SEISMIC SURVEY OF COLIMA VOLCANO (MEXICO) NOVEMBER 2005 – MAY 2006

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1. Introduction

In the framework of the FIRB project # 2-13-3-46-23 aimed to study high risk explosive volcanoes, a seismic survey on Colima volcano was carried out by the Osservatorio Vesuviano – INGV, the Observatorio Vulcanologico of Colima University and the Instituto Andaluz de Geofisica – Universidad de Granada, from November 2005 to May 2006.

At the present several studies on the seismic wavefield associated to the activity of quiescent volcanoes (Deception Island Volcano, Ibanez et al., 2000; Mt. Vesuvius volcano, La Rocca et al., 2001; Etna volcano, Saccorotti, 2004) have been carried out in order to better understand the eruptive dynamics, to associate the seismic precursors to the different phases of the volcanic activity and therefore to improve the risk analysis. This may result very useful also for those volcanoes, like Mt. Vesuvius, whose explosive activity has never been observed since the installation of the modern monitoring systems.

In this context Colima volcano was selected by considering the characteristics of its volcanic activity and the easy logistic favourable to carry out a four months continuous seismic survey. Colima volcano displayed a wide spectrum of eruption styles, including phreatic explosions, major block-lava effusions, and large explosive events. At the time of the experiment its volcanic activity consisted in small volcanian eruptions (2-3/day). During this seismic survey a considerable data set composed by high quality digital signals was acquired by four broadband sensors recording in continuous way. This small mobile seismic network was installed at the end of November 2005 and remained in function until the beginning of May 2006. In addition, the available database includes seismic waveforms recorded by the permanent seismic network operating on Colima volcano, managed by the Observatorio Vulcanologico of Colima University.

The aim of the present experiment is the detailed study of the elastic wavefield associated with the eruptive dynamics of Colima volcano. In particular, several analysis will be performed in order to retrieve:

a) the properties of the wavefield of both tremor, volcanic quakes and volcano-tectonic earthquakes in the frequency range between 0.01 and 20 Hz.

b) the moment tensor associated with the source of volcanic quakes.

c) the seismic wave propagation pattern in the highly heterogeneous geological structure of Colima volcano.

d) the spatio-temporal evolution of the seismic wavefield associated with the eruptive behaviour, pre- and post- eruptive periods of this volcano.

The present report provides information about Colima volcano geological settings and about the seismic network set up, operation and data format.

2. Colima volcano and its recent activity

Colima volcano is located in an extremely complex tectonic region, where the North American, Pacific, Cocos, and Rivera lithospheric plates interact. Although nominally a part of the Mexican Volcanic Belt (MVB), which is pointedly nonparallel to the orientation of the local subduction trench, the Colima-Nevado-Cantaro system axis trends N-S, almost perpendicularly to the MVB (Fig. 2.1). These volcanoes, of which Colima is the only one currently active, are located within a graben-like structure oriented roughly N-S (Colima Rift) and connected at its northern end with two other graben structures, the Chapala (trending roughly E-W and including the Primavera caldera) and the Zacoalco (trending roughly NW-SE and including the Tequila, Ceboruco and Sangangtey volcanoes). This arrangement has led some scientists to propose the Colima graben as a spreading center where the Jalisco block separates from the continent (Luhr et al. 1985; Bourgois et al. 1988).

Colima volcano (19.512° N, 103.617° W), also known as Fuego or Zapotlàn volcano, is an andesitic strato-volcano rising nearly 4 km above sea level, and is the most active volcano in Mexico. It is located at the western end of the Mexican Volcanic Belt (FIg. 2.1) and, together with the

Pleistocene Volcano Nevado de Colima, forms the Colima Volcanic Complex. The present cone grew within a horseshoe-shaped caldera-like structure about 4-5 km wide, produced by a large Mount St. Helen's type debris avalanche, which destroyed the ancient Paleofuego volcano more than 4000 years ago. The collapse of the huge ancient volcanic structure produced massive avalanche deposits covering a large area south of the volcano. Currently, about a quarter million people live in the area covered by these deposits, and a similar event could have catastrophic results unless appropriate measures are taken.

Historical activity of Colima volcano has been reported by eyewitnesses since 1560; 25 eruptions have been reported since then; of these at least six had large magnitudes and intensities. This volcano has shown a wide range of eruption

