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COMPUTER MODELING AS TOOL FOR VOLCANIC HAZARDS ASSESSMENT: AN EXAMPLE OF PYROCLASTIC FLOW MODELING AT EL MISTI VOLCANO, SOUTHERN PERU

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ABSTRACT:

Volcanic eruptions pose a threat to people that live around active volcanoes. Volcanic phenomena such as lava flows, debris flows, pyroclastic density currents and ash fall can affect everyone in the proximity of the volcano as well as in distant areas. The necessity of having a better understanding of volcanic phenomena and therefore to improve the delineation of hazard maps, has led scientists to develop different methods to assess volcanic hazards, including the creation of several computer codes that can simulate different volcanic phenomena. In this paper, we present an overview of several computers codes, with a particular emphasis on those used for pyroclastic flow hazard assessment and modeling. We include an example of the application of Titan2D software on El Misti volcano; an active Quaternary stratovolcano in Southern Peru that represents a threat to the ~ 1,000,000 people living in and around the city of Arequipa.

Keywords: *volcanic hazards, computer models, pyroclastic flows hazard assessment, Titan2D.*

1. INTRODUCTION

Nowadays it is estimated that roughly 500 million people live near active volcanoes, due in part to the environment rich in natural resources characteristic of volcanic terrain. Of note are several large urban centers that lie in the shadow of active volcanoes; namely Naples, Italy (near Vesuvius); Mexico City, Mexico (just 50 miles from Popocatepetl); Kagoshima, Japan (near SakuraJima) and many others. Different volcanic phenomena related to different types of eruptions pose direct risks to humans and their livelihoods. These may be constrained to a small area around the volcano (e.g. *ballistic ejecta)* , or may impact wide areas (e.g. *tephra fallout)*. The following potentially deadly phenomena can affect large areas away from the volcano:

- Tephra fallout: - tephra is a general term used to describe all particles ejected from volcanoes during an eruption, regardless the size, shape and composition. Large tephra fragments fall back to the ground in the proximity of the volcano cone whereas finer fragments, ash size particles, are carried away by the wind and may cover extended areas.
- Pyroclastic density currents (PDCs): *Pyroclastic density currents* (PDCs) are rapidly moving mixtures of hot volcanic particles and gas (with or without free water) that flow across the ground under the influence of gravity. They form by the gravitational collapse of lava domes, by the fallback or continuous fountaining of vertical eruption columns or by lateral blasts (*Druitt, 1998*), and even as decoupled currents from a main flow (e.g. *Merapi, 2006; Unzen, 1991*). These PDCs reach high speed and destroy everything in their path.

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- Lava flows: - lava flows are common wherever molten rock reaches the surface without fragmenting explosively. Such flows come in many shapes and sizes, and feature many kinds of distinctive surface with differences mostly controlled by variations in magma viscosity and supply rates at the time of eruption (*Lockwood and Hazlett, 2010*).

- Volcanic debris avalanches – a sector collapse of a volcanic edifice produces a debris avalanche. They are large masses of rock and soil that fall, slide, or flow very rapidly under the force of gravity. A debris avalanche is triggered typically by intrusion of new magma, a phreatic explosion, or an earthquake. A debrs avalanche is generated at water – undersaturated conditions (*Ui et al., 2000*)

Debris flows (lahars): - a flow of poorly sorted heterogeneous debris, primarily consisting of volcanic rocks of all sizes mixed with water, sometimes referred to a mudflow (*Mader et al., 2006*).

We know from geological and historical records, as well as from direct observations of recent volcanic eruptions, that these phenomena have affected extensive areas around volcanic centers in the past, killing large numbers of people. Of the most deadly eruptions recorded we mention the 79 A.D eruption of Vesuvius, Italy, where PDCs killed ~ 3360 people; the 1902 eruption of Mont Pelee, Martinique, where pyroclastic surges killed ~ 30,000 people ; the 1985 eruption of Nevado del Ruiz, Colombia, where lahars killed ~ 25,000 people in the city of Armero and surroundings. In 1815 an eruption of Tambora, Indonesia, is thought to have led to the deaths of 92,000 people by starvation; tsunamis generated by the 1883 Krakatau, Indonesia, eruption killed ~ 36,000. Roof collapse due to ash deposition following the 1991 eruption of Pinatubo, Philipines, killed roughly 350 people in 1991 and a flank collapse at Mount Unzen, Japan, in 1792 killed ~ 15,000 people.

