (e.g. frequency / magnitude), and (ii) *epistemic* uncertainties that arise due to our limited knowledge of the entire system. By merging all of the information available such as theoretical models, a priori beliefs, monitoring observations, and every kind of past data, BET is a probabilistic model that calculates the probability of any possible volcano related event (Marzocchi et al., 2008).

II.3.2.2. BET_VH

BET_VH scheme (Fig. 19) is a natural evolution of the short-term eruption forecasting code BET_EF (Bayesian Event Tree for Eruption Forecasting) described above and is devoted to eruption forecasting purposes (Marzocchi et al. 2010). The event tree used for volcanic hazard assessment enables us to compute the conditional and absolute probability of a specific hazardous phenomenon i.e. tephra fall, ballistics, pyroclastic density currents, debris flows and debris avalanches, to occur and affect a specific area.

II.4. Basis for volcanic hazard assessment : computer modeling of PFs and BA at El Misti

II.4.1. Computer modeling of pyroclastic flows

II.4.1.1. Input parameters for TITAN2D

According to these eruption classes, the input parameters for the modeling of pyroclastic flows generated by column collapses at El Misti will be discussed. For the purpose of the probabilistic assessment, 29 simulations with TITAN2D have been made according to the eruptive scenarios: **9 simulations** for the *small* size eruption (Vulcanian / Phreatomagmatic); **10 simulations** for the *medium* size eruptions (Subplinian / Plinian) and **9 simulations** for the *large* eruption (Plinian). As input parameters it was used: *initial volume (V) and starting location, friction angles (internal* (ϕ_{int}) *and bed friction* (ϕ_{bed})) *and initial velocity (**v**) of the flows.* Simulations run to simulate 1200 real-time seconds, and carried out on a DEM that covers an area of 32x31 km and encompass El Misti volcano and the city of Arequipa (South America UTM, zone 19S) as shown in Figure 22. The **DEM** has a resolution of **30 m**. The simulated volumes are gradually increasing, to mark the transition between the different types of eruption: (1) ***small*** (Vulcanian / Phreatomagmatic) – between **6 x 10^6 m^3 and 3.5 x 10^7 m^3**; (2) ***medium*** (Subplinian / Plinian) – between **5 x 10^7 m^3 and 5 x 10^8 m^3**, and; (3) ***large*** (Plinian) – between **10^9 m^3 and 3 x 10^9 m^3**. The *internal friction angle* (ϕ_{int}) corresponds to friction arising from particle-particle interactions and was set at 35. The *bed friction angle* (ϕ_{bed}) corresponds to the friction that develops due to particle ground interactions. Simulations were done with: (1) bed friction of (ϕ_{bed}) *= 22*$^\circ$ for pyroclastic flows generated by a *small* (*Vulcanian)* event; (2) (ϕ_{bed}) *= 14°* for those generated by a *medium*

(*SubPlinian)* event, and (3) ***(ϕ_{bed}) = 11°*** for pyroclastic flows resulting from a *large* (*Plinian)* event.

II.4.1.2. TITAN2D results

In general, the spatial extent of the simulated pyroclastic flows show similarities with the past pyroclastic flows deposits, except the wide spreading across the interfluves. The flows are covering the summit area all around El Misti and they are canalized in the main Quebradas towards the break-in-slope. On large scale, the simulated flows show few similarities with the pyroclastic-flows deposits in the field.

Figures 24 a,b,c,d,e,f,g,h,i presents the nine simulations of pyroclastic flows with volumes from 6 x 10^6 to 3.5 x 10^7 m^3 generated by a **Vulcanian** eruption. The flows are restricted to the upper part of the cone and become confined in the ravines which converge to the three Quebradas – San Lazaro, Huarangal, Agua Salada and NW scar. It is assumed that less material will flow towards N and NW. ***Subplinian eruption****:* Several SubPlinian and Plinian episodes in the last 35,000 years produced tephra fall and pyroclastic flow deposits (Legros, 2001). In Figures 26 it is shown the extent of simulated pyroclastic flows for the Subplinian / Plinian eruption. The flows are following the ravines and Quebradas San Lazaro, Huarangal and Agua Salada, where the thickness of the deposits is about 10 to 100 cm. ***Plinian eruption.*** In Figures 28 a,b,c,d,e,f,g,h,i, simulations show that large Plinian events with volumes of > 10^9 m^3 will produce flows that may advance far into the city of Arequipa. Due to the large volume and the vertical drop, the large Plinian flows will have a higher velocity allowing them to travel as far as the city center.