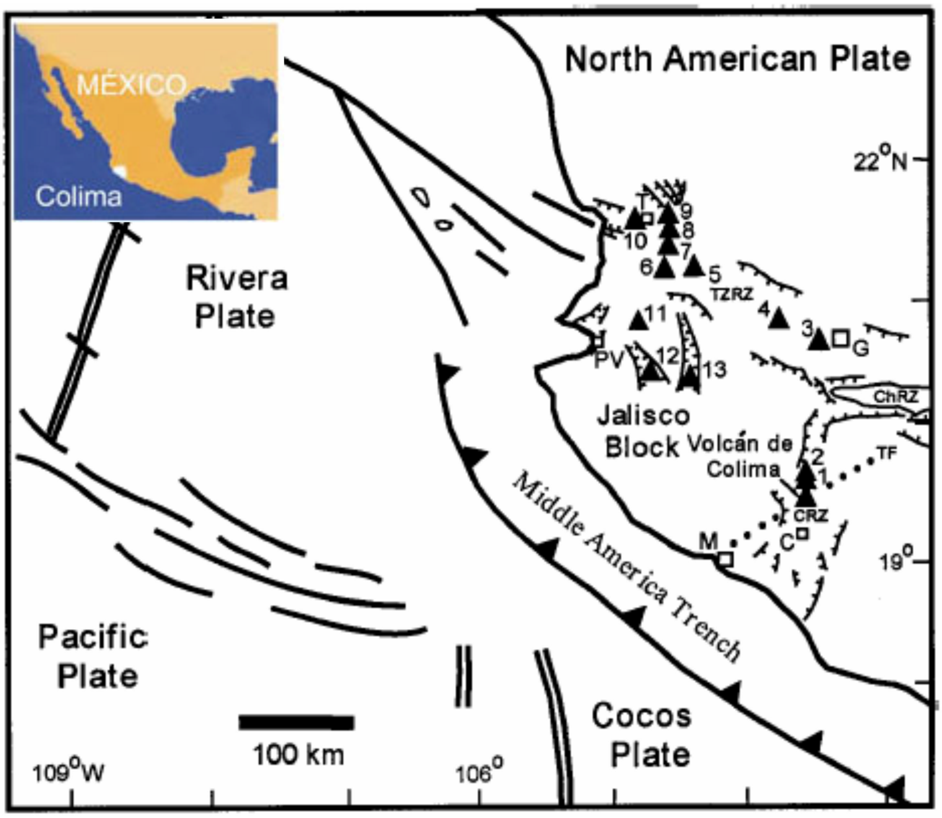

Figure 2.1: Generalized map showing the location of Volcán de Colima in southwestern México. Taken from Zobin et al. (2002b); prepared by J. Luhr. On-land faults are adapted from Johnson and Harrison (1990), Allan et al. (1991), Carmichael et al. (1996), and Ferrari and Rosas-Elguera (2000). These faults outline three major rift zones: CRZ Colima Rift Zone; ChRZ Chapala Rift Zone; TZRZ Tepic–Zacoalco Rift Zone. The dotted line running through Volcán de Colima is the proposed Tamazula Fault zone. Other major volcanic centers from the western Mexican Volcanic Belt are shown as triangles: 1 Nevado de Colima; 2 Volcán Cántaro; 3 Sierra la Primavera; 4 Volcán Tequila; 5 Volcán Ceboruco; 6 Volcán San Pedro; 7 Volcán Tepetiltic; 8 Volcán Sangangüey; 9 Volcán las Navajas; 10 Volcán San Juan; 11 San Sebastian Volcanic Field; 12 Mascota Volcanic Field; 13 Los Volcanes Volcanic Field. Open squares show major cities: G Guadalajara; C Colima; M Manzanillo; PV Puerto Vallarta; T Tepic. Offshore plate-boundary features were mainly taken from DeMets and Stein (1990) and Bourgois and Michaud (1991).(modified by Zobin et al., 2002).

types, ranging from dome growth and lava flow accompanied by frequent small block avalanches, to intense pyroclastic explosions, like those of 1585, 1606, 1622, 1818, 1890, and 1913, which produced ash flows and heavy ash falls over distances of hundreds of kilometers away from the volcano. Although a small part of the Colima volcano risk area is now a national park, several towns and cities, as well as numerous agricultural and industrial centers and important communication lines, are located within the vulnerable area. At present Colima volcano has very steep slopes and currently a growing lava dome is plugging the summit crater, creating a potentially unstable and therefore hazardous configuration.

Since 1961, when the lava filling the 1913 conduit and crater started overflowing the crater rim, three episodes of lava flow issuing from the summit dome have occurred in 1975, 1982, and 1991. These flows have been accompanied by numerous merapian avalanches and, in some cases, by dilute pyroclastic flows resulting from the crumbling of older, altered and/or juvenile dome material. The observed block and ash flows of the 1991 episode were larger than during the previous episode, and it was the first time that significant and evolving seismic activity was detected prior to and during the effusive activity.

Colima's most recent unrest began on November 28, 1997 with a sharp increase in seismic activity and a significant shortening of geodetic lines around the volcano. It developed in two stages. The first stage began with the initial deformation of the volcanic edifice lasting for 12 months and culminated in the production of a block-lava flow that began on November 20, 1998 and ended about 80 days later in early February, 1999, producing 3.9×10^7 m^3 of lava (Navarro-Ochoa et al. 2002).Activity then became explosive and continued for the next two years (Zobin et al. 2002a).During the 1999 the largest recorded explosion since 1913 occurred (Saucedo et al., 2005). This event formed a 10-km high volcanic plume above the summit. The generation of important pyroclastic flows in November 1998, February and July 1999 developed a pattern of short quiet periods followed by progressively more explosive events with time.

The second stage of activity began in May 2001 with the growth of a new lava dome in the crater. The crater was filled in February 2002 and, during the following year, eight block-lava flows, accompanied by a few pyroclastic flows and thousands of rockfalls, were directed down the volcano's western and southwestern flanks. Effusion ceased at the end of February 2003, forming a new lava dome and thousands of small explosions and degassing occurred beneath the dome during March–June.

