HISTORICAL ANALYSIS AND STRATIGRAPHY OF THE POST-XII CENTURY PYROCLASTIC ACTIVITY AT COTOPAXI VOLCANO, ECUADOR. IMPLICATION FOR LAHAR HAZARD ASSESSMENT

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INTRODUCTION

Cotopaxi volcano is one of the largest and highest active volcanoes in the world. Its perfect, ice capped cone reaches an elevation of 5897 m and it is considered one of the principal eruptive centers of the Ecuadorian Eastern Cordillera, the mountain chain that forms the eastern border of the InterAndean Valley. Cotopaxi is a young stratovolcano worldwide known also for its capability to produce very dangerous debris flows (Barberi *et al.*, 1992). The volcano is located about 60 km south of Quito, capital of the Republic of Ecuador, and is surrounded by several villages and country's rural infrastructures.

The history of the volcano involves six principal eruptive periods beginning about ~ 0.5 Ma; since the arrival of the Spanish conquistadores in 1534, Cotopaxi has experienced about 13 important eruptions (VEI 3-4), based upon tephrostratigraphy and historic accounts, corresponding to 5 main eruptive cycles all of andesitic activity (Hall & Mothes, 2007).

During the past centuries volcanic eruptions and concurrent rapid snow/ice melting have resulted in large debris flows (lahars) which have caused major devastations to the settlements around the volcano and traveled downstream for hundreds of km from the source. As a result of historical activity, lahar hazard assessment is a major focus of volcanic hazard work in Ecuador, as it represents the basis for effective mitigation actions in the field of both civil protection and land-use planning. In this work tephra fallout architecture over the period XII century to present was reconstructed: 21 main tephra beds were identified in the field and described from physical and chemical points of view. Tephra deposits were furthermore characterized with volume and column height calculations.

A detailed mapping of the lahar deposits was also conducted, aimed at assessing the relative scale of different debris flow events, based on thickness, maximum block size and extension of the deposits. Precise and unequivocal identification and chronostratigraphic attribution of different lahars was made, within a radius of 25 km from the volcano, by identifying and tracing fallout beds interlayered with the lahar units. Stratigraphy of tephra was used as a tool to unravel lahar deposit complexity by using a multifaceted field approach of linking tephra, pyroclastic flow and lahar deposits.

The socio-economic impact of future eruptions will be considerably more serious since the population and the number of infrastructures continue to spread into the high risk zones of this volcano, particularly within the areas of tephra fallout and lahar channels. In the present day, about 100,000 people live in the lahar flow path of the last eruption, that of the 1877, and are potentially threatened by future Cotopaxi lahars (Mothes *et al.*; 2004; Mothes, 2006). This fact qualifies Cotopaxi as one of the most dangerous volcanoes of the Americas.

STRATIGRAPHY OF TEPHRA

A regional stratigraphic marker (1150 AD ash layer from Quilotoa volcano) has been chosen as the base of the studied period. The stratigraphic reconstruction of the past-XII century was assessed examining more than 450 stratigraphic sites and a total of 21 main tephra beds were recognized around the volcano, divided in two main periods separated by a major stratigraphic unconformity (Fig. 1). Each tephra layer has been characterized with the main physical-volcanological parameters (grain-size, dispersal, volume, column height and geochemistry).

Two tephra layers (X_C and X_W) are below the unconformity and are separated by soil interposition; X_C in particular has features fully compatible with a blast deposit.

After a period of intense erosion, activity resumed with two plinian fallout (M_B and M_W) with associated scoria flow events. M_W has a series of three main pulses and, in proximal area, the deposit shows clear evidences of surge intercalations. A long-lasting black ash emission followed (N_V) and the following activity is represented by three main tephra layers (N_D, N_L and N_E); the first and the last one are associated with scoria flow deposits. Layer N_D, in particular, is formed by two main tephra beds (N_{DC} and N_{DF}) separated by a reddish ash layer. Layer N_E is the last significant event and the recent activity is represented only by three thin ash layers.