A critical step in mitigating risk in such highly exposed, densely populated areas is the development of accurate volcanic hazard assessments. The most popular approach is to create hazard - zone maps based on the eruptive history of the volcano. Volcanic hazard maps usually display the current or potential extent of dangerous volcanic flows (lava, pyroclastic or lahar) together with the potential distribution of tephra fallout (*Haynes et al., 2007*). If a volcano erupts sufficiently frequently, there are likely to be well-preserved deposits from at least the most recent eruptions. Geologists can identify and map out these deposits, so that the common styles and sizes (magnitude) of activity are readily measurable. The most likely ranges of distances from the volcano at which people may be at risk from the various kinds of activity can be defined and drawn on a map of the area (*Parfitt and Wilson, 2008*). Where there are volcanoes with long periods between eruptions, and thus the likelihood for past deposits to be eroded, the statistical approach for hazard assessment is often used.

Computer models have been developed for individual hazards, using various parameters in order to find the best fit with the field data. Examples of for different volcanic hazards are: - *Eject! - A program* for *the calculation of ballistic trajectories of volcanic blocks* (*Mastin, 2001*); *Volc Flow* for mass flows (*Kelfoun, 2005; 2008; 2009; Davies et al., 2010*) *; Flow3D* for mass flows such as debris avalanchesPDCs and lahars (*Sheridan et al., 2000*) –; *Titan2D* for mass flows (*Sheridan et al., 2005; Sulpizio et al., 2010, Procter et al., 2010*); - *FLOWGO* for lava flows (*Harris and Rowland, 2001*); – LaharZ for lahars (*Schilling S.P., 1998; Munoz - Salinas et al., 2009; Vargas et al., 2010*);, *HAZMAP* (*Macedonio et al., 2005*), *ASHFALL* (*Hurst, 1994*), *TEPHRA* and *TEPHRA 2* (*Bonadonna, 2005, 2006; Connor, 2006*) for ash fall.

In this paper we present an example of how we can delineate the extent of pyroclastic flows (PFs) in a future eruption at Misti volcano in Southern Peru, by using the computer software TITAN2D.

2. EL MISTI VOLCANO

Misti is a 5822 m high composite volcano in the Central Volcanic Zone (CVZ) of the Peruvian Andes. Unlike the other nearby volcanoes – Chachani and Pichu – Pichu, it poses a direct threat to the city of Arequipa and the inhabited surroundings. Misti is known to have produced at least 12 pumice falls deposits during the past ca. 50,000 yr (*Thouret et al., 2001*). It is known for eruptions ranging in styles from Vulcanian (e.g. 1440 – 1470 AD) to sub-Plinian (e.g. ~2050 BP) and Plinian (e.g. ~14,000 yr BP, ~25,000 yr BP, ~34,000 yr BP), which have produced a series of hazardous volcanic phenomena - tephra falls, ballistics, PDCs (i.e. flows and surges), debris flows, and debris avalanches.

Pyroclastic flow and fall deposits from Misti overlie the Arequipa debris avalanches deposits, one from Pichu – Pichu to the South (~ 1 million years old), one from Misti (70 – 110 ky old) (*Thouret et al., 2001*) and another one known as the Chachani scoriaceous succession to the West (*Legros, 2001*). Based on the type, extent, and volume of the Holocene and historical deposits, it is possible to assume that future volcanic events at El Misti, even if moderate in magnitude, will pose a serious threat to the densely populated areas in Arequipa (*Vargas et al., 2010*). A more detailed description of the geology of Misti can be found in *Thouret et al. (2001)*.

3. PYROCLASTIC FLOWS MODELING

There are mainly two types of density currents: - *pyroclastic flows* (PFs) and *pyroclastic surges* (PSs).

Pyroclastic surges (PSs) 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 speeds and can easily overrun topographic barriers. PSs travel at high velocities but the run out distance is typically confined to few kilometers, although some surge deposits associated with ignimbrites are much more widespread (*Druitt, 1998*).