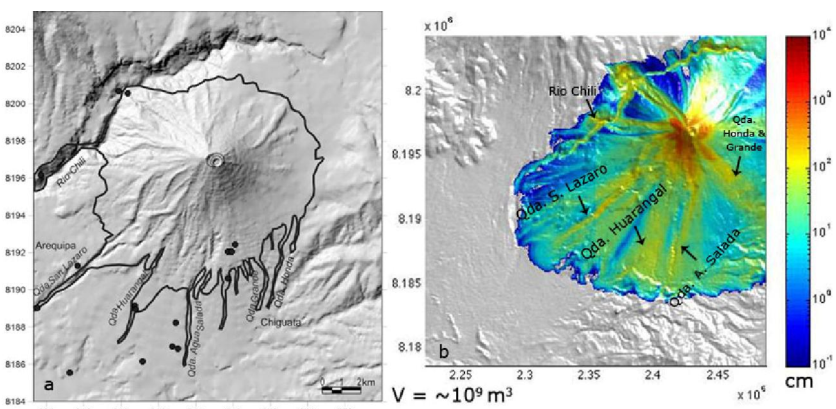

Figure 2. Comparison between the extent of the pyroclastic-flow deposits of the c. 2030 yr. B.P. eruption at El Misti (a) and one TITAN2D simulation for the same ~ $1km^3$ volume (b). One major difference is the area covered by the TITAN2D simulated flows unlike the field deposits that are more confined in the channels on the lower flanks after the break-in-slope. Both cases present similarities in terms of the run-out distance in the major Quebradas reaching up to 12km from the vent (*image from Cobeñas et al., 2012*).

II.4.1.3. Implications of DEM resolution in TITAN2D modeling: example of block-and-ash-flows (BaFs)

In their study, Capra et al. (2010) have tested TITAN2D model by simulating block-and-ash-flows on different DEM's at Colima volcano, Mexico. They tested flows over DEMs with cell resolution of 5, 10, 30, 50 and 90 m. Given their rheological behavior, the volcanic mass flows proved to be highly sensitive to topographic changes such as break in slope, obstacles, ravine deviation (Capra et al., 2010). Simulations of block-and-ash-flows at Misti were done on two **DEMs** of **20m** and **30m** resolution in order to visualize the effects of topography on the flows and to conclude how this affect the hazard and risk assessment

II.4.1.3.1. TITAN2D input data for BaFs

Simulated volumes are of ~ $\boldsymbol{3 \times 10^6 m^3}$, ~ $\boldsymbol{1 \times 10^6 m^3}$ (Charbonnier and Gertisser 2008, 2012, Procter et al. 2010), and ~ $\boldsymbol{0.5 \times 10^6 m^3}$ (Sulpizio et al. 2010), generated from a single pulse dome collapse. Input parameters for block-and-ash-flows simulations are summarized in Table 9 alongside parameters used by other authors to simulate the same type of flows. Justifications of the input are described bellow.

II.4.1.3.2. TITAN2D results for BaFs

The simulations results showed that the BaFs follow the channels on SE, SW flanks for 2 – 5km. In general the low friction angle (i.e.11^0) showed distribution of the flows where some field observations spotted BaFs deposits in the Quebrada Huarangal and San Lazaro (Thouret et al., 2001). The less realistic results were obtained with bed friction angle of 20^0, where the flows traveled < 1km. The short distances traveled may be due to the low slope angle bellow the Misti's break-in-slope. A general characteristic for the BaFs simulations is that on a higher resolution DEM (i.e. 20m) the flows reach longer distances and stay more within the channel, whereas on lower resolution DEM (i.e. 30m), the flows travel bit shorter distances but present more overflow features. As Capra et al. (2010) showed the DEM resolution modifies the width and depth of the ravines.

II.4.2. Computer modeling of volcanic ballistics (BA)

II.4.2.1. EJECT input

A total of 16 simulations have been carried out and the results were equally assigned to all three eruptive scenarios at Misti.

II.4.2.2. EJECT results

Sixteen simulations have been performed with EJECT code and established that ballistics are distributed within distances ranging between 1.6 and 3.9 km. Blocks of the simulated sizes have been recorded within these distances during the Arenal 1968 eruption (Fudali and Melson, 1972; Steinberg and Lorenz, 1983) and Mt. Spurr 1992 eruption (Waitt et al., 1995).