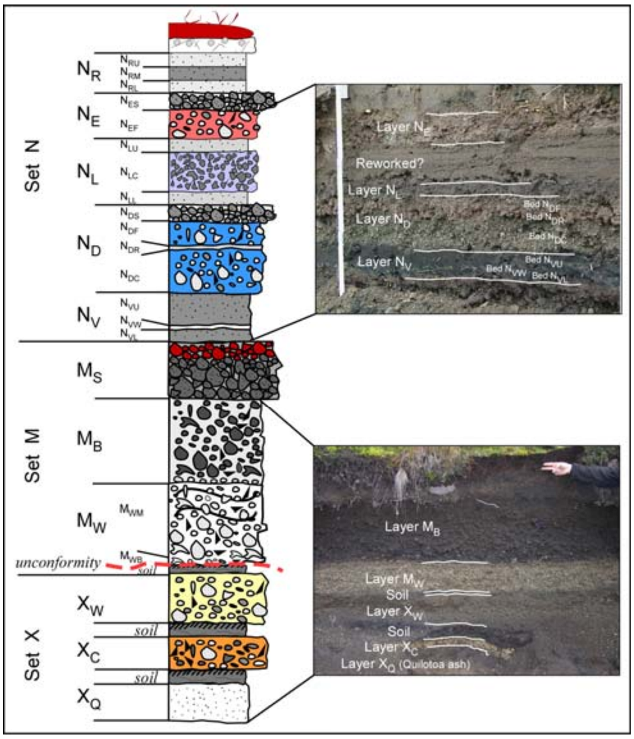

Fig. 1 - Reconstructed stratigraphic column of post-XII century Cotopaxi eruptive history. The column corresponds to the tephra fallout sequence that can be observed in the southern sector although more recent layers are better exposed on the opposite side (upper right picture). Scoria flow deposits are included in this stratigraphic reconstruction but they are visible only in specific areas around the volcano.

Juvenile material is composed by pumice clasts from light yellow to dark green or black in color. Fragments have high vesicularity and only in some cases denser, low-vesicular crystal-rich clasts are present. Total volumes of 6 main layers have been calculated according to Pyle (1989) since obtained thicknesses versus the square roots of isopach area plots fit in our case a single exponential decay law and yielded values comprised between 0.14 and 0.01 km^3. Chemical analyses (both major and trace elements) mark a quite uniform chemistry with narrow compositional range, varying from basaltic andesite to andesite. Geochemistry highlights that Cotopaxi samples have clear characteristic features of adakites-like products.

As a whole, Cotopaxi volcano experienced two main eruptive cycles after Quilotoa ash deposition: the first period has been characterized by two mid-scale events. After a period of repose and strong erosive events, activity resumed with the two more powerful explosive eruptions of the investigated period which are related to main scoria flow events. After that, activity went on with the same style but with minor intensity towards the last explosive event. In this period too tephra layers are related to scoria flow deposits. The two main eruptive cycles are nevertheless not separated by any change in major or trace elements chemistry, apart from e higher degree of evolution of layer X_C, which is compatible with the general decreasing trend of SiO_2 content started from the older sequence (see layer 3 in Barberi *et al.*, 1995) towards the last period.

Column heights yielded values comprised between 17 and 36 km. Layer M_B represents the higher intensity event of the post-XII century activity of Cotopaxi with a column height ranging from 25 to 36 km (considering five different methods) followed by layer M_W (19 to 32 km) which has similar dispersal and magnitude but smaller clasts (smaller intensity).

LAHAR DEPOSITS

The use of tephrostratigraphy was intended in this work as a tool to assess stratigraphic correlations of lahar deposits and also to establish the temporal link of lahar episodes to eruptive events. Tephra layers were used in two main settings: in a plain at the base of the northern sector of the cone, where mapping of debris flow was carried out, fallout beds allowed the discrimination of lahar units on the basis of the tephra sequence blanketing each lahar unit. Hand-dug pits were used to assess the tephra stratigraphy and build up a general scheme of debris flow deposits. It was possible to assess that N_1 and N_2 lahar deposits are by far the most widespread, covering major part of the plain. Also in terms of block sizes, N_1 and N_2 lahars show the largest blocks indicating a large carrying capacity of the flow respect to younger lahars (*e.g.*, N_3 deposits). It was not possible to establish a precise comparison with M series lahars because they crop out only in small areas and are almost completely covered by N_1 and N_2 debris flows. Where observed, the M series deposits show similar features of N_1 and N_2 lahar deposits. In some cases an alternation or a progressive transition from scoria flows to lahar deposits were observed, probably due to continuous incorporation of water.