This activity culminated in July–August, 2003 with two large explosions. The first large explosion occurred at 05:28 local time on 17 July. While blocks from the lava dome were expelled to heights of about 500 m, the ash-fraction of the column rose beyond 3,000 m. The explosion was accompanied by five pyroclastic flows and about 20 rockfalls on the W–SW slopes of the volcano, with the lengths of pyroclastic flows estimated to be up to 2 km. The second large explosion, at 23:52 on 28 August, formed an ash column at least 3,000 m high and distributed ash up to 60 km to the W–NW. It was accompanied by a series of pyroclastic flows up to 2.5 km long that practically covered the whole volcano.

The explosion sequence of March–August, 2003 produced a new summit crater, 200 m across and 30 m deep. About $2x10^6 m^3$ of the former lava dome was ejected as volcanic bombs to distances of about 1–2.5 km. Based on erupted volume and column height, the 2003 March–August explosive eruption at Colima volcano had a VEI of 1–2.

In summary, the behaviour of Colima volcano for the last 40 years has been characterized by alternated phases of andesitic lava domes building ($\sim$8) at the summit and phases of lava flows effusion and/or dome disintegration (collapse) propelling Merapi type pyroclastic flows. Somewhat change in the Colima behaviour can be dated after the 1998-99 lava dome and lava flow formations, when a series of both small and strong explosions occurred. The growth of a new lava dome during the 2002-03 and lava flows and explosions destroyed the previous lava dome at the summit.

The petrologic and mineralogical study by Luhr (1990) shows few changes of the magma composition in the last 40 years.

3. Seismicity of Colima volcano

The seismic activity at Colima volcano is characterized by distinct crises, where a seismic crisis refers to a sudden increase in the rate of earthquake occurrence lasting long enough to generate a significant number of events. The onset of seismic crises can be identified from the sharply upwards curving parts of the cumulative seismicity plots. The end of the crisis period is marked by the beginning of the declining slopes (Fig. 3.1).

Colima's most recent unrest in 1997, began with a sharp increase in seismic activity associated with the absence of surface volcanic activity. The eruption characterized by block-lava flow began on November 1998, and evolved toward an explosive phase lasting the next two years (Zobin et al. 2002b). The seismic activity preceding the lava eruption (November 28, 1997 to November 19, 1998) has been studied in detail (Dominguez et al. 2001; Zobin et al. 2002b, 2002c). This seismic activity consisted of five swarms of volcano-tectonic microearthquakes that occurred in November-December 1997, March, May, June-July, and October-November, 1998. About 600 events with magnitude ranging from 0.5 to 2.7 were located within a 50-squared-kilometers-wide area including the active crater of Colima and the region between Colima Volcano and Nevado de Colima, which is located 5.5 km to the north. Most hypocenters had a depth shallower than 5 km b.s.l. (Fig. 3.2). Temporal migration in event depths was identified in the November-December 1997 and June-July 1998 swarms [from 4 km b.s.l. to 4 km a.s.l.] and in the October–November 1998 swarm [from 0 to 4 km a.s.l.]. No decrease in the rate of seismic energy release was observed with the end of the precursory volcano-tectonic earthquake swarm and the beginning of lava eruption. The volcano-tectonic earthquakes stopped to occur and the seismic signals, characterized by the same or higher magnitude of energy release, started with the lava eruption.

The sequence of seismic events that currently occur at Colima volcano during the present eruptive activity is characterized by two types of signal. They can be distinguished in those produced by rockfalls and those triggered by explosive

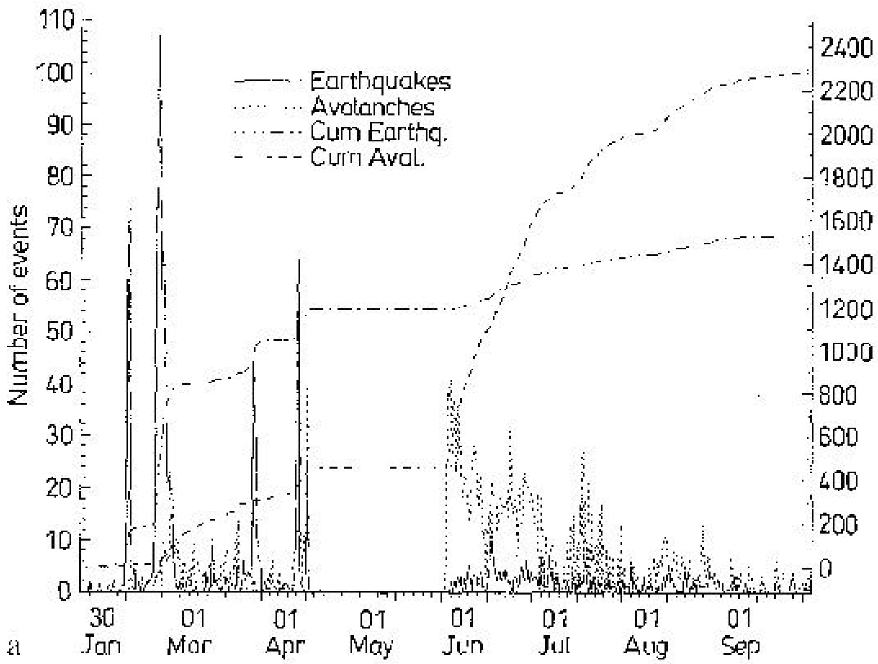

Figure 3.1: Number and cumulative number of volcanic earthquakes and avalanches counted every 12h, at EZV6 station, during the eruptive process of 1991. From 16 April to 31 May it was not possible to count events due to saturation of the analogical records. The five peaks in the seismic activity before 16 April correspond to five seismic crisis (from Nunez et al., 1994).

