Cartographic Production (1998 - 2006) of the Popocatépetl Volcano and the Ventorillo Glacier for the Analysis of Hydrovolcanic Risks

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Abstract

The Popocatépetl volcano is situated in the middle of the Transmexican Volcanic mountain range, at less than 80 km between the centre of Mexico city and the city of Puebla. This is elevated from 4,000 m forming a considerably regular cone of some 13 km in diameter at its base.

The cartographic projects realized on the Popocatépetl volcano (crater and Ventorillo glacier) has an objective of contributing to the methodology and the techniques necessary to perform an effective monitoring of the volcano and the possible risks of catastrophes provoked by lahars. The last active volcanic period began December 21, 1994, and is currently still going on.

In the period 1998 - 2003, restorations with stereoplotter were made at a scale of 1/5,000 (equidistance of 10 m) of the volcanic cone. For this, the flights made by “Secretaría de Comunicación y Transportes (SCT)” in December 1998, June 1999, June 2002, December 2002 and February 2003 were used. In addition, cartography with a scale of 1/20,000 was obtained of the area surrounding the volcano.

The cartography was produced using the “SD-2000” analytical stereoplotter. With the obtaining of the different temporal cartography, both the evolution of the internal dome of the crater and the loss of volume of the Ventorillo glacier can be observed.

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KEY WORDS: Popocatépetl volcano, Ventorillo glacier, cartography, photogrammetry, hydrovolcanic risks

1. Introduction and geographical setting

The Popocatépetl volcano (19°02'N, 98°62'W; 5,424 m) is located in the center of the Trans Mexican Volcanic Range, at less than 80 km from the center of Mexico City to the west, and the city of Puebla to the east (Fig. 1). The volcano begins at an elevation of 4,000 m, forming a considerably regular cone, of some 13 km in diameter at its base and whose origin can be traced to a series of eruptions that occurred before the year 800 D.C. This cone has hidden previous edifices, of which only a few rock buttresses remain, such as "El pico del Fraile" (5,000 m), and the remains of another previous cone destroyed 5000 - 3500 years ago. The arrival of the Spanish in Mexico coincides with a period of great eruptive activity from the volcano, with emissions of ash and lava, which lasted for the entire period of the 16th century. Afterwards, the volcano reactivated in the middle of the 17th century and the first part of the 18th century. After a century of total calm, the activity reappeared for a short period of time from 1919 to 1927. Once again, the activity began again on the 21st of December 1994 and continues to be active at the present time. The most characteristic eruptive process has been the formation of lava domes in the interior of the crater, its gradual growth and its posterior destruction from explosive activity, with the consequential pyroclastic emissions.

Figure 1: Geographic location of the Popocatépetl volcano with respect to Mexico City and Puebla.

The new eruptive period, initiated in December 1994, has very negatively influenced the extension of the glacier located in the north slope of the volcano (Fig. 2). The pyroclastic emissions have covered the glacier and have brought about its reduced the "albedo". As a consequence of this, massive fusions have developed in a very short period of time. Large quantities of water descended to the proglacier ravines, which were blocked by volcanic ash, moraine and slope deposits, and remains of large avalanches. This sediment, mixed with water, formed debris flows with a great great capacity for transport and range. These debris flows, generated by volcanic activity, are called lahars. In April 1995, lahars of this type descended more than 6 km, transporting boulders of up to 1 m in diameter (Palacios et al. 1998). In July 1997, lahars of great proportion occurred in the proglacier gorges of Tenenepanco, La Espinera and Tepeteloncocone, until they converged into one single flow in the Huiloac ravine (Palacios et al. 2001). These lahars were capable of transporting boulders of more than 2 m in diameter a distance of greater than 17 km, where they reached the communities of Santiago Xalitzintla and San Nicolás de los Ranchos. In January 2001 a new lahar originating from a pyroclastic cloud, again traveled through these gorges for more than 12 km (Capra et al. 2004).