Diameter *(m)*	**Velocity** *(m / s)*	**Ejection angle** *(^{0})*	**Ejection angle** *(^{0})*	**Distance** (Cd = var.) *m*	**Distance** (Cd = 1) *m*	**Maximum height** (Cd = var.) *m*	**Maximum height** (Cd = 1) *m*
0.5	150	35	-	**2077**	**1678**	*370*	*328*
0.5	150	-	45	**2203**	**1735**	*560*	*489*
0.5	200	35	-	**3565**	**2585**	*184*	*134*
0.5	200	-	45	**3770**	**2642**	*974*	*789*
1	150	35	-	**2107**	**1881**	*372*	*350*
1	150	-	45	**2235**	**1969**	*565*	*526*
1	200	35	-	**3689**	**3065**	*657*	*593*
1	200	-	45	**3903**	**3182**	*995*	*885*

Table 1. Input parameters and the resulted traveled distances (bold characters) and maximum heights (*italic characters*) of the simulated volcanic ballistics with EJECT code.

II.5. Probabilistic hazard assessment

II.5.1. An Event – Tree for El Misti

Quantitative data from numerical simulations with TITAN2D and EJECT and from historical record at El Misti will be used as input in BET_VH framework in order to produce probabilistic maps of the selected volcanic phenomena. A complete event – tree was proposed for El Misti (Fig. 35) by (Sandri et al., 2012 in prep.), according to the instructions of Marzocchi et al. (2010). Data used at each computational node will be highlighted. The time window selected for the long – term hazard assessment proposed is one year. "Long – term" refers to the timescale of the expected significant variations in volcanic processes. While during unrest the time variations occur in short timescales (from hours to few months), the changes expected during a quiet phase of the volcano are much longer (Marzocchi et al., 2010).

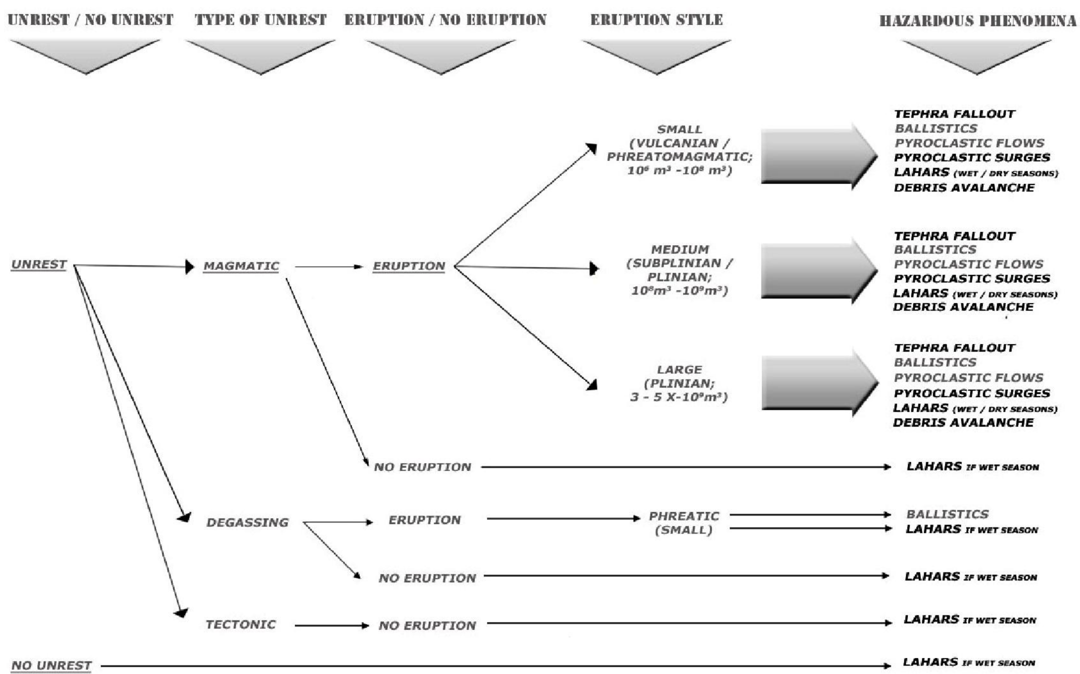

Figure 3. The complete event – tree proposed for hazard assessment at El Misti (Sandri et al., 2012 in prep). With light-gray color are highlighted the paths and nodes of the event – tree used for the assessment of pyroclastic flows and volcanic ballistics in the present study. Other considered phenomena at El Misti are represented with black color and they were proposed accordingly to seasonal changes in the region (e.g. tephra fallout; lahars) and to the eruptive sizes proposed by Thouret et al., (1996, 1999a) and Delaite et al. (2005).