The main limitation encountered in this area was the lack of deep vertical cuts and the use of tephra beds blanketing lahar deposits only allowed the assessment of a "minimum age" of lahar deposits.

We had the opportunity of avoiding this limitation and analyzing complete lahar sequence in active quarries located 15 km W from the vent. In the quarries tephra layers are extremely well preserved (even for thickness of 1-2 cm). Preservation of tephra beds was excellent in lateral banks of the main channel, where flows overbanked and started deposition; along drainage axis, tephra beds are not always preserved and interpretation of the lahar stratigraphy become more difficult.

Lateral banks observations gave us the possibility of assigning precise age to lahar deposits using the tephrostratigraphic scheme reconstructed around the cone and furthermore develop a tool to assess the relative scale of lahar deposits (Fig. 2). From this point of view it was possible to establish that:

1) all debris flow episodes are related to eruptive events. Only X_2 lahar unit (which ranks as a very large lahar) is comprised in the quarry between a soil and a reworked layer; we did not find around the cone any other tephra layer with different dispersal at that stratigraphic height possibly related with X_2 lahar event;

2) each fallout deposit is sealed by stream sediment deposits eventually accumulated during the elapsed time between time-separated eruptions;

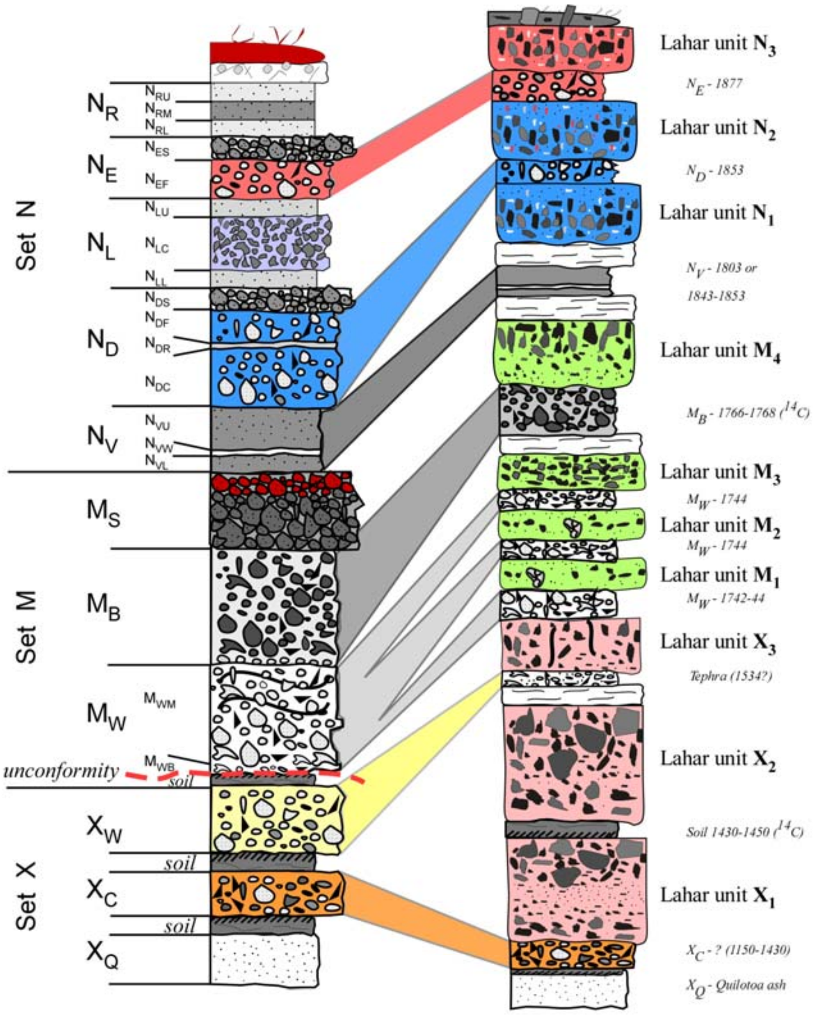

Fig. 2 - Stratigraphic correlations between the composite tephra sequence (Fig. 1) and the stratigraphic column of deposits (lahars and tephra fallout layers) idealized from observations carried out in the quarries. Almost the entire group of tephra layers was recognized in the quarries with the relative associated lahar units.