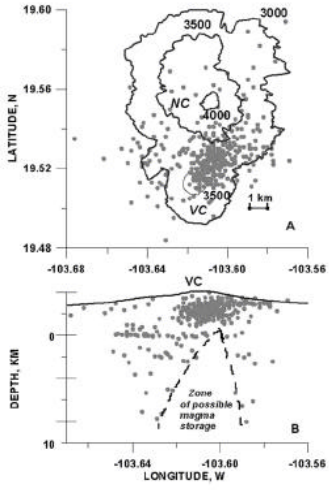

Figure 3.2: Distribution of epicenters (a) and hypocenters of earthquakes (b) located within the Colima Volcanic Complex during the seismic crisis of 1997–1998. Contour lines at 3,000, 3,500 and 4,000 m show the relief of the Colima Volcanic Complex. VC Volcan de Colima; NC Nevado de Colima. The seismic stations are shown as triangles. An earthquake-free zone is outlined in the cross section (from Zobin et al., 2005).

events. More details about the seismicity of explosion sequences are in Zobin et al. (2006).

4. Instruments and data recording

During the seismic survey of November 2005 – May 2006 four Lennartz MARSlite stations were installed by the Osservatorio Vesuviano (INGV) on the Colima volcano flank (Fig. 4.1). The stations were equipped with four Lennartz LE-3D/20s sensors, that were buried in approximately 30 cm deep holes. The 3-D sensors were deployed with the horizontal components oriented in the N-S and E-W directions. The sensor coordinates were measured using GPS positioning, with a precision of about ten meters in absolute sensor location (Fig. 4.1, Tab.1). Synchronization at each stations was achieved using the GPS time signal. Data were digitized at 62.5 samples/s.

Batteries were changed every two weeks and a check of the instruments was made at the same time. Data recorded by the stations were stored on Magneto-Optical (MO) disks and transferred every two weeks.

TAB. 1

STATION	LATITUDE	LONGITUDE	ELEVATION
COBA	19.4846° N	103.5374° W	580 ± 20 m s.l.m.
COME	19.4821° N	103.6744° W	1710 ± 20m s.l.m.
COTE	19.5815° N	103.7329° W	1740 ± 20 m s.l.m.
COCA	19.5375° N	103.6315° W	3170 ± 20 m s.l.m.

The OV-INGV seismic network was operating from November 2005 to May 2006. Figure 4.2 shows the time-log of the four stations.

The permanent Colima Telemetric Seismic Network (REd Sìsmica de COlima, RESCO) managed by the Observatorio Volcanològico de Colima (OVC, Universidad de Colima) was in operation during the same period in which the OV-INGV Mobile Seismic Network was in function.

In the 1989 the RESCO seismic network began to be deployed to study local and regional seismic activity. Currently, this network consists of 9 stations distributed on and around the volcano and other 12 stations located until 35-40 km south and southwest of it , all of them telemetered by radio to a central receiving and processing centre (Fig. 4.3).

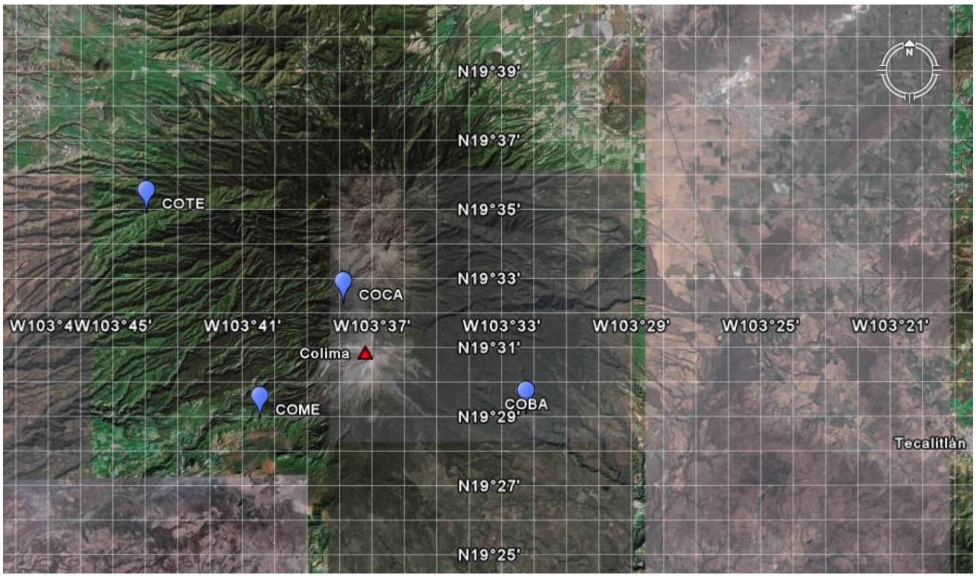

Figure 4.1: Map of the OV-INGV Mobile Seismic Network stations (circles) installed on Colima volcano during the 2005-06 seismic survey.