II.5.2. Setup of computational Nodes 1 – 6 for El Misti

II.5.2.1. Node 1 – 2 – 3

In BET_VH (Marzocchi et al., 2010), node 1-2-3 is a combined node in which the probability of an eruption during the selected time window is computed. Following the structure of BET_EF (Marzocchi et al., 2008), the nodes 1 (unrest or not), 2 (origin of unrest, conditional to occurrence of unrest) and 3 (eruption, conditional to occurrence of magmatic unrest) will be separated to calculate their probability density functions. After having these probabilities, the probability N 1-2-3 is the product of them.

The N1-2-3 probability is the product of N1, N2 and N3 and it was calculated at **0.0039 yr^{-1}.**

II.5.2.2. Node 4

At Node 4 the probability of *vent opening* is computed. To define other vent locations for the probabilistic assessment, Misti's edifice was divided into a radial structure characterized by a central (C) vent location of 900 m diameter centered on the top of the cone enclosing the two nested craters, and four radial sectors, NE, SE, SW, and NW. Based on evidence of faulting and fracturing (refer to Thouret et al., 2001), it was considered as *prior model* that the central location is the most likely location for an eruption to start , followed by the NW sector (which is cut by an active system of faults), the SW sector (characterized by fractures) and, least likely, the SE and NE sectors. These geological considerations were translated into subjective 'best guess' probabilities of 90% for the central location(C - *1*), 6% for the NW sector (*5*), 1% for the NE sector (*2*), 2% for the SW (*3*) and 1% for SE (*4*).

II.5.2.3. Node 5

For the case of *unrest* due to an *increased magmatic degassing* it is a expected a *(1) phreatic exposion* (VEI < 2). If the unrest is *magmatic* in origin, than sustained magmatic eruptions will be considered as described in TITAN2D modeling section:

- *(2) small (Vulcanian / Phreatomagmatic*; VEI < 3) – with a volume between 10^6 m^3 and 10^8 m^3, resembling the 1440 – 1470 A.D. Vulcanian event (Thouret et al., 2001);
- *(3) medium (Subplinian / Plinian*; VEI 3 - 4) – with a volume between 10^8 m^3 and 10^9 m^3 resembling the 2030 yrs B.P. Subplinian / Plinian eruption (Thouret et al., 2001; Cobeñas et al., 2012);
- ***(4)*** *large (Plinian*; VEI > 4) – with a volume between 3 and 5 x 10^9 m^3 resembling the very large events like those of ~ 34,000 yrs B.P , ~ 21,000 yrs B.P. and ~ 14,000 yrs B.P. (Thouret et al., 2001; Cacya et al., 2007).

The *prior model* is represented by a power law implying that smaller eruptions are an order of magnitude more likely than larger ones (Marzocchi et al., 2004), therefore the prior probabilities are:

$$P_{small} = 0.6,\ P_{medium} = 0.3 \text{ and } P_{large} = 0.1.$$

II.5.2.4. Node 6

For El Misti and Arequipa case study the same DEM of 32 x 31 Km with a resolution of 30m as used for numerical modeling are used here. On this DEM a grid of 960 cells is draped in order to represent 960 locations (= areas) expected to be reached by the hazardous phenomena (Figure 33). The grid cell is 1 x 1 km. This size may not be accurate in delineation of hazard, but in order to be conservative, it is fairly assumed that is almost impossible to draw a line that perfectly delineates an area potentially of being impacted within tens of meters.

No *past data* are considered at this node and the *prior models* are represented by the prior best guess as: - 100% probability for volcanic ballistics to occur given any type of magmatic eruption and during the phreatic ones; - the prior best guesses for pyroclastic flows were compiled from Newhall and Hoblitt (2002 – Table 1) where the probabilities were computed as a function of the volcanic explosivity index: - *10%* probability to have pyroclastic flows from a *Vulcanian eruption; 50%* for a *Subplinian / Plinian and 70 %* for a large *Plinian eruption*.