3) layer M_W is subdivided into 3 sub-layers with the interposition of possibly syn-eruptive debris flows. This could be due to intra-eruptive lahar generation or to the formation of layer M_W as the result of events that were distinct in time. The lack of stream sediments, however, suggests the first hypothesis as the most likely;

4) N_1 and N_2 lahars are present both at the bottom and at the top of N_D tephra layer: this could be due to the absence of bed N_{DC} in this area and in accordance with the presence of two main lahar units as found in the northern mapping. The nature of the matrix is in agreement with the same deposit observed in the Limpiopungo plain and the presence of scoria bombs is a clear evidence of the close relationship between scoria flows and lahar events. A progressive transition from scoria flow deposits to lahar deposits was also observed in the plain: this phenomenon could be exasperated in the quarries, where only some scoria bombs are present;

5) N_3 lahar is present only in quarry 1: deposits are smaller in terms of thickness, transported blocks and areal distribution, in agreement with what observed in the northern side, where they did not cover entirely older deposits. Deposits show significant lateral variations: near the valley centre, flows deposited coarser material and big boulders, grading towards the lateral bank in matrix-rich with few blocks, poorly stratified facies.

In the post-unconformity period, debris flow events were strictly related to scoria flow activity (Fig. 3), as also described in historical chronicles: each lahar deposit is related in the quarries to a tephra unit, and each tephra unit has around the cone its corresponding scoria flow deposit. Lahar deposits of the pre-unconformity period (X_1, X_2 and X_3) are greater events respect to the younger post-unconformity lahars; X_1 and X_3 were associated to X_C and X_W tephra layers but around the volcano were not identified related scoria flow deposits. This could be due to burial of older scoria flows although a different generation mechanism for lahars (*e.g.*, directly from fallout material on the glacier) cannot be excluded.

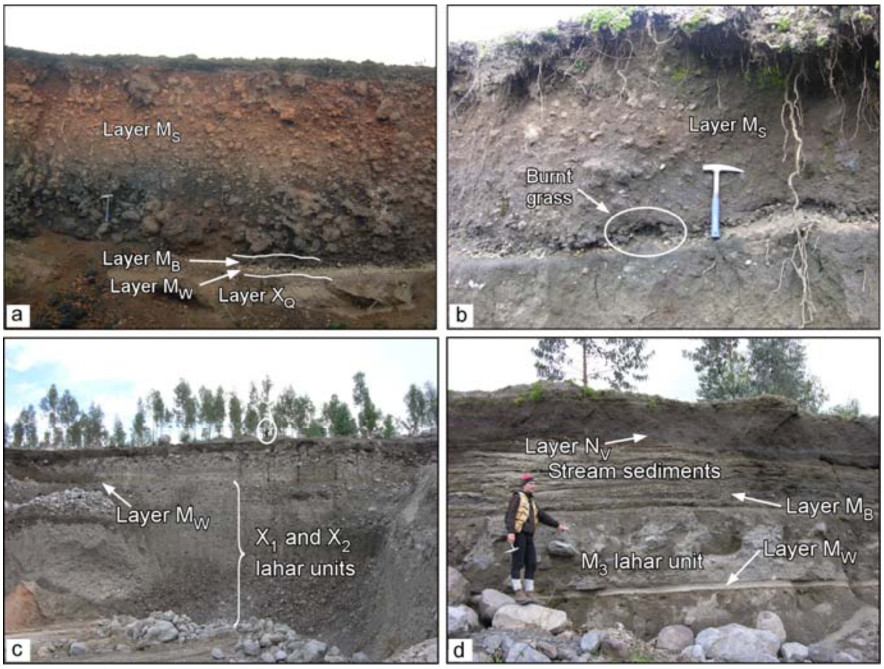

Fig. 3 - (a) M_B-related scoria flow deposit with the oxidized upper part; (b) burned grass found at the base of layer M_S used for ^{14}C dating; (c) X_1 and X_2 lahar deposits between Quilotoa ash and the stratigraphic unconformity (man for scale in the circle); (d) layer M_W, M_B and N_V with intercalated M_3 lahar deposit and stream sediments.

