Short chronological analysis of the 2007-2009 eruptive cycle and its nested cones formation at Llaima volcano

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Abstract. The Llaima volcano (38°41'S / 71°43'W) is one of the most active volcanoes of South America. In the present work we have combined direct field and sequential photography observation plus remote sensing of low cost, making possible to reconstruct its 2007-2009 eruptive cycle. Llaima volcano eruption began on January 1, 2008 at 18:11 local time, preceded by seismic and surface precursory activity. The onset of eruptive activity was followed by a second paroxysmal eruption occurred on April 2009, and the occurrence of Hawaiian, strombolian and phreatomagmatic reactivation pulses which edified a series of small nested scoriae and spatter cones inside the main crater of volcano. Their evolution was widely registered, defining with clarity two eruptive stages and nine eruptive phases. Several basaltic pahoehoe and AA lava flows descended from the main crater, producing glaciers melting and then lahars, which transported large-size blocks of ice and boulders. Also, pyroclastic flows and ash fall events where observed. This activity persisted until 2009 when finally ended. The record is very important to learn about Llaima eruptive behavior and could be used in population risk management.

Keywords: Llaima, 2007-2009 eruptions, remote observation, Southern Andes, Chile.

1.- Problem

Llaima volcano (3179 m s.n.m.) is a complex composite-shield volcano sited on the Chilean Southern Andes Volcanic Zone (SAVZ) of Araucanía Region (Fig.1 A). It is formed by a buried caldera and 40 parasitic scoria cones [1] covering an area ca. 500 km² and with a volume ca.400 km³ [2], being one of the largest volcanoes at this volcanic region. Llaima has grown since the Late-Pleistocene (0.126-0.0117 Million years) times and its eruptive behavior is of mainly Strombolian and Hawaiian in type, however, intermittent sub-plinian activity poses a high hazard potential, including pyroclastic flows, ash falls and lahars [3]. Several historical eruptions have generated lava flows and consequent lahars when Captrén (north), Trufultruful (southeast), Lanlán and Calbuco (western slope) rivers have been affected [2]. On 1 Jan 2008, the Llaima volcano began a new eruptive cycle, after 5 years from its last eruption on 2003. Reconstructing volcanic activity is a problem which requires to be solved, because appears like a irreplaceable tool for understanding future events.

2. Objectives

If there are many ways to record volcanic eruptions, in this contribution we like to reconstruct the time evolution of the 2007-2009 eruptive cycle using direct-observation and remote sensing satellite imagery tools, and also we try to identify morphological changes on the crater area, lava effusion and lahars based in several field surveys. Those techniques are low in cost, easy of control, and widely applicable to follow volcanic activity, making possible to measure important volcanic behaviors with small resources, also reducing the human presence in the field, especially when there are problems in the access to the volcano during winter time or the activity persist by a long time. In this context, possibilism is clearly present because human owns the inteligence and resources to study natural phenomena without its own exposition and risk.

3.- State of art: Llaima volcano

According with [4] Volcanism at SAVZ appears as result of subduction of oceanic Nazca plate beneath the South American plate, and also the control of Liquiñe-Ofqui Fault Zone (LOFZ, Fig. 1A). Llaima Volcano (38°41'S / 71°43'W), is a complex composite–shield volcano, with a buried caldera and 40 parasitic scoria cones, formed by basaltic and andesitic lava flows, andesitic pyroclastic flows and dacitic surge and pumice fall deposits [3] which has grown since the Late-Pleistocene, initially dominated by effusive activity. The historical activity consists mostly in effusive behavior interrupted by numerous smaller explosions and accompanied by quiescent degassing [5]. Since 1640, about 53 eruptions have been reported, with phreatomagmatic, strombolian and subplinian eruptions [3, 6]. Most frequent eruptions are VEI=2 (77,3%), followed by VEI=3 activity (13%) and occasionally VEI=1 (7,5%) and VEI=4 (1,8%) eruptions. Statistics in eruptive history are in Fig.1 B. Llaima shows one VEI=2 eruptions (Fig. 1C) every 5.6 years ([7], Fig. 1D). Products are mainly lavas and minority pyroclasts, both of andesitic-basaltic (50-59% SiO2) and poor silica compositions (60-65%SiO2; [3]).