These lahars have reached the neighboring communi-

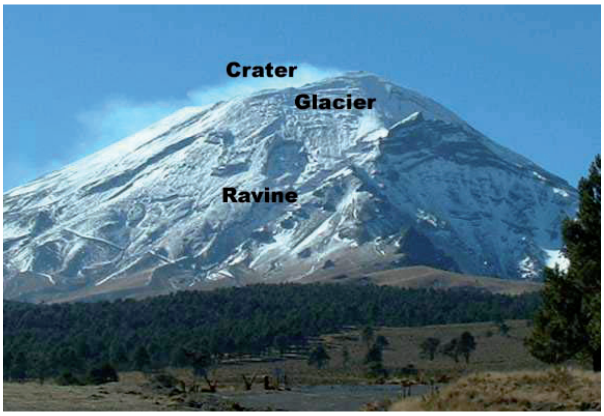

Figure 2: General view of the Popocatépetl volcano, the Ventorrillo glacier and the Huiloac ravine.

ties and have potentially threatened several million inhabitants. For the entire eruptive period it has meant a constant challenge to study the evolution of the interior dome of the crater and predict the maximum possible strength of a probable explosion. On the other hand, another great challenge has been that of calculating the maximum amount of water that, originating from the fusion of the glacier, could be contributed to the slope and provoke the formation of lahars. However, the direct observation and monitoring of the crater and glacier are impossible while the volcanic activity lasts. Access, even for scientific and preventative motives, is absolutely prohibited within a radius of 10 km from the volcano because of the frequency of fallen and pyroclastic flows in this area. In order to resolve this problem, the "Secretary of Communication and Transportation (SCT)" of the Mexican Government makes monthly photographic flights and provides the information gathered to "The National Disaster Prevention Center (CENAPRED)", the local agency responsible for the monitoring and prevention of volcanic risks.

The "LAHAR" project, financed by the Spanish Government (REN2003/06388), has as an objective contributing to the methodology and techniques necessary to carry out an effective monitoring of the volcano and its possible risks of catastrophe provoked by lahars. Given the impossibility of direct access, the treatment of aerial photographs using analytic and digital photogrammetry, is currently considered a rapid and important tool in the observation of the variations or spatial-temporal changes of the surface and thickness of both glaciers and volcanic formations, allowing the evaluation of the risks related to the formation of lahars and other geomorphic processes, as has been demonstrated in recent studies (Julio and Delgado 2003).

In addition to photogrammetric techniques, topographic and geodesic techniques have also been used to significantly improve the interpretation of the morphologic variations of the crater, the glacier and the ravine generated by the fusion of the glacier. In short, with this study our objective is to apply geomatic techniques in the calculation of the morphologic transformations of the volcano and to quantify them. Likewise, we are attempting to discover the precise evolution of the glacier and of the new volcanic formations from the years prior to the existence of lahars. The majority of the techniques presented are well suited for the difficulties of field work pertaining to the high altitude, terrain, volcanic activity and the dangers involved.

2. Methodology

Geomatic techniques (topography, geodesy, photogrammetry, remote sensing,...) are the most commonly used in the observation of the displacement and representation of the variations of relief forms (glaciers, dunes, sliding slopes,...). Depending on the resources available, the techniques that can be used range from the simplest: inclinometers, marker poles, and metric tapes to the modern: reflectorless total stations, GPS, photogrammetric cameras, and laser scanners (Sanjosé et al. 2004a).

Next, each of the geomatic techniques applied in the study and monitoring of the geomorphic variations of the Popocatépetl and their application in the prevention of catastrophe will be analyzed. We will make the greatest reference to the acquisition of maps by means of the use of photogrammetry, for the subsequent acquisition of the volumetric variations of the crater and glacier.

2.1. Topography

In order to carry out the topographic project, the "no hurry" total station TOPCON GTS-701 was used. Topographic projects carried out during the development of the three data collecting campaigns (September 2003, September 2004 and March 2006), have consisted of the following actions:

2.1.1. Topographic survey and profiles of the lower bed of the ravine

When carrying out adequate disaster prevention it is necessary to know how much sedimentation and erosions have occurred on account of the lahars throughout the ravines of the volcano. With this objective in mind, in the 2003 campaign a section of the ravine was selected with a longitude of 550 m. Initially, the system of coordinates was local, since the previous photographs (made before beginning the project) showed thick vegetation over the entire zone of the ravine and we thought that the use of GPS would be impractical (Fig. 3). However, during the following campaign of 2004, we took the opportunity to take points with GPS in highlighted areas discovered near the vegetation and thus transformed the local coordinates of the 2003 campaign into UTM coordinates.