II.6. Results of the probabilistic assessment of pyroclastic flows

II.6.1. Nodes 7 and 8 input

In order to evaluate the extent of pyroclastic flows and volcanic ballistics and to provide the probabilistic maps, the grid map of 1 x 1 km draped on the 30m DEM (Fig. 36) is used. Node 7 and 8 come together as we are able to define which area is reached or not by the hazardous phenomena (N7) and if a predefined threshold (e.g. area reached or not by a pyroclastic flow; tehpra load exceeds 100 kg / m^2) is overcome in models and past data in a chosen location (N8). For this case study, as *past data* it was used the extent of pyroclastic flows deposits of past eruptions according to the three eruptive scenarios. Working on the selected grid, the cells (locations) were marked as reached (1) or not reached (0) by pyroclastic flows in the past. The data are uploaded in a table according to the specifications of BET_VH manual.

II.6.2. Probability maps for pyroclastic flows hazard assessment

The conditional probabilities (Fig. 37 a,b,c) are always conditioned by the chosen eruptive scenario (Marzocchi et al. 2010). In our case, the maps show the conditional probabilities for pyroclastic flows to reach a certain location, given an eruption of one of the three selected sizes.

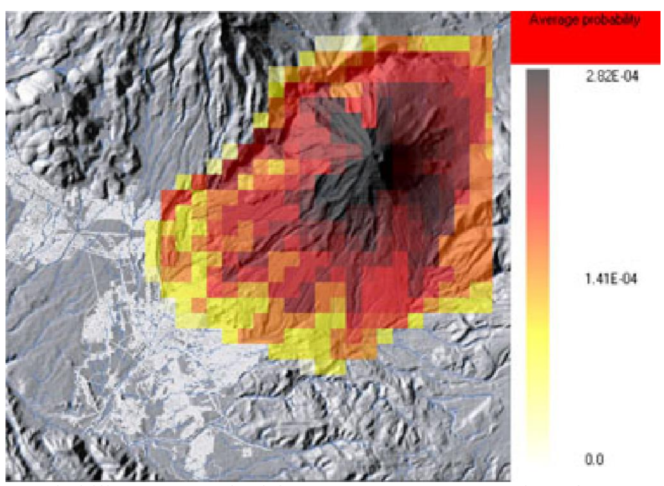

Figure 4. Absolute probability map resulted from BET_VH computations for pyroclastic flows from a magmatic eruption (either Vulcanian, Subplinian or Plinian).

The absolute probability (Fig. 38) map shows the probability of a location to be reached by a pyroclastic flow generated by an eruption of any size. BET_VH takes into account all the possible eruption scenarios and not just those from a specific set of conditions. The probabilities are lower than the conditional ones. One of the most notable things is that the probabilities provided by BET_VH are confined, but not only, to the areas where field observations showed the extent of pyroclastic flows from past eruptions.

II.7. **Results of the probabilistic assessment of volcanic ballistics**
II.7.1. **Nodes 7 and 8**

No complete data catalogue for *past data* is available at the time for volcanic ballistics at El Misti. As *prior models*, the 16 trajectories obtained for the simulated volcanic blocks with EJECT code (Table 11, columns 5 and 6), were measured and delineated on the grid map prepared for the assessment. The resulted probabilities have been converted in a table according to BET_VH Manual, and uploaded for computation of final probability maps.

II.7.2. Probability maps for volcanic ballistics hazard assessment

The conditional probability maps (Fig. 39 a,b,c) show the probability of a ballistic block to reach a location given a specific type of eruption. For instance, a ballistic block will reach the Rio Chili valley only if a Size 3 (Plinian) eruption occurs. In other words, the probability of a ballistic block to reach such a distance is conditioned by specific conditions such as a Plinian eruption. Absolute probability maps (Fig. 40 a,b) show the absolute probability of a ballistic block to reach a specified location regardless the size of eruption. The probability sums to 1, meaning that given the fact that we do not have enough information about the size of the incoming eruption, what will be the probability of the ballistic blocks to reach a location if we have an eruption of any size.