AGE ASSIGNMENTS

Two ^{14}C datings were performed using burned grass found at the base of the scoria flow M_S, the only tephra deposit where suitable charcoal was found. An additional ^{14}C dating has been performed on the soil sampled in a quarry site between the two lahar units. Starting from these ^{14}C results, coupled with other layers of certain age (Quilotoa ash and the last event occurred in 1877) we have assigned other tephra layers to historic events by comparing deposit features with eruptive sequences, dispersion, material size and thickness of pristine deposits given in the chronicles.

We were able to assign an absolute age to tephra units by:

1) identifying in the field all tephra layers mentioned in the chronicles;

2) matching chronicles descriptions with deposit features (eruptive sequences, dispersion, material size and thickness of pristine deposits given in the chronicles);

3) performing two radiocarbon datings on charred material found at the base of M_S scoria flow deposits sampled in the northern side of the volcano.

Thanks to the particular location of the quarry sites (along one of the main drainage systems of the volcano and close enough to the volcano to have fallout deposits interfingered with the lahars), we could successfully identify lahar units and constrain their age on the basis of tephro-chronology. Each lahar unit was related to the generating explosive event which was represented by the fallout layer preserved at the base of the debris flow itself.

The additional ^{14}C dating was performed on a soil sampled in the quarries between X_1 and X_2 lahar units to constrain more precisely lahar age assignment with tephra age and the result was consistent with our reconstruction. Also lahar deposits were matched, when available, with historical descriptions.

A general chronostratigraphic reconstruction both for tephra and lahar deposits is presented with few uncertainties.

CONCLUSIONS

This work has investigated the post-XII century eruptive and lahar activity of Cotopaxi volcano.

In particular the work focused on the period between 1150 to present carrying out the following investigations:

i) detailed revision of historical chronicles and also using new, previously unknown, documents recovered in archives in Ecuador;

ii) precise and extensive field study of tephra deposits post-dating the 1150 AD ash bed produced by the Quilotoa volcano;

iii) field study of lahar deposits in two separated areas (in active gravel-quarries of Río Cutuchi and in the Limpiopungo plain, located in the northern sector).

Tephra stratigraphy was crucial to the chronological study of lahars deposits. The comparison of lahar deposit features observed in different valleys and topographic contexts were fundamental to constrain scale and dynamics of past debris flows.

After the general reconstruction of tephra and lahar deposits stratigraphy, the following step consisted in the assigning of an absolute age to each unit. Since in quarry sites most of lahar deposits were related to a tephra bed, we could assess lahar chronology on the basis of tephra age.

To actually do this, we first carried out a match between historical information regarding eruptive events by using all data from the chronicles (type and size of pyroclasts, dispersion, volumes). The reconstructed chronology of both tephra and lahar deposits compared well with available historical information regarding lahar events which could match with our observations on debris flows. Three ^{14}C datings were also performed using burned grass found at the base of a scoria flow and on a soil sampled in the quarry between the two oldest lahar units.

The first period of activity of the volcano after the Quilotoa ash emplacement was characterized by mid-level activity marked by time-separated small eruptions. After a period of intense erosion, activity resumed with two eruptions with associated surge and scoria flow events. The 1742-44 activity consisted in the formation of repeated plinian events in a close time period. A long-lasting black ash emission followed. Activity resumed by mid-XIX century producing a series of explosive events which emplaced three thin tephra beds (N_D, N_L and N_E); the first and the last one are associated with scoria flow deposits. Layer N_D, in particular, is formed by two main tephra beds (N_{DC} and N_{DF}) separated by a reddish ash layer (N_{DR}). Layers N_D and N_L should be related to the 1853 activity, in particular based on the associated lahar scale and scoria flow generation. N_D-associated scoria flows show multiple pulses and are present at the top of both layers N_{DC} and N_{DF}. They were encountered both on the northern and on the southern side of the volcano and they have probably the widest areal extent respect to all the other observed scoria flow deposits.