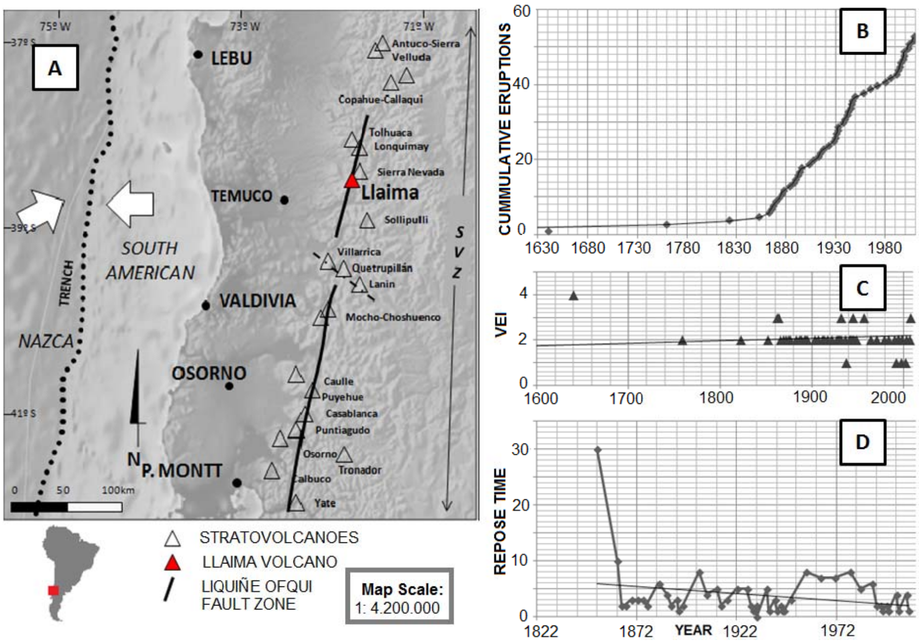

Figure 1: Llaima volcano. A: Location of the Llaima volcano showing the main structural settings and volcanic centers along SAVZ of Chile. Base image GTOPO30-Smith and Sandwell (Version 6.2). B: The plot shows the cumulative number of historical eruptions. C: Volcanic explosivity index distribution for historical eruptions. D: Repose time variations.

4.-Methods

Activity was registered by the POVI group (www.povi.cl) , using two main methods: first one consists in direct field observation. Second one is based on remote sensing data. By this latter, programmed sequential photography (every 10-60 seconds) was obtained using two cameras were distant 18 km S from vent. Also, seismic records were obtained using a Mark L4B uniaxial sensor distant 19 km SSW from vent. Adittionally, satellite imagery and thermal abnormalities were acquired from ASTER, ALI, GOES-12 and OMI being useful to understand Llaima eruptive behavior. If there are other techniques that could have been applied, most of them are more expensive. With this technology, this is expected to measure and quantify seismicity, ash ejections, thermal abnormalities and SO2 emissions.

5.- Results: Chronology of the 2007-2009 eruptive cycle and its products

The eruptive cycle could be divided into 2 stages; Pre-eruptive and Eruptive, and several phases which occurred along 2007-2009 period. The map of erupted products is presented in Fig. 2A, and a summary of eruptive phases is given in Table 1. The Pre-eruptive stage starts with a land deformation which was followed by an INSAR inverse modeling, and an uplift period was inferred (05/2007 to 01/2008), with volume increase of 6 – 20 × 106 m³ [8]. Anomalous seismicity was registered on May 2007 and presented 15-20 RSAM units, occasionally 350, associated to moderate explosions [9] and LP pre-eruptive earthquakes [10].

Phreatomagmatic explosions deposited fresh ash on 0.3 km² at June 3 2007, near the vent, and fine lapilli fragments were found 8 km E from crater, being accompanied by radiance values between 0.55-29.92 [Wm^{-2} sr^{-1} μm^{-1}] as observed by MODIS 21 Band. A first hotspot was detected by ASTER on November 23 2007 in the main crater. By Jan 1 2008, the increase of temperature at Llaima crater was detected at 10,00lt. Then, temperature increased from 2, 5 to 10, 5°C [11].