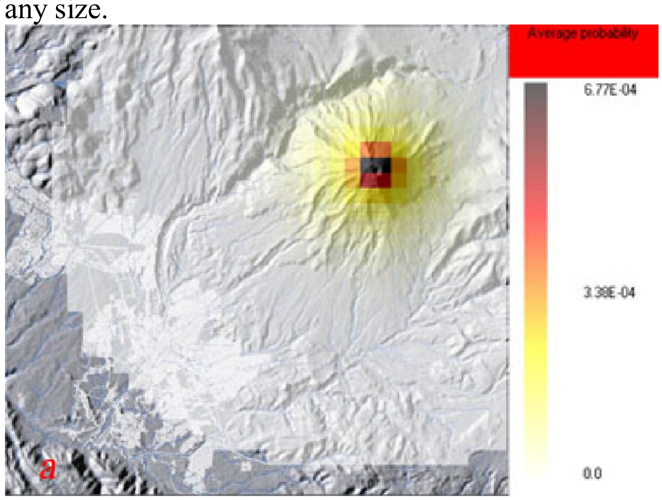

Figure 5 a. Absolute probability maps resulted from BET_VH computations for ballistics from a magmatic eruption.

PART III: Implications of the computer modeling and probabilistic assessment of volcanic hazard

III.1. Implications of computer modeling of pyroclastic flows in physical vulnerability assessment

III.1.1. Aspects of vulnerability to pyroclastic flows

Casualties and infrastructure damage occur due to the pyroclastic flow temperatures (between 100 and 800°C) and lateral dynamic pressure loading on buildings, leading to fire initiation, wall collapse and corrosion (Pomonis et al., 1999). People usually die because of exposure to high temperatures, and structures may be affected by lateral loading, corrosion or ignition of flammable materials. The structural integrity of the building is a key factor for the evaluation of damage and live loss if a pyroclastic flow reaches a populated area.

III.1.2. General characteristics of building stock in the suburbs of Arequipa and exposure to PFs

Due to the poverty, the buildings in the suburbs of Arequipa do not present a strong structural integrity as those in the other parts of the city. Some of the buildings are situated right in the valley bed. As the geological investigations (Thouret et al. 2001) showed, a large number of people and buildings lay in valleys where deposits of debris flows and pyroclastic flows were identified and are expected to occur in future eruptions (Fig. 41).

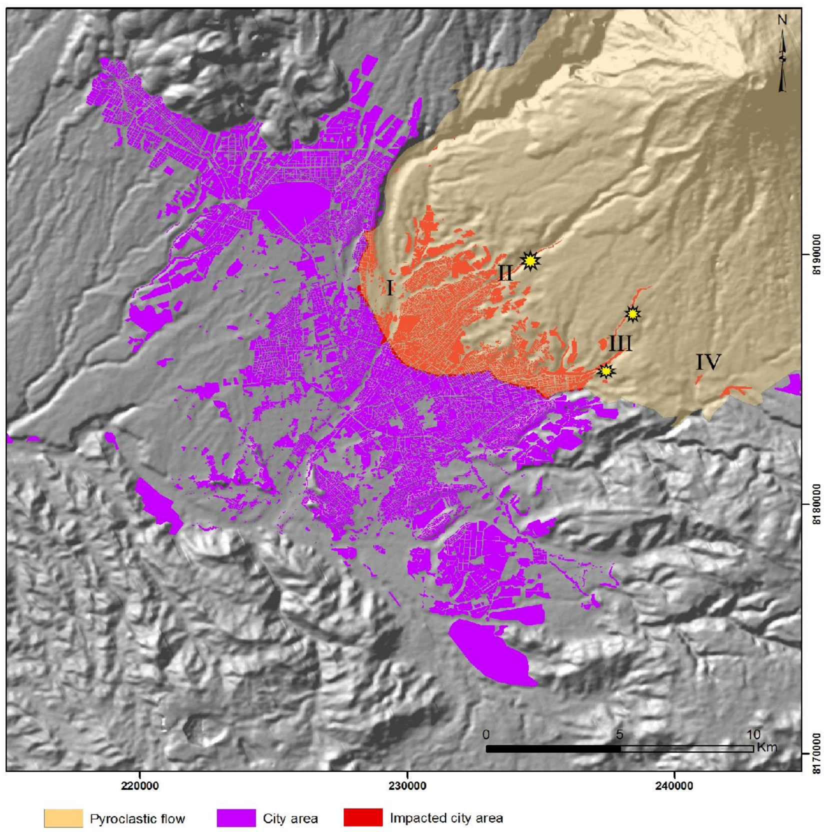

Figure 6. The extent of the large Plinian pyroclastic flows over the built area of the Arequipa suburbs on the SW and S flank of Misti. I – Downstream Rio Chili Valley, II – Quebrada San Lazaro , III – Quebrada Huarangal, IV – Quebrada Agua Salada. The estimated built area impacted by pyroclastic flows (red) is ~ 16 km^2. This is an estimation based on TITAN2D results but this area cannot be impacted by PFs equally as local topography, channel morphology and other landforms will prevent some of the interfluves to be impacted. Yellow stars show the locations where dwellings are built in the valley bed.