Pyroclastic flows(PFs) are high-particle concentration flows, generally producing poorly sorted deposits (*Druitt, 1998*). Driven by gravity, PFS seek topographically low areas of the volcano and thus tend to be channeled into valleys. Large scale PFs associated with caldera-forming ash flows can move distances of more than 100km (*Nakada, 2000*). Most PFS are formed by lava dome collapse, and they are called *block-and-ash-flows*; PFs formed by column collapse are called *scoria flows* or *pumice / ash flows* depending on magma composition and whether they have moderate or high vesicular components (*Druitt, 1998*). In our study, we assess PFs generated by column collapse.

In the past, hazard assessment was based largely on field observations of past eruptions, and at similar volcanoes; in recent years this has been enhanced by several numerical and computer modeling tools developed to assess the behavior, movement, deposition and extent of PDCs. The main input parameters and output from a range of these models is presented in **Table 1**.

Malin and Sheridan (1982) proposed the ENERGY CONE model to mimic the 1980 blast eruption of Mount St. Helens. The energy cone was used by Malin and Sheridan for assessing the distance at which a pyroclastic flow would run out from the volcano, taking into account of: the site where the energy line intersects the volcano base line (as a break in slope), and a coefficient of friction. The energy cone model has been applied at Vulcano, Italy (*Sheridan and Malin* (*1983*) and at Colima, Mexico (*Sheridan and Macias, 1995*). Again, *Sheridan et al.* (*2000*) used the same model in comparison with computer simulations from FLOW2D and FLOW3D, at Citlaltepetl volcano in Mexico. FLOW2D computer code was created by *Sheridan and Macias* (*1992*) and it is an improved method of the energy cone as it is able to take into account the topographic features unlike the energy cone that assumed a straight line.

As FLOW2D didn't take into account the lateral movement of the flows, FLOW3D emerged. The FLOW3D code is based on the generation of a digital elevation model (DEM) representing the topographic surface along which the gravity flows move on a Triangulated Irregular Network (TIN) of elevations. This kinematics model is easy to construct from various types of data sets and a variety of geometric configurations (point source, radial distribution, linear or random) can be used to model flow initiation (*Sheridan et al., 2005*).

VOLCFLOW is another computer code that simulates mass flows. It was extensively used in debris avalanche modeling at Socompa volcano, Chile (*Kelfoun et al., 2005, 2008*) and for a pyroclastic flows at Tungurahua, Ecuador (*Kelfoun et al., 2009*). This model uses the depth – average approximation. It uses the mass and momentum conservation equations as well as the retarding stresses that slow down the flow (e.g. viscous, frictional and turbulent stresses) gravity, rheology and the topographical component. The equations used by VOLCFLOW and the mathematical method are best described in *Kelfoun and Druitt (2005)* and *Kelfoun et al. (2009)*. The application by *Kelfoun et al. (2009)* at Tungurahua volcano, Ecuador, showed some constraints of the code. At a first glance, the area occupied by the deposits generated by the model covers that of natural flow deposits yet, the model is unable to reproduce accurately the behavior of the dense pyroclastic flows at Tungurahua *(Kelfoun et al., 2009)*. A key point of the model is that it only simulates dense flows and that it is unable to reproduce ash – cloud or ash – cloud physics (*Kelfoun et al., 2009*), and that it is showed by the geometry of the deposits. The author emphasizes the fact that the incompatibility between the numerical results and field data is not due to the numerical code and it is not applicable only to Tungurahua case, but rather on the local conditions like slope variations which is common to most volcanoes. The quality of the simulations are highly dependant of the Digital Elevation Model's reolution and thus has great implication in hazard – zonation.

PYROFLOW is a model introduced by *Wadge et al. (1998)* and tries to solve for the areal extent of the flows generated by dome collapse. The model has an avalanche and a surge component. The avalanche component simulates the movement of the basal flow and the surge component in PYROFLOW is generated from the avalanche and moves away laterally to produce an envelope of thinner surge deposits around the valley-controlled avalanche deposit. PYROFLOW is a simple model for a complex set of processes and does not capture the full range of physical processes involved (*Wadge et al., 2010*). The model was used to simulate the 12 May 1996 pyroclastic flows at Soufriere Jills, Montserrat and is described in Wadge et al. 1998. PYROFLOW is used to generate the outline of individual flows by assuming the source point of the flow, its velocity and different frictional parameters. The frictional parameters are taken from the observed natural flows and than calibrated in the model. *Wadge (2010)* describes how a pyroclastic flows hazard assessment can be done with PYROFLOW. A database of parameters to be sampled randomly is created by sorting parameters that fitted the observed flows.