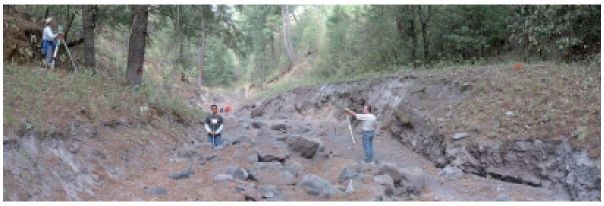

Figure 3: Huiloac ravine originating from the Popocatépetl Volcano and the Ventorrillo Glacier.

The topographic activities in the lower part of the Huiloac Ravine during the year 2003, consisted of (Sanjosé et al. 2004b):

- Topographic survey: More that 25 codes exist (levee, talweg, lahar 1997, terrace, fans, points of terrain,...) for the topographic survey points. The points taken with the "reflectorless" total station have errors in the positions of less than 5 cm, while the points taken with the "reflector" are inferior to 10 cm (they lack prism verticality). Therefore, the general map of the ravine has a scale of 1/500, where approximately 1,700 points have been measured (Fig. 4). In 2006, topographic surveys

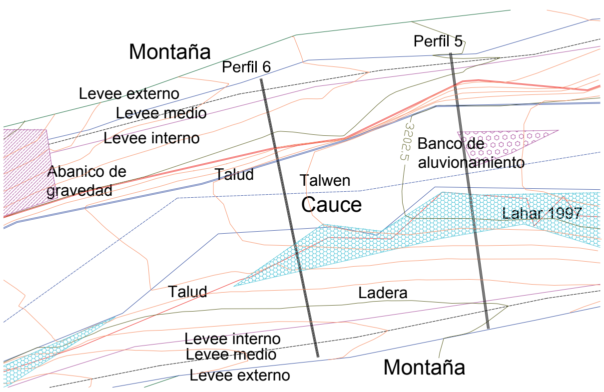

Figure 4: Detail of the topographic survey of the Huiloac ravine at a scale of 1/500.

were carried out in the zones of the ravine where important variations were produced from the measurements taken in 2003.

- Transversal profiles: The limits of 29 transversal profiles were placed starting at the stations of the polygonal. The profiles were captured with "reflectorless" total station in the field campaigns of 2003 and 2006. In this way, it is possible to calculate the volumetric differences produced in the ravine between each observation (Fig. 5).

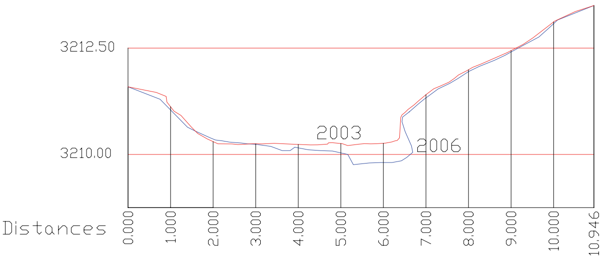

Figure 5: Profile comparison 10 of the 2003 and 2006 campaigns.

2.1.2. Topographic survey and profiles of the source of the ravine

In hydrovolcanic risk prevention it is also important to know the volume of sediments towed by the lahars throughout the eruptive period. With this purpose, profiles of the source of the ravine were taken during the 2004 and 2006 campaign. In addition, in the 2006 campaign a topographic survey was done on the source of the ravine (under the glacier) (Fig. 6). For this project UTM coordinates that were previously calculated using GPS techniques were employed.

With this topographic survey, the goal was to obtain the volume of material (volcanic ash, pyroclastic,...) that has been transported by the lahars to the lower ravine zone. In order to determine the volume, two maps are needed. One is the field measurement made during the 2006 campaign (Fig. 6) and the other is obtained by joining the points of the sources of the slope (maps made before the sliding). Through the comparison of the two maps it was possible to obtain a volume of 26,500 cubic meters.

2.2. Global Positioning System

GPS was employed to obtain global coordinates in the system UTM (NAD27); this is the system which is contained in the National Map of Mexico (INEGI 2000). The methodology employed was the differential positioning in static mode by difference of phase in post processing and RTK.

2.2.1. Photogrammetric control points

The volcanic activity of the Popocatépetl volcano (ash accumulation, snow, landslides, lava emissions, lahar formations,...) make it very difficult to identify common points in the different photographic flights taken from the year 1998 to the present. For this reason, the control points were taken on the periphery of the volcano from elements that had remained invariable, primarily abandoned edifices.