Vargas et al. (2010) and Martelli (2011) studies focused on Quebrada Huarangal and Rio Chili valley and their buildings survey identified that the three major building materials in these valleys are bricks and concrete, bricks and bricks and sillar (a variety of tuff rock in

Arequipa). Many of these dwellings are located in the valley bed and on the lower terraces. Also, at the volcaniclastic fan apex in Quebrada Huarangal there are few poor – quality houses (Vargas et al., 2010). Such poor qualities houses are made of make shift materials like wood, bricks but they lack in structural design.

Large Plinian events with volumes exceeding 10^9 m^3 produce simulated flows that would reach 15 km distance, i.e ~ 3 km beyond the extent of existing similar deposits. Figure 43 shows the extent of the city of Arequipa (purple color) on the flanks of El Misti, the extent of the large Plinian pyroclastic flows and the area of the city covered by the flows (brown color). The built area of the city impacted by the large Plinian flows (Figure 43, red color) is estimated at 16 km^2.

III.1.3. Implications for the physical vulnerability assessment

As the present study is not intended to present a thorough physical vulenrability assessment from the data of Vargas et al. (2010) about the building materials and types in the suburbs and Rio Chili, and the exposure of the city to pyroclastic flows, it is possible to draw the following conclusions:

-the distance at which the built area impacted by the simulated flows is greater than 9 km; -the velocity tends to zero upon deposition; and the thickness of the flows does not exceed 0.3 m. from this it is possible to conclude that the dynamic pressure of the pyroclastic flows in this area is <1kPa;

-considering the type of buildings in the impacted area (mostly of concrete and bricks) and the observations made by Baxter et al., (2005), it is expected no serious structural damage at dynamic pressures < 1kPa;

-the most vulnerable buildings may be those located higher up Qb. San Lazaro and in Qb. Huarangal (yellow star on Figure 42) and in the valley bed. In Qb. San Lazaro, for example, at ~10 km away from the summit, the TITAN2D simulations showed a thickness of the large PFs of ~0.5 m. Infiltrations may lead to ignition of materials and thus affect the structural integrity of the building and possible kill the inhabitants. For a complete vulnerability hierarchy one must study these possible impacted areas as a function of the frequency and intensity of the phenomenon (Irimuş, 2006), in this case pyroclastic flows.

III.2. Implications for risk assessment

In general, the risk is a function of the hazard and the vulnerability and is regarded as the loss of human lives and livelihoods. Risk perception implies its management with the help of risk maps (Irimuş, 2005). Giving the complexity of volcanic eruptions and the fact that they are rare events in human time scale, one good probabilistic approach is the Bayesian one because allows merging of theoretical models of the eruptive process, historical and geological data, and even monitoring data. Thus it allows aleatoric and epistemic uncertainties of the model to be dealt with in a formal way, and all to be accommodated in a hazard or risk assessment (Marzocchi et al, 2004). The quality of the input data is important in order to reduce the epistemic uncertainties raised by the poor knowledge of the system. The probabilities obtained in the present study for the pyroclastic flows are reliable giving the amount and quality of the used data, but the quality of the probabilistic results can be improved as more reliable data becomes available. Despite the probabilities obtained with BET_VH, the lack of a complete data set for vulnerability at this stage can only help to draw some qualitative conclusions for pyroclastic flows risk at El Misti and Arequipa. In case of El Misti, the risk may decrease if the decision makers will take mitigation measures as moving people from upstream of Quebradas in other safe places, demolish the unfitted makeshifts constructions and improve those with good structural features. Improving the buildings to avoid as much as possible infiltrations and ignition may decrease the risk. Since 2011, local laws banned the constructions in the high risk areas.