Than a runnout – frequency ratio of dome growth / collapse and different weighted source regions of the flows around the volcano are used to produce a probability map of future possible inundated areas. An example of how this was used at Soufriere Hills volcano in Montserrat is described in *Wadge (2010)*.

Table 1. ***Parameters and outputs of different models***

Model	Input	Assumption	Solves for
ENERGY CONE (EC)	H (height of collapse) and L (length / horizontal distance from vent) ratio; initial velocity	A friction parameter extracted from H / L ratio	Approximate runout distance of gravity – driven flows
FLOW2D	Shear resistance; basal friction; viscosity	The shear resistance is dependent of the basal friction angle and viscosity	Unlike EC, shows overrunning of topographical barriers
FLOW3D	DEM; Source geometry; viscosity; turbulence; basal friction	Constant thickness; center of mass at ground level	Steepest slope angle; viscous dissipation model; total resistance to flow
VOLCFLOW	DEM; Volume; Direction; Retarding stress	Depth – average approximation	Flow height conservation; x, y momentum conservation
PYROFLOW	DEM, Source coordinates, Direction. Basal friction, Viscosity, Turbulence. T^0 of flow; Gas content.	Assumes constant atmospheric pressure and temperature of the flow.	An indication of the possible region affected by the flows.
PDAC2D	Mass rate flux; magma water content; T^0 at the vent; Diameter of vent; Pressure at vent; Velocity of the mixture; Gas fraction; Particle fraction; Terrain roughness	Multi-phase mixture model	Solves the mass conservation equations for each phase and each gas component; the momentum and energy balance equations are solved for each phase separately
LAHARZ	DEM; Volume; Upstream inundation boundary	Equations that predict inundated valley cross-sectional and planimetric areas as functions of volume	Inundation zone
TITAN2D	DEM; Volume; Direction; Friction (internal; bed)	Flow height conservation; x, y momentum conservation	Speed of the flows and thickness of the deposits; runout

PDAC2D is a model of pyroclastic flows propagation that uses the concept of multiphase mixtures: a gas phase representd by water vapour and air, and a solid phase represented by solid spherical particles of the same size (*Todesco et al., 2002*). *Neri et al.,* (*2001*) provides a full description of the model and an application on Vesuvio and Campi Flegrei, Italy is presented in *Todesco et al.* (*2002, 2006*).

LAHARZ was written to delimit areas of potential lahar inundation from one or more user-specified lahar volumes. If the user enters multiple lahar volumes, LAHARZ produces a lahar-inundation hazard zone for each volume. The planimetric area of lahars inundation hazard zones often increase in width and length as lahar volume increases (*Schilling, 1998*). LAHARZ is a code written in ArcInfo Macro Language that uses a DEM and semi – empirical equations that predict the valley cross- sectional area and planimetric area inundated by lahars. An application of LAHARZ for a rapid delineation of the areas at risk of being inundated given block – and – ash flows and surges at Montserrat and Merapi volcanoes is described in *Widiwijayanti et al.* (*2009*).

A newer computer code to simulate geophysical mass flows is TITAN2D. The code was applied by different authors for various types of mass flows. Because TITAN2D is used in the present study, it is discussed separately in the following section.

4. TITAN2D

TITAN2D is free software created by the Geophysical Mass Flow Group at State University of New York at Buffalo (U.S.A.), which allows users to simulate granular flows over digital elevation models of natural terrains (DEM) (*Patra et al., 2005*; Sheridan et al., 2005; *Pitman et al., 2003*). The TITAN2D program is based upon a depth-averaged model for an incompressible Coulomb continuum for 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 such is Grass GIS. (*TITAN2D User Guide, 2007*). In **Table 2** we present Titan2D applications carried out by other authors and parameters they used.