2.2.2. Georeferentialization of the topographic survey and profiles

From the points highlighted with GPS, coordinates have been taken of the points that form the topographic and profile basis used in the upper and lower parts of the Huiloac Ravine.

2.3. Photogrammetry

Applying the "general photogrammetry method" it is possible to obtain three-dimensional information from bidimensional imagines with covering. In order for the map acquired from photogrammetric restoration to have the adequate quality the following should be used (Sanjosé and Serrano 2002):

- Photogrammetric Camera (aerial or land).

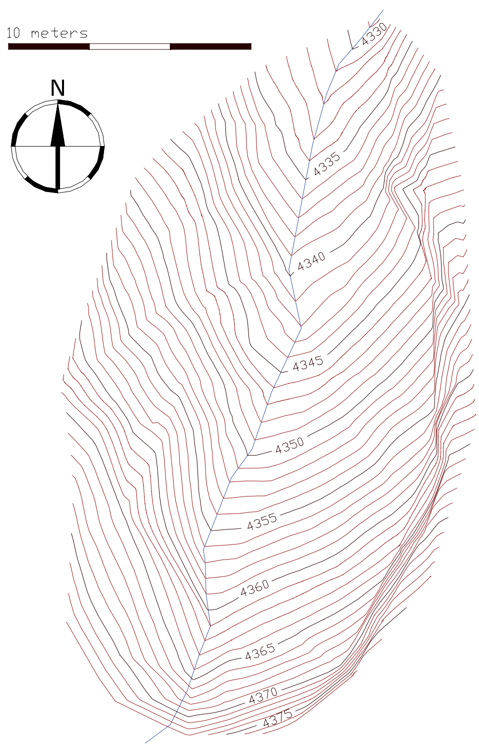

Figure 6: Detail of the sliding of the upper ravine and the topographic survey.

- Photographs with contrast, avoiding shadows, clouds, smoke,...
- Photogrammetric scanner for the use of digital photogrammetry.
- State of the art analytic restorer or a digital restorer.
- Geometric conditions of the photographic shots (base-distance relationship, coverings, scale,...).
- High quality field equipment.

The following should be taken into account for the production of the map of the glacier and the crater of the Popocatépetl volcano in different periods (1998 - 2003) using photogrammetric techniques:

- Aerial photographs in which there exists the problem of smoke expulsed from the volcano in a way that it makes the restoration difficult in some areas.
- The summit of the volcano is found at 5,400 m and the front of the glacier is at 4,500 m, which provokes different scales of flight for the same map. In addition, each photogrammetric flight has a different scale because of the difference in altitude of the airplane.
- Because of the inaccessibility of the zone there are no "control points" available. The solution was to resort to an old map (1982) with a scale of 1/10,000 from which the reference points were taken.
- For the digital restoration the photographs were scanned at 21 micras with the Vexcel 5000 scanner.
- The map was produced in the first rate analytic restorer "SD-2000" and in the "Photopol" digital restorer.

The absolute orientation in the "general photogrammetric process" was less than 2 m, in each flight, while the control points obtained in the map at a scale of 1/10,000; possibly have greater errors (5 m). However, because the same control points have always been used for all the restorations, the relative error in comparing the different campaigns is that which was obtained in the absolute orientation.

2.3.1. General map of the study area

The current map of the entire surrounding area is that which was made by INEGI at a scale of 1/50,000. For this project, a map has been produced with a scale of 1/20,000; equidistance of the level curves of 20 m, and in UTM coordinates (Fig. 7).

2.3.2. Detailed restorations of the crater and the glacier

Photogrammetric flights of the Popocatépetl volcano provided by CENAPRED were used for the production of detailed maps of the crater and the glacier. In some flights made for the acquisition of the map, serious problems exist that are caused by the recent snow fall or by the fumaroles of the volcano dome. The dates of these flights are: December 1998, June 1999, June 2002, December 2002 and February 2003.