III.3. Discussions: limitations and caveats of computer modeling at El Misti

For the purpose of the present hazard assessment, simulations were done with TITAN2D in order to see the spatial extent of the flows at El Misti. Several simulations have been carried out with different parameters in order to calibrate the model with the field data, but still there is no 100% fit due to the various parameters of the simulations and theyr sensibility to local conditions (e.g. morphology, surface roughness). From the simulations performed for this study, it was possible to observe the sensitivity of TITAN2D modeling input parameters. Bed friction angle is highly sensitive to the flow surface leading to unrealistic results if the DEM resolution is high. As other authors showed, the input of the model dictates the accuracy of the output. To increase effectiveness and reduce uncertainty in the probabilistic assessment proposed in our study several factors may be improved: (i) Obtain a higher resolution DEM that is improving the roughed surface of the ravine network; (ii) Completion of a catalogue that contains accurate information about the distribution of past flows at El Misti and their volumes; (iii) Increase the number of simulations and use alongside TITAN2D other computer models that solve for different aspects of the flows; (iv) Take into account the pyroclastic surges; (v) detailed study of the geomorphologic features of the cone and the drainage network; (vi) a detailed survey of the building stock in the exposed areas and mechanical tests to determine their resistance to dynamic pressure and (vii) a GIS analyses for risk and vulnerability to pyroclastic density currents.

Conclusions

IV.1. Summary of the results and general conclusions

The present study shows how different techniques such computer modeling and probabilistic methods can be combined in order to assess pyroclastic flows and volcanic ballistics hazards. For the city of Arequipa, beside the lahars that may occur even without an eruption, pyroclastic density currents from El Misti volcano are among the most significant hazards.

The *first goal* of this study is to obtain a spatial extent of pyroclastic flows and volcanic ballistics with the help of computer modeling with TITAN2D and EJECT codes, based on field data and information from analogue volcanoes. For the *pyroclastic flows hazard assessment* at El Misti, 28 computer simulations with TITAN2D code were conducted in order to simulate flows generated from an eruptive column collapse given one of the proposed scenarios (i.e. Vulcanian; Subplinian / Plinian; Plinian). The computer simulations with TITAN2D revealed the fact that the city suburbs at ~ 9km away from the vent are highly exposed to pyroclastic flows from large Plinian eruptions. Simulations were carried out for small *block-and-ash-flows* on 20m and 30m resolution DEMs of El Misti in order to test the influence of the topography and simulation parameters over the results of TITAN2D. A general characteristic for the BaFs simulations is that on a higher resolution DEM (i.e. 20m) the flows reach longer distances and remain more confined to the channel, whereas on lower resolution DEM (i.e. 30m), the flows travel bit shorter distances but present more overflow features. The 16 simulations using the EJECT code for *volcanic ballistic* blocks showed that the maximum traveled distance expected for a ballistic block of 0.5 and 1 m diameter at El Misti is less than ~ 4 km and therefore will not affect the areas built in the Rio Chili canyon on the WNW. Blocks of the simulated sizes have been recorded within these distances during the Arenal 1968 eruption (Fudali and Melson, 1972; Steinberg and Lorenz, 1983) and Mt. Spurr 1992 eruption (Waitt et al., 1995). The second goal of this assessment consists of a *probabilistic hazard assessment* for the pyroclastic flows and volcanic ballistics, which has important implications on the risk assessment. Given the Bayesian approach, the possibility to combine various sources of information is used, thus it is showed how individual separate models can be used and how they influence the distribution of probability. For a practical point of view, the conditional probability maps, describing the probability of a hazardous phenomenon to reach a specific location given a certain activity scenario, have a much more important use in risk analyses, as it focuses on a specific event with a specific set of conditions. The conditional and absolute probability maps are important assets for long-term hazard and risk assessment and possibly help the decision-makers in the future urban extension planning. BET proved to be able to assign probabilities according to the frequency and extent of the phenomena both in past data (i.e., geological data) and prior model (i.e., TITAN2D simulations). Noteworthy, given a certain eruption size, BET assigns the highest probability where both past data and prior model show that pyroclastic flow will travel.

IV.2. Recommendations for future research at El Misti

From a single hazard assessment to a multi-hazard approach, in case of El Misti and the city of Arequipa additional research is needed that may incorporate different approaches and areas of expertise.

Even though at El Misti geological and stratigraphical studies (e.g. Thouret et al., 2001; Legros, 2001) conducted so far revealed its eruptive behavior and its predominant activity, many small sized events can be missed in the records. The completeness of a field data catalogue for pyroclastic density currents deposits or any other volcanic hazard is required in order to improve the hazard assessment. In order to decrease uncertainty in a probabilistic assessment it is recommended the use of different computer modeling tools that solve for different physical aspects of the volcanic mass flows. Besides geological and stratigraphical studies on a particular event, it is highly recommended that physical vulnerability studies to be carried out in the city suburbs with respects to pyroclastic flows behavior. A physical vulnerability study may help decision-makers to undertake mitigation measures in order to decrease the future risk.

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