Table 2. ***Other applications and parameters used in TITAN2D***

Application	Volume ($V= \#m^3$)	Internal friction angle (^{0})	Basal friction angle (^{0})
Mount Taranaki, NZ Block-and-ash flow (BAF), (*Procter et al., 2010*)	$1 * 10^6$	30^0	Between $15^0 – 25^0$
Mount Merapi, Indonesia, BAF, (*Charbonnier and Gertisser, 2009*)	$1 * 10^6$ $6 * 10^6$	30^0	$16^0 – 28^0$ 10^0 - 24^0
Colima, Mexico, BAF, (*Sulpizio et al., 2010*)	$2 * 10^6$	30^0	11^0, 12^0, 16^0
Cerro Machin, Colombia, Pyroclastic flows (PFs), (*Murcia et al., 2010*)	$2.5 * 10^6$ $1 * 10^7$ $1 * 10^8$ $3 * 10^8$	34^0	15^0
Colima, Mexico, BAF, (*Capra et al., 2010*)	$2.7 * 10^4$ $7.5 * 10^4$ $13.5 * 10^4$	30^0	5^0, 10^0, 15^0, 20^0, 25^0
Little Tahoma, Mount Rainier, USA, Debris avalanche (DA), (*Sheridan et al., 2005*)	$1 * 10^6$	33^0	12^0

The output of Titan2D computations is in the form of thickness and velocity of the flow at a given moment, as well as the extent of the deposits. The basic parameters used as input in Titan2D are described below along with the parameters used for our example. For this study we present an example of Titan2D modeling with an application on Misti volcano. The PFs are assumed on the basis of geological studies to occur from an eruption column collapse in case of Vulcanian, SubPlinian and Plinian eruptions and from dome collapse in case of Pelean eruptions. Given the fact that Titan2D cannot simulate a column collapse, we assumed the starting position of the flows around the crater as being the position where a PF generated from an eruption column will most likely hit the ground.

1. Simulated volume

This parameter represents the volume of the pile of material to be simulated i.e. the volume of a lava dome, volume of PFs etc. For our simulations we choose different volumes (**Table 3**) according to different eruptive scenarios, using volumes taken from field observations (*Thouret et al. 1996, 1999, 2001; Legros 2001*) and from compilations obtained in the literature. We also include large volumes not present in the geological record, 1.4 * 10^9 m^3, to see the extent of pyroclastic flows generated by a less probable large Plinian eruption.

For each scenario, these volumes were divided into several smaller piles distributed into circular positions around the crater, on top of preexisting channels i.e. the headwaters of ravines (locally termed Quebradas) where PFs deposits were identified from past eruptions.

2. Simulation time and minimum thickness

Simulation time was set at 1200 seconds assuming that this time frame should be enough from the initiation of the flow up to the final deposition of material. Other authors used the simulation time in accordance with the minimum velocity or minimum thickness. *Stinton* (*2007*) used minimum thicknesses of 0.5 and 1 m to simulate pyroclastic flows with volumes in the order of 10^6 m3. To look for a maximum extent of the finer particles of the flow, considering volumes on the order of from 10^7 - 10^7 m^3, we used a minimum thickness of 10^{-1}cm to confine the final distribution of the resulting deposits, and to take account of the fact that the suspended particles of the flow will run up and overcome topographic heights.

3. Internal Friction Angle and Bed Friction Angle

The internal friction angle corresponds to friction arising from particle-particle interactions within the material and is equivalent to the natural slope of the free-surface that would form if a cylindrical pile of the granular material were placed on a flat plane and allowed to collapse under its own weight (*TITAN2D User Guide, 2007*). The internal friction angle was set at 35^0, after we tested a value of 30^0 used in previous works (*i.e. Sheridan et al., 2005; Capra et al., 2008, Procter et al., 2010*).

The bed friction angle corresponds to the friction that develops due to particle ground interactions (*TITAN2D User Guide, 2007*). The bed friction angle proved to be very sensitive for the simulations showing that the distribution of the deposits of the same volume is different for various values of this angle. We tested flows with bed friction angles ranging between 80 and 250 and by comparing the distribution of the real deposits in the field (*Thouret et al., 1996, 1999, 2001*) with the distribution of the simulated deposits by Titan, we agreed to use values for the bad friction angle of 22^0 for PFs generated by a *small* (*Vulcanian)* event, 14^0 for those generated by a *medium* (*SubPlinian)* event and 11^0 for PFs resulted from a *large* (*Plinian)* event. We also argue that the mobility of a lithic-rich pyroclastic flow generated by a Vulcanian event will be lower than the mobility of a pumice-rich pyroclastic flow generated by a Plinian one.