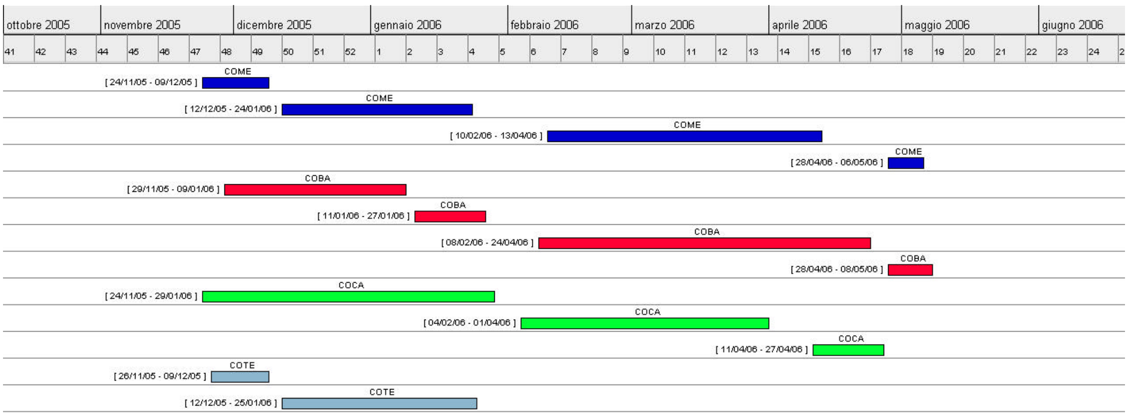

Figure 4.2: Time-log of the OV-INGV Mobile Seismic Network stations installed on Colima volcano flank during the 2005-2006 seismic survey.

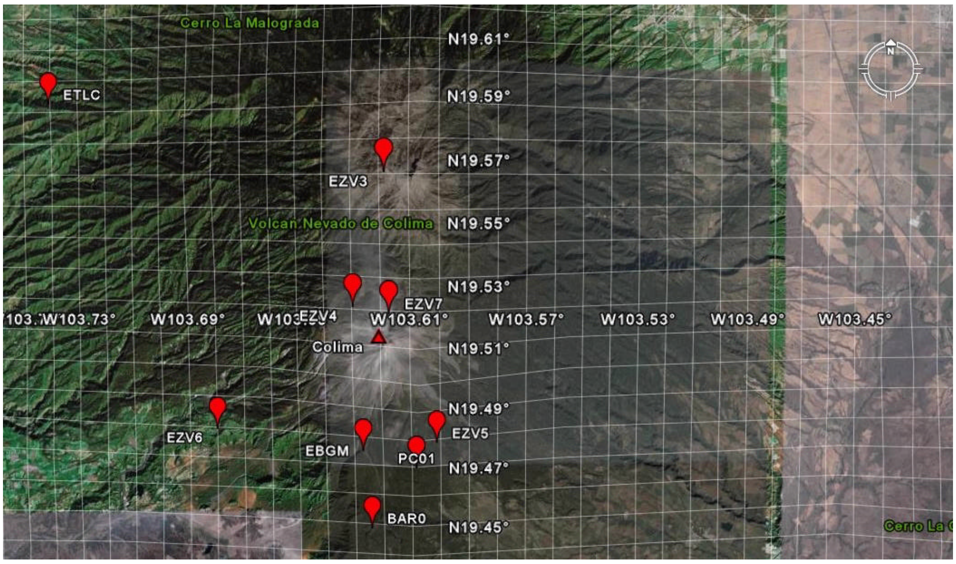

Figure 4.3: Map of the RESCO seismic network stations (circles) installed on and around Colima volcano.

Each RESCO station is equipped with a SS-1 Ranger short period (1Hz) vertical seismometer. Analogical data are transmitted to the headquarters at Colima city where they are recorded and stored as digital time series.

The third scientific institution involved in this FIRB project was the Instituto Andaluz de Geofisica (IAG, Universidad de Granada, Spain). The IAG contributed with the installation of a seismic array on the southern flank of the volcano. The Spanish seismic array acquired data from October 2005 to July 2006 (Fig. 4.4). It was composed by ten Mark L25 seismometers, with natural frequency of 4.5 Hz, among which nine with vertical component sensors and one with a three component sensor (Fig. 4.5).

The figure 4.6 depicts the location of all the seismic stations (OV-INGV mobile seismic network; RESCO seismic network and IAG seismic array) working on Colima volcano during this seismic survey (November 2005-May 2006).

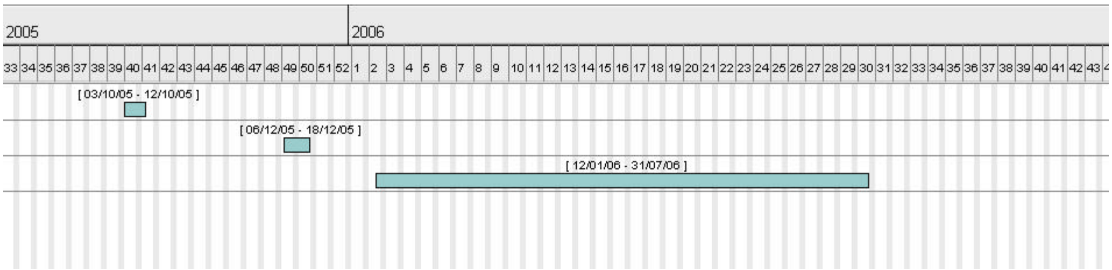

Figure 4.4: Time-log of the IAG seismic array installed on Colima volcano south flank during the 2005-2006 seismic survey.