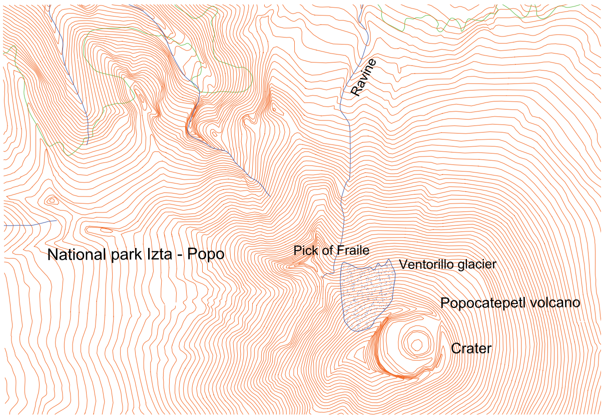

Figure 7: Map at a scale of 1/20,000 (equidistance of 20 m).

The objective of the different restorations was to analyze the evolution of the size and volume of the internal dome of the crater and the glacier (Fig. 8), (Fig. 9). For this, once each flight was restored at a scale of 1/5,000 and an equidistance of 10 m, the volumetric variation was calculated with the TCP-IT topographic design program and the INROADS program. In addition, the variations were calculated with a Geographic Information System (ARC-GIS). In addition, we used the ArcGis-Arcinfo „cut/fill" command to calculate the differences in volume between the two layers in raster format.

The techniques employed with the TCP-IT program were:

- Grids of level curves: The volumes of leveling and embankment were calculated from the two drawings (CAD) generated by their level curves. These grids have the same origin and each cell of the grid has 4 meters of side. Both grids are superimposed, and for each cell the average altitude in each drawing is calculated. Later they are subtracted, with which the volume is obtained.
- Digital model grid: The volume is determined using the difference between the two grids that originated from the generation of the Digital Terrain Model (DTM). A series of triangular prismatiodes are obtained, the program calculates the average altitudes of the lower and higher faces of each model. The difference between the altitudes of the prismatiodes multiplied by the base of the triangle determines the volume.
- Difference of the transversal profiles: The volume is obtained from the comparison of the same transversal profiles through an axis in the two models that are to be compared. This technique was employed in the direction north-south and west-east.

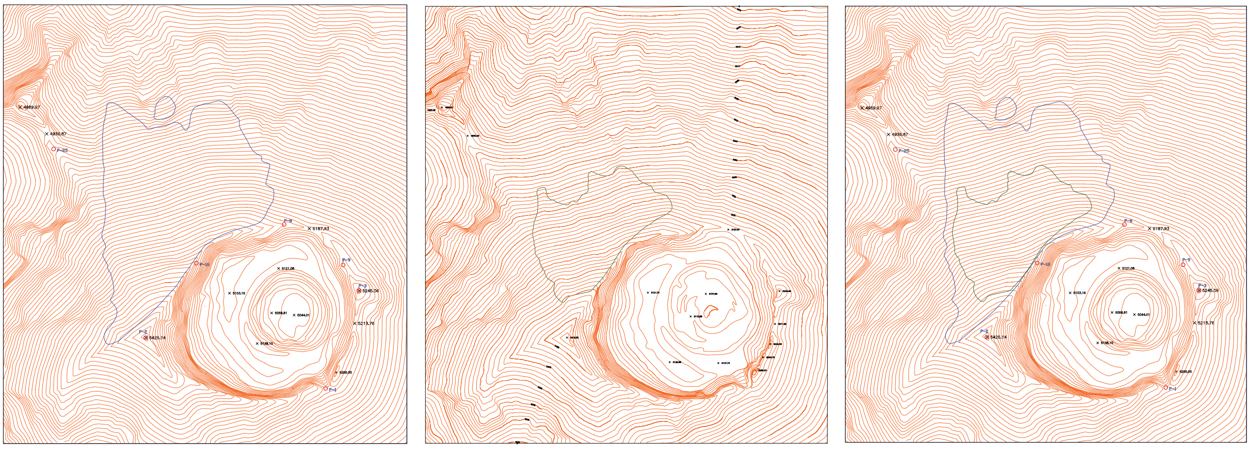

Figure 8: Map at a scale of 1/5,000 (June 1999) and (June 2002) and comparison of the loss of frozen glacier mass.