Eruptive stage starts on January 1, 2008 at 18,11lt (local time) as was directly observed from Melipeuco town, after 5 years of quiescence. Eruption consisted in central-vent reactivation and onset was initially phreatomagmatic in type, turning into a strombolian phase which lasted 9 hours. Maximum 10 Dobson Units (DU) of SO_2 concentration was measured in the plume by OMI, which dispersed until Atlantic Ocean. Awaking was followed by several small eruptive pulses with formation of lava flows, lava lakes, several pyroclastic flows (Fig. 2B), fast lahars, tephra fall deposits with scoriae fall (Fig. 2C) and small cinder cones. A new paroxysm occurred at April 3, 2009 23,00lt being preceded by a surface temperature increasing (~8 days before) as observed with ASTER and a sustained tremor 19h before.

In a interesting eruptive event registered in April 2009, both hawaiian and strombolian activity from two main fountains were observed, one of them with profuse lava effusion totally measured in ~1.8 x 10^{-3} km³ (non-DRE lava volume measured using ALI images and field observations) responsible of 3 AA flows formation. Second fountain was rich in fragments forming a 1.990 kt mass of SO_2 with 9.39 DU max concentration in ash plume as observed with Aura/OMI. This last large event persisted around 8 days.

Products of 2007-2009 eruptions consisted mainly in basaltic (51-52% SiO2; [12]) olivine and plagioclase black-grey flows and pyroclasts. Lava lake and central lava flows where pahoehoe in type, meanwhile AA flows were commonly observed far from the vent. Pyroclasts consisted in bombs, blocks and spatter. Latter ones fell near the vent (<2 km), while scoriae (lapilli) and black scoriae ash fell away from the crater.

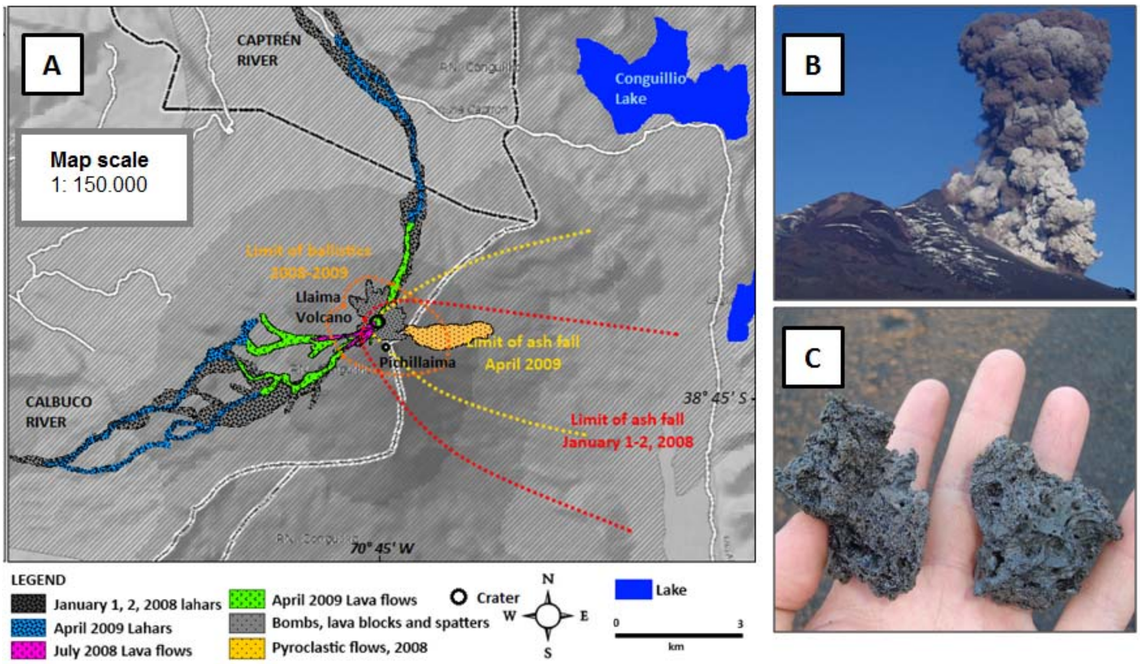

Figure 2: The 2007-2009 eruption. A: Distribution of erupted products (lava flows, lahars, pyroclastic flows and tephra fall). B: A pyroclastic flow current produced on January 17, 2008 (Miguel Yarur). C: Lapilli size scoriae emitted by the 2008 eruption (Víctor Marfull). Base elevation model from MOP (Chile).