4. Initial speed

The probable initial velocity of the pyroclastic flows was determined by using a simple relationship between potential and kinetic energy, where the initial velocity (v) is equivalent to:

$$v = \sqrt{2gh}\ ,$$

where g is the acceleration due to gravity ($\sim 9.806ms^{-2}$) and h is the height of collapse (*Murcia et al., 2010*). According to our eruptive scenarios we assumed the following heights from where a collapse may occur: Vulcanian eruption ~ 500m, Sub-plinian eruption ~ 1000m and for Plinian eruption ~ 2000m (**Table 3**). The heights of column collapse where compiled according to the models developed by *Wilson et al.* (*1980*).

It is also possible to set up a threshold in order to test the thickness of the flow at a certain point of interest, but in the example presented here we look only into the extension of the flows.

A summary of the data used for the selected simulations for our considered eruption sizes is represented in **Table 3** along with the output in form of the runnout distance of the flows from the starting point towards the city of Arequipa.

Table 3. ***Summary of the parameters used in TITAN2D simulations***

	INPUT				OUTPUT
Eruption type	**Volume** (m^3)	**Initial Velocity** (*m/s*)	*Internal Friction Angle* (^{0})	*Bed Friction Angle* (^{0})	**Distance traveled towards the city** (*Km*)*
VULCANIAN	$\sim 10^7$	*98.8*	*35*	*22*	*~ 2*
	$\sim 0.6 * 10^7$	*98.8*	*35*	*22*	*~ 2 – 2.5*
SUBPLINIAN	$\sim 5 * 10^7$	*140*	*35*	*14*	*~ 8*
	$\sim 1.4 * 10^8$	*140*	*35*	*14*	*~ 8 – 8.5*
PLINIAN	$\sim 1 * 10^9$	*198*	*35*	*11*	*~ 8.5 – 9*
	$\sim 1.4 * 10^9$	*198*	*35*	*11*	*~ 9 – 15*

*(with red are the distances traveled by the simulated flows towards the city, extracted from output)

5. RESULTS

For the present study we ran simulations for pyroclastic flows occurring from an eruption column collapse at Misti, therefore the simulations present a radial distribution of the PFs around the volcano. The 3 choosen eruptive scenarios i.e. Vulcanian, Subplinian and Plinian, were selected in accordance with the past activity at Misti (section 2, *Thouret* *et al,. 1996, 1999, 2001*). For the purpose of this study we choose to run 2 simulations per scenario in order to see if the distribution of the simulated volumes resembles the distribution of the past deposits described in *Thouret et al.* (2001).

Vulcanian eruption; - the last recorded Vulcanian eruption at Misti was in 1440 – 1470 A.D. We also consider that this type of eruption will be the most likely to occur because of the existing plug in the vent. This eruption produced a volume of < 6 * 106m3 of ash fall. The distribution of the deposits is presented in *Thouret et al.* (*2001*).

Fig. 1 presents the simulation of PFs of ~ 10 ^{7} m3 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 (**Fig. 3**,and *Thouret et al., 2001*) and NW scar. We can assume that less material will flow towards N and NW. This might be due to a higher elevation of the crater rim in that direction and also the distance from the existing vent which is located in the opposite direction to the S E of the crater. Also, PFs are likely to occur towards the SE where there is a notch in the crater rim representing a low resistance point for the flows, and therefore will guide the flows in that direction.

Subplinian eruption: - Several SubPlinian and Plinian episodes in the last 35.000 years produced tephra fall and PDCs flow deposits (*Legros, 2001*). The 2030 – 2050 B.C. SubPlinian / Plinian event, produced pumice – fall deposits as thick as 30cm as far as 13km away from the vent to the SW. From the isopleths it was estimated a height of the eruption column of roughly 21 km. Around 0.7km3 of pumice – flows deposits are channeled in the valleys around Misti and are extended up to the nowadays Arequipa (**Fig. 3**). Giving the 2030 B.C event, we consider 2 simulations with larger volumes - ~ 5 * 10 7 and ~ 1.4 * 10 8 m3. In **Fig. 4** it is shown the extent of simulated PFs of 5 * 107 m3. The same characteristics as for the Vulcanian event are noticeable here too. 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. In case of a SubPlinian eruption, simulation runs show that the flows will reach the boundaries of the city suburbs that are expanding up the three Quebradas - San Lazaro, Huarangal and Agua Salada and upstream the Rio Chili Valley. The ash-cloud surges and/or finer-grained ashfalls related to PDCs may cover the interfluves beyond the river valleys. The SubPlinian flows with a volume of ~ 1.4*108 m3 are consistent with the deposits of the c.2030 yr BP-old (VEI4) eruption (*Thouret et al., 2001; Cobeñas et al., 2011*).