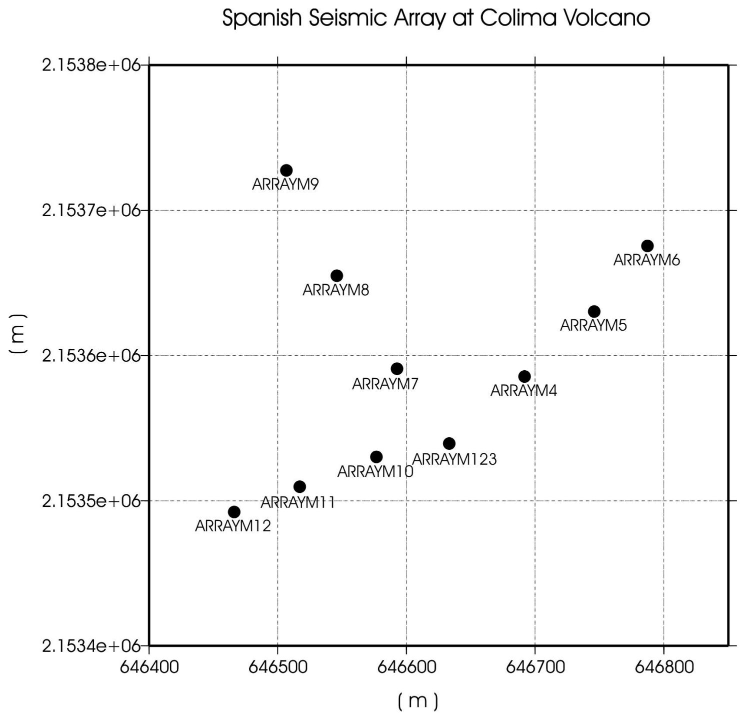

Figure 4.5: Map of the IAG seismic array stations (black circles) installed on the south flank of Colima volcano. In the site ARRAYM123 a three component sensor was installed.

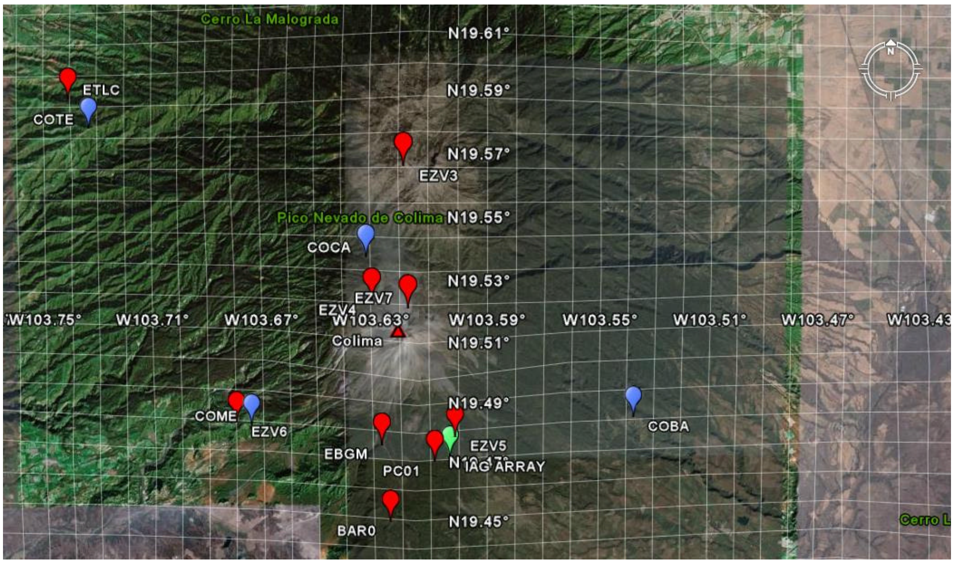

Figure 4.6: Sketch map illustrating the location of all the seismic stations installed on The Colima volcano during the 2005-06 seismic survey. The blue circles indicate the OV-INGV Mobile Seismic Network stations; the red circles show the RESCO seismic network stations and the green circle represents the IAG seismic array stations.

5. OV-INGV Mobile Seismic Network data collection and storage

The volcano-seismicity recorded by the Mobile Seismic Network of Osservatorio Vesuviano (INGV) during the present survey results to be mainly composed by low energy volcanic tremor, low-frequency events (LP) and volcano-tectonic (VT) events. In addition, wave-packets generated by rockfalls and explosive eruptions of Colima are also present in the background.

In Figure 5.1 seismic waveforms associated to the volcanic activity of Colima and their spectrograms are shown.

The figure 5.1 (a) shows a clear volcano-tectonic event type, with energy content in the 0.05-4 Hz frequency band. The figure 5.1 (b) illustrates recordings of a Long-Period (LP) event followed by a rockfall. This event was recorded duringone of the small daily vulcanian eruptions [picture in Figure 5.2]. The characteristics of these phenomena are well evidenced in the associated spectrogram, in which the energy distribution can be clearly distinguished in different frequency bands: 0.05-1Hz for the LP event and 0.5-4 Hz for the rockfall.