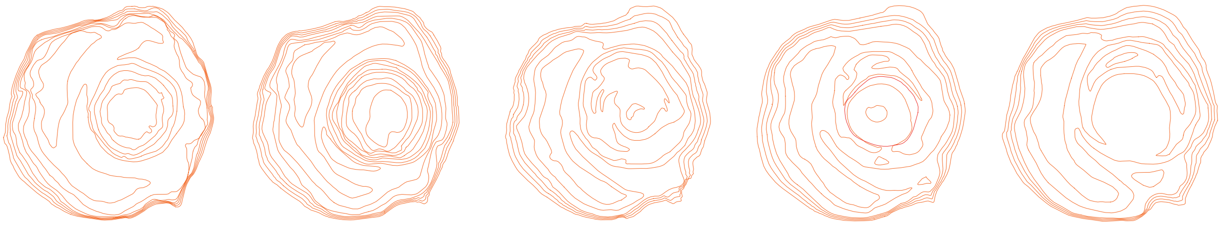

Figure 9: Restorations of the crater dome, from the level curve of 5,180 par the flights: December 1998, June 1999, June 2002, December 2002 and February 2003.

3. Results of the photogrammetric restoration

It should be noted that the results shown for each one of the previous techniques (TCP-IT, INROADS, ARC-GIS) are very similar.

By analyzing the tables and the previous graphics the influence of the volcanic activity on the behavior of the glacier is evident. For example, the most significant loss of glacier volume is produced between June 1999 and June 2002, which is possibly provoked by the lahar with a pyroclastic cloud that originated in January 2001.

The volumetric results for both the crater and the glacier are shown (Tab. 1 and 2):

4. Conclusions

As expected, it has been demonstrated with this project that the application of geomatic techniques are efficient in the acquisition of data on the geomorphologic variations that a volcano develops during its eruptive periods. For the topographic survey at a scale of 1/500 of the sectors of the Huiloac ravine and the production of profiles between the years of 2003 and 2006 allow us to calculate the quantity of sediments transported by the lahars and the erosive capacity of the posterior flows. This data is essential in developing numeric models that allow the mathematical simulation of the maximum possible flows and demarcate their flood areas.

Crater (m3) + : Win - : Lost	Grid TCP	Triangulation TCP	Profiles TCP	Triangulation INROADS	Triangulation ARC-GIS
December 1998 - June 1999	No dates	No dates	-341.790	-347.230	-363.931
June 1999 - June 2002	5.725.819	No dates	5.559.114	5.538.371	5.501.503
June 2002 - December 2002	No dates	275.022	258.660	269.632	279.100
December 2002 - Febrary 2003	No dates	456.791	424.376	423.723	418.166

Table 1: Variation of the volume of the crater dome.

Glacier (m3) + : Win - : Lost	Grid TCP	Triangulation TCP	Profiles TCP	Triangulation INROADS	Triangulation ARC-GIS
December 1998 - June 1999	-1.106.743	-1.094.502	-886.212	-1.129.541	-1.019.229
June 1999 - June 2002	-1.241.005	-1.310.753	-1.149.306	-1.261.909	-1.283.353
June 2002 - December 2002	-229.547	-229.992	-172.667	-245.752	-118.289
December 2002 - Febrary 2003	No dates	No dates	No dates	No dates	No dates

Table 2: Variation of the volume of the Ventorrillo glacier.

In this particular case, the development of photogrammetric techniques has allowed the acquisition of maps of the crater and the glacier for the flights carried out between the years of 1998 and 2003. The acquisition of the volumetric differences of the glacier before and after a laharic event allows us to know the quantity of water contributed to the transport of masses of sediment. This is also a key piece of information in the elaboration of numeric simulations and analogical modeling in the laboratory. In addition, the knowledge of the volume of lava emitted in the interior of the crater allows for the evaluation of the maximum growth threshold of the domes before its explosion.

For the production and the cartography using photogrammetric techniques, we encountered some inconveniences:

- Arial Photographs in which the problem exists of smoke emitted from the volcano in such a way that it makes the restitution difficult in some areas.
- The summit of the volcano is located at 5,260 m and in front of the glacier it is at 4,500 m, which provokes different scales of flight for the same cartography. Also, each photogrammetric flight has different scales due to the changes in the altitude of the flight.
- Because of the inaccessibility of the zone, we could not have "control points". The solution was to turn to existing cartography from 1982 with a scale of 1/10,000, from which we obtained the reference points. Given that the same control points have always been used, the relative errors between the different restorations were reduced to 2 m of the absolute orientation.

The data that could possibly be obtained in the next field campaigns will complete the monitoring of the volcano in an efficient way.

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