Plinian eruption: - large Plinian eruptions at Misti have a recurrence of about 10.000 years. Based on the identified pumice fall and flow deposits of the large ignimbritic eruptive episodes around 34.000, 25.000 and 14.000 B.C (*Thouret et al., 1999*) we consider 2 simulations with volumes of 109 – 1.4 * 109 m3. Though the pyroclastic flow deposits were not delineated accurately, there are points around and inside the city of Arequipa where flow deposits were identified. Also, thick flow deposits are observed in the canion of Rio Chili (*Thouret et al., 2001*).

In **Fig. 2**, simulation shows that large Plinian events with volumes of ~1 * 10^9 m^3 will produce flows that may advance far into the city of Arequipa. The city center is located about 17 km from El Misti crater. Comparing with the observed pyroclastic-flow deposits we can indicate that the areas covered by PDC deposits, as delineated in the simulation runs, are far more extended than the present-day river channels or valleys. The deposits of the c. 34,000 yr BP eruption (*Thouret et al., 2001*) show that PFs and surges from a Plinian event are likely to extend over these areas..In case of a Plinian eruption, the deposition of the material more than 10^1 cm is consistent with the deposits identified in the existing river valleys and the Quebradas (*Fig. 2A, 2B, 7A, 7B, Thouret et al., 2001*). A large amount of material is deposited in thick layers in the Rio Chili Valley towards the N – W where the simulations show that the flows run up the opposite slope and bounce back. This might be due to the steepness of the volcanic edifice on the N-W slope where it is scared by a possible flank collapse. Such very large event may occur only if a caldera-forming eruption with larger ignimbrites occur, such as the presumed c.40,000-44,000 yr BP eruptive episode (*Thouret et al., 2001*).