In the figure 5.1 (c) is represented volcanic tremor with the energy distributed in 0.05-1Hz frequency band.

The small network operated from November 2005 to May 2006 recording not only signals related to the volcanic activity of Colima volcano but also several local, regional and telesism events.

The seismic data were acquired in gse MARS-Lite file format and finally, at the end of experiment, converted in SAC (Seismic Analysis Code) file format. The available data were collected in single files for each component with one-hour time duration.

The RESCO network seismic data and IAG seismic array data were available in SEISAN file format.

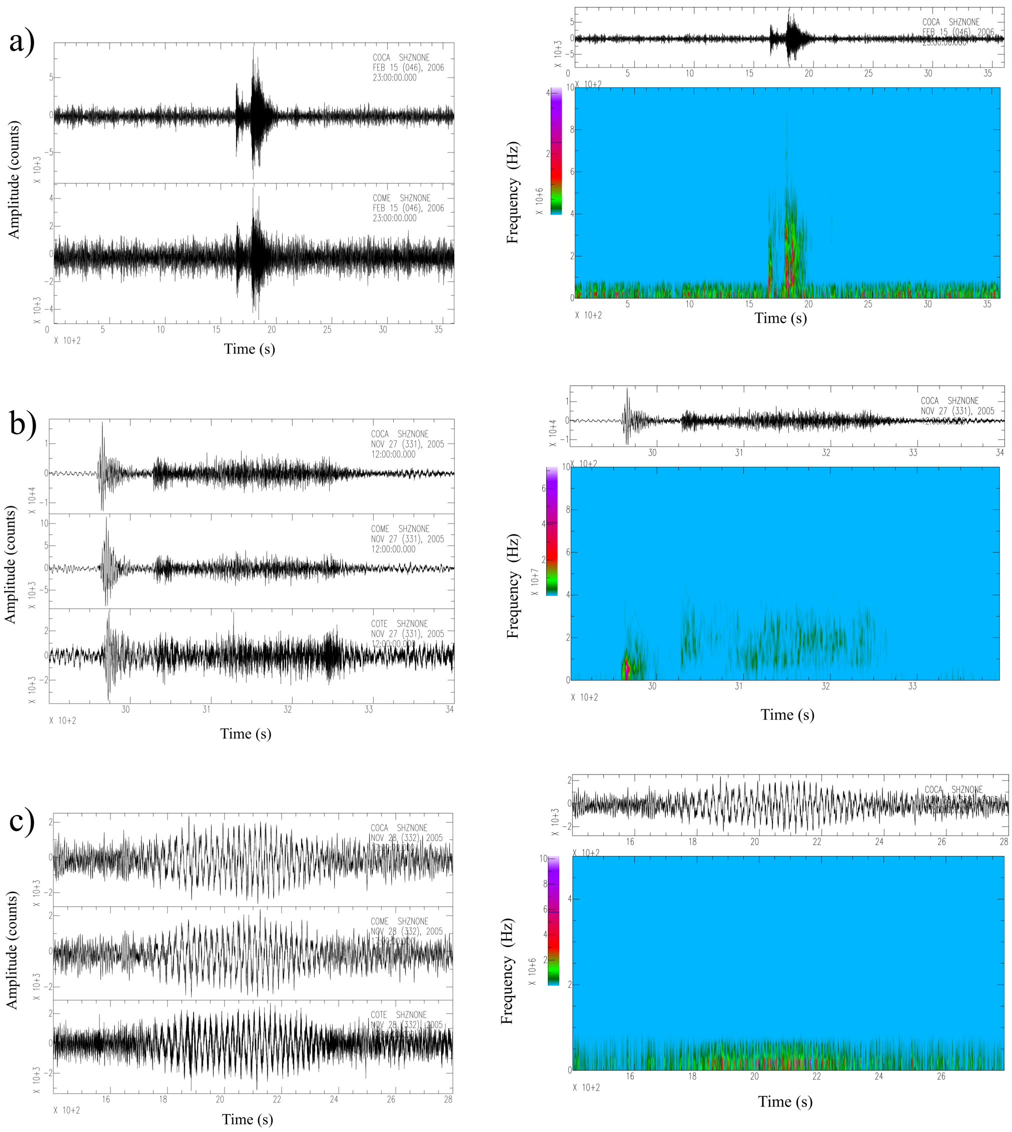

Figure 5.1: Examples of seismic waveforms and spectrograms associated to the volcanic activity of Colima volcano. The signals were recorded by the OV-INGV Mobile Seismic Network stations during the 2005-2006 seismic survey.

Figure 5.2: Picture of one of the daily vulcanian eruptions produced by Colima volcano. This one was occurred the 27/12/2005 at 12;49 and was recorded by the OV-INGV Mobile Seismic Network stations as showed in Figure 10 (b).