Layer N_E is the last significant event and the following activity is represented only by three thin ash layers. As stated in the historical review, the 1877 event is described very precisely both for eruption sequence and lahar features. In our reconstruction the suitable candidate is layer N_E in terms of dispersion, material nature, lahars and scoria flow characteristics.

The flowage of gas-rich, pyroclastic mixtures (pyroclastic flows and surges) on the iced-cap is described in the historical chronicles as the triggering mechanism for Cotopaxi's lahars (Sodiro, 1877; Wolf, 1878). In the field, lahar deposits were recognized to be tightly linked to explosive events accompanied by either scoria flow or surge generation although for older lahars (X_1, X_2 and X_3) correspondent scoria flow or surge deposits were not identified. This could be the result of burial or erosion of deposits although penecontemporaneity with tephra fallout on the glacier cannot be excluded. Evidences of interaction of scoria flows with the glacier are the occurrence of quenched rims of the scoria clasts and radial jointing on large juvenile clasts (bombs).

Previous assessment of the lahar impact scenario along the valleys of Río Pita and Río Cutuchi was accomplished using numerical models and assuming as maximum, probable expected scenario an event similar to that of 1877 (Barberi *et al.*, 1992; Mothes *et al.*, 1998, 2004; Pareschi *et al.*, 2004). The assumption roots on the fact that the release of water during this event was believed to have maximized by the effective interaction of pyroclastic flow with the glacier and also considering that the present ice cap extension is significantly reduced as compared to that of the second half of XIX century (Cáceres, 2005; IRD, 2004; Jordan, 1983). However, the strength of this assumption is far from being demonstrated, as mechanism of catastrophic release of water is possibly linked to a larger number of factors than the area covered by snow and ice. On the other hand it is obvious that the choice of proper parameters (namely peak discharge and/or volume) is crucial because their possible underestimation could broaden areas exposed to hazard and thus to a possible life loss toll of unimaginable proportions. The choice of the 1877 event as maximum expected scenario derived basically from the assumption that the magnitude of past and next lahars depend on the total volume of the glacier. This is in turn based on the interpretation of Wolf (1878) observations made by some works (*e.g.*, Mothes *et al.*, 2004; Pareschi *et al.*, 2004) which concluded that the glacier tongues encountered an overall destruction. Little can be said, however, about the 18th Century glaciers, as basically no one measured their altitude on the volcano, nor hardly made mention of them with respect to their extent. As everywhere in the Andes, glaciers are making a fast retreat, and from 1976 to 1997 the glacier cap's area on Cotopaxi shrunk by some 30% (Mothes *et al.*, 2004).

The hypotheses of the 1877 event as the maximum expected event derived basically from the assumption that the magnitude of past and next lahars depend on the total volume of the glacier. It is evident however from our historical chronicles revision that only a part of the ice coverage was melted during the last eruption; although a fast retreat of the ice during the last centuries, future eruptions could therefore generate lahar with equal or higher volumes if compared to the 1877 event, although the 1/3 shrinkage of the glacier in the last decades. The type of interaction of pyroclastic material with the glacier during the explosive event (*e.g.*, scoria flows *vs.* surges) can lead to different mechanisms of water release and seems to have a control on final lahar volume and deposit characteristics (*e.g.*, ash/blocks ratio) more incisive than the total extension of the glacier at the moment of the eruption. The physics of this phenomenon are obscure; flume studies in which pyroclasts flow over snow (Walder, 1992, 2000) are hard to interpret owing to the interplay of mechanical and thermal processes.

The retreat of the glacier can be considered a main factor for future lahar scale generation but, contrary to assumptions of previous works, it cannot allow as a direct consequence the reduction of the maximum expected event. If we consider the scale of debris flows in the time period investigated we conclude that the 1877 lahar is not an upper limit for this type of event: lahars comprise between 1150 and 1853 are probably one order of magnitude higher than 1877 debris flows. On the basis of stratigraphic reconstructions, we suggest that, although a general retreat of the ice cap, hazard assessment should not be scaled on an 1877-type event, but should also take into account the possibility of a more powerful, lahar-generating eruption. Inhabited areas of Latacunga and Los Chillos Valley could be seriously affected with the occurrence of events similar in scale to those after 1200.

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