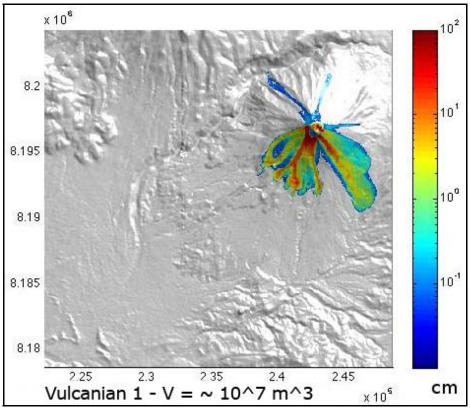

Fig. 1 Simulation 1 for Vulcanian eruption

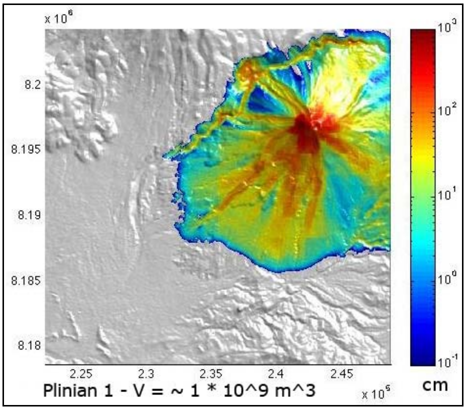

Fig. 2 Simulation 1 for Plinian eruption

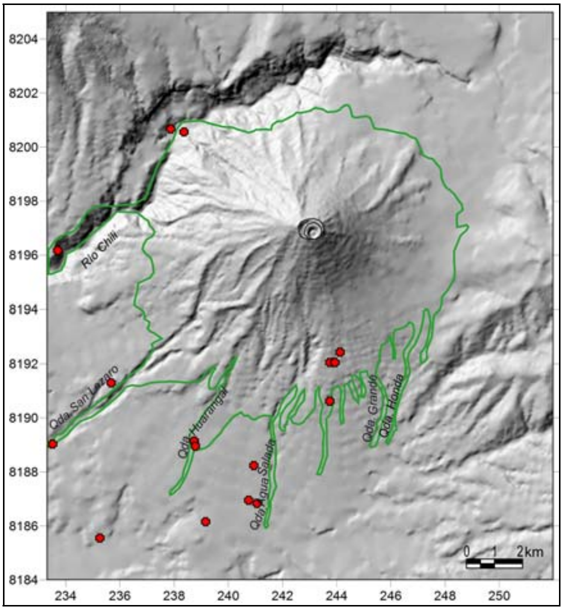

Fig. 3 Map showing the distribution of PF from 2030 B.C. eruption

An important thing to be taken into consideration when we are talking about PDCs in general at Misti, is the H / L ratio. The vertical drop at Misti is high, from the top (5822m) to the city of Arequipa (~2300m) is of ~ 3500 m in about ~ 20km horizontal distance. The H / L ratio for Misti and Arequipa (Fig.12 Thouret et al.1999) varies from 0.1 to 0.24, and this can explain the high mobility of the large volume PFs.

Fig. 1, **2** and **4** show selected results from Titan2D simulations according to the three types of eruption. In general, the results fit the field observations of past PFs deposits and extent, (*Thouret et al., 2001; Thouret, 2007*). In the same time, large volumes used for the Plinian eruptions reach further distances up to 15km towards the city, than the existing deposits 9 – 12 km. For all 3 scenarios it is noticeable the confinement of the flows and the deposition of the material in Quebradas San Lazaro, Huarangal and Agua Salada, as well as in the Rio Chili valley and the steep scar on the northwest flank.

We notice for the Sub-plinian and Plinian scenarios, a wide spread of the thinner deposits (blue, light-blue color) of 10-1 – 100 cm . We consider that these deposits are ash-cloud surges associated to PFs that cover the interfluves beyond the valley channels. Many thin layers of fine ash are observed in stratigraphic sections and may be related to ash-laden surges or ashfall deposits deposited from the flows (*Thouret et al., 2001*). These deposits might have been eroded away on large areas giving the elapsed time ~ 14.000 years since the last large Plinian eruption.

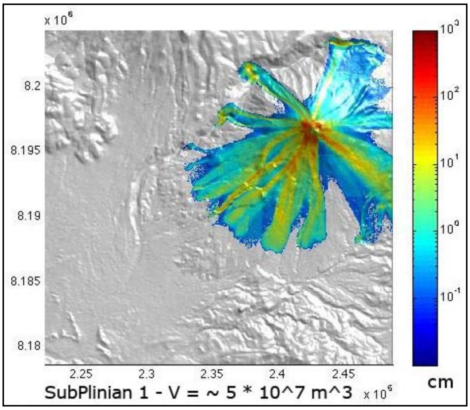

Fig. 4 Simulation 1 for SubPlinian eruption

6. CONCLUSIONS AND FINAL REMARKS

Pyroclastic density currents are among the most dangerous and destructive volcanic phenomena. Among geological studies and laboratory experiments, computer modeling can be a good assisting tool that can help to improve the PDC hazard zonation. The numerical and computer models discussed here – Energy Cone, Flow2D, Flow3D, Volcflow, Pyroflow, PDAC2D, LaharZ and Titan2D – were created in order to provide a better understanding of PDC behavior. Based on different assumptions each of these models tries to solve for different aspects of the PDCs. If the simple energy cone model is giving a quick idea of the possible run out distance of a flow, the more complex PDCA2D models tries also to give us insights about the dynamic of the PDC as a complex multiphase mixture. Regardless their assumptions, each of the above mentioned models were applied for several volcanoes and offered good results. The Titan2D application described here shows us how we can find the field extension of PFs at Misti giving an eruption of Vulcanian, Subplinian and Plinian types. Even if the Titan2D output is not representing completely the field deposits, we can still see an approximate image. The confinement of the simulated PFs in the existing valleys and river channels and the run out distances traveled are representing the field deposits. One of the purposes of using computer modeling, in our case Titan2D, is to see what you can expect from a future event at Misti. In order to achieve this, a complete database of the volumes and distribution of past PFs according to specific events, together with a higher – resolution DEM and a large number of simulations with randomly sorting the basal friction angle will help in the calibration of the model with the field conditions. Once the model is calibrated with a well known event, simulations can be carried out in order to improve the PFs hazard zonation at Misti.

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