6. Geo-volcanological investigations during the seismic survey

A short field survey was associated during the OV-INGV seismic data acquisition with the aim to deal with a comparative study between seismic activity, eruptive events and related (pyroclastic) deposit. Several comparative investigations have been worldwide performed on several volcanoes since the '80-'90, studying the seismic signal associated with the lava effusion, strombolian explosions or dome growth (e.g. Stromboli, Etna, Merapi, Yasur volcanoes). However, a seismic analysis oriented to understand - during higher magnitude explosions - the processes of magma fragmentation and particles formation in the conduit, blast and final Pyroclastic Density Current (PDC) deposition is still lacking. In other words, at Colima, as well as for most of the explosive volcanoes active in the world, the possible link between some eruptive events - recorded by seismic networks – the released energy and volcanic deposits (i.e. the various type of PDC), is not constrained or unknown. As we believe that a correlation between eruptive event(s), seismic signals and volcanic products exists, the ongoing activity of Colima appeared as a good opportunity to go deeper in this topic. It is obvious that the ideal and most brilliant goal would be to depict a quantitative correlation between magma fragmentation and energy involved in the explosion by the analysis of seismic data.

Therefore the planned steps to reach these goals were: a) identification of the main pyroclastic deposits emplaced during the activity of the OV-INGV mobile seismic network; b) outcrops observations, stratigraphic measures and samples collection (juvenile ash and/or fresh pumices); c) petro-chemical and textural study of the rock samples by microprobe and SEM.

For what concerns the first point, unfortunately, no significant volcanic eruption forming a PDC and producing a pyroclastic deposits was recorded by the temporal seismic network during its period of acquisition (Nov. 2005-May 2006). Therefore, after a careful examination of the seismic signals recorded by RESCO seismic network in the last 3 years and the images (photo, video) shot during the

Figure 6.1: The eruption and column collapse of 5 June 2005.

major explosive events, we made the choice to study the pyroclastic products associated to the explosive events occurred between the October 2004 and July 2005. Noteworthy, after their deposition, the Colima pyroclastic products are not well recognizable on the field for a long time due to the intensive actions of weathering and water erosion already after one single season of heavy rains. For this reason, the even more important events of the Nov. 1998 – Jan. 1999, 10 Feb. 1999 and 17 July 1999 described in various papers (Navarro-Ochoa et al. 2002; Saucedo et al. 2002; Saucedo et al. 2005) and generating pyroclastic flows (Ash&Block flows of Merapi- and Soufriere-type, probably some Ash&Pumice flows with upper dilute, turbulent clouds i.e. Pyroclastic Surges) were not considered as possible objects of our studies.

These eruptions were preceded by a sequence of seismic signals of different type for a time-span ranging between 50 and 90 hours. In general and qualitative terms and according to indications of the OVC researchers, these signals can be identified as: rock-falling (derumbles), steam explosions, volcano-tectonic events, PDC-forming explosions showing a rather complex signal, made of at least two parts: a) the initial true explosive phase and the following Impact + Run-Flow which overlaps on the first when the column collapse occurs.

Going into details, we have observed and studied on the field:

1) the PDC deposit deriving from the dome collapse of the October 2004 and

emplaced along the La Lumbre Barranca (SW sector of the volcano);

2) the PDC deposit deriving from the column collapse of the (30) May-June 2005 (see picture in Fig. 6.1) and emplaced along the San Antonio and Monte Grande Barrancas (S sector of the volcano) overlaid by the pyroclastic flow of September 2005 just at the Monte Grande Barranca;

3) the PDC deposit deriving from the column collapse of the July 2005 and emplaced along La Arena Barranca (E sector of the volcano).

One of the main problems related to these eruptions and the associated products, which involve the presence of a lava dome, is the distinction between the juvenile component of the upraising fresh magma (if present) and the lava or rock fragments deriving from the simple disruption/destruction of the dome by over-pressurised gas pockets. For this reason, the field-work was even focussed in finding and sampling the levels (strata, laminae) of fine pyroclastics both because the finer fraction of the fragmented material is that giving the larger information on the energy and it is that with the highest possibilities to consist entirely of juvenile clasts. In Figure 6.2, one of the sampled deposit emplaced during the 5 of June 2005 along the Barranca di Monte Grande (q. 2430 m a.s.l.) is reported. The glass shards and the possible mineral phases that form the laminated horizons will be analysed by ICP-MS and the results will be compared with the petro-chemical data on the Colima magmas erupted in the last century (Luhr et al., 1990; Luhr, 2002; Mora et al., 2002).

Figure 6.2: Picture of one of the sampled stratigraphic section at the Barranca di Monte Grande (samples taken in the laminated horizons over the blue pick)

7. Conclusions

The quantity and high quality of the collected data encourage to carry on detailed analysis to understand the explosive activity and the internal structure of Colima volcano.

In particular, this data set will be used for the following purposes:

1) the study of the characteristics of the seismic wavefield related to explosive eruptions by decomposing the broadband signals with several techniques;

2) the classification of the different types of seismic events composing the database by means of innovative techniques, i.e. that based on wavelet transform;

3) the source location of the LP events and of the volcanic tremor;

4) the moment tensor inversion to understand the dynamics of the seismo-volcanic sources;

5) the determination of the quality factors and characteristic frequencies (and their temporal variations) for the LP events, in order to infer the properties of the fluids involved in the dynamic process.

6) the definition of the velocity model of the volcanic edifice through a travel-time tomography, using a joint data set, composed by the OV-INGV and by the RESCO network seismic data;

7) the identification and the definition - in seismic terms - of the link (parameter) between the mechanical energy released by the explosion and the Pyroclastic Density Current intensity.

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