5.1.- Evolution of main crater architecture

Main crater architecture during evolution stages could be seen in the Fig. 3. On 2006, crater had 300 m maximum diameter and more than 250 m in deep with steep walls and open conduit. Prior the 2007 eruptions (on 1994), crater showed a fumarolic-filled deep vent [6]. On 24 December, 2007 morphology of crater exhibit abundant cracks and landslides as result of increased seismicity and instability. Internal crater walls exposed hydrothermal alterations and fumarolic activity inside the upper conduit. Also, a recent ash fall deposit covered crater’s snow. After the January 1 onset, scoriae covered partially the crater and three small spatter cones were edified, central with constant lava emission (Fig. 3a). By February scoriae filled the crater, rims exceeded ~80 m the base (Fig. 3b). Last three spatter cones were higher (30-70 m height) and fumarolic activity persisted inside them. Annular cracks with degassing on the base of main crater showed descent of magmatic plume and subsequent subsidence and a lava lake was formed toward W (Fig.3b1). Complex of nested craters showed only two vents on February 2009, with 100m height and 300 m of basal diameter (Fig. 3c). Those structures, especially central nested cone, continued growing until April 2009 when finally converged in a single 200 m diameter cone (Fig. 3d). Finally, descent of magma and stability of this cone caused partial internal collapse and following subsidence.

Table 1: Chronology of the 2007-2009 eruptive events at Llaima volcano. L means Local.

Start of activity		Eruptive Phase	
Date	L. Time	Characteristics	Duration
Jan 1, 2008.	18,11	1. Phreatomagmatic: Occurrence of a continuous increasing of intensity of ash emission and a maximum 4.5 km height column was seen at 18.53lt.	2h 13min.
Jan 1 to 2, 2008	20,34	2. Strombolian: Continuous strombolian phase, eruptive columns reaching 3 to 1.5 km and lava effusion reached 0.05-0.5 km above the vent. Projection of large (metric) lava bombs.	~9 hours
Jan 2, 2008.	11,30	3. Strombolian/Vulcanian: Several small pyroclastic flows, ash explosions and low-angle directed explosions were emitted on 2, 3, 5, 7, 11, 17, 19 Jan and 01 Feb.	1 month
Feb 3 2008	06,15	4. Hawaiian/ Strombolian: Large lava effusion, lava lake formation, small occasionally ash explosions, thermal abnormalities, glacial melting with lahars formation.	4 days
April 24 2008	06,50	5. Strombolian/ Phreatomagmatic: Several explosions, small strombolian activity, ash emission, eruptive columns reaching 1-1.5 km above the crater, projectiles expulsed at velocities of 60 km/h.	1h 24min.
July 1 2008	01,45	6. Strombolian/ Hawaiian: Thermal abnormalities, large lava effusion occurred on July 1-3, 10 and 26, ash explosions, glacial melting, lava fountain, pyroclastic flows, small lahars, ballistics reaching 0.7km height. Activity occurred on July 1, 2, 3, 4, 7, 10, 12, 14, 15, 19, 24 and 26.	26 days
July 27 2008	--	7. Small Strombolian/Phreatomagmatic: Small lava accompanied by ash emissions occurred on August 13, 17, 18, 21, 22, 23 and 24, September 3, November 16 and December 11, 22 and 24. Small block and ash flows were observed in W flank on December 11. On January 1-6, frequency of phreatomagmatic eruptions was 1-7 events/hour. Columns were smaller than 100 m.	9 months
April 3, 2009	23,00	8. Hawaiian/ Strombolian: Thermal abnormalities, seismic tremors, lava effusion, ash emission, formation of three large lava flows, two descended by W flank and one to the N face of volcano, ash plume was dispersed ~200 km to E and column reached 4.0 km above the vent. Lahars affected Calbuco and Captrén rivers.	8 days
April 12, 2009	--	9. Phreatomagmatism: This ending phase showed small phreatomagmatic oriental flank-eruptions, small lava emission and decreasing of all eruptive activity. Was followed by occasional passive degassing.	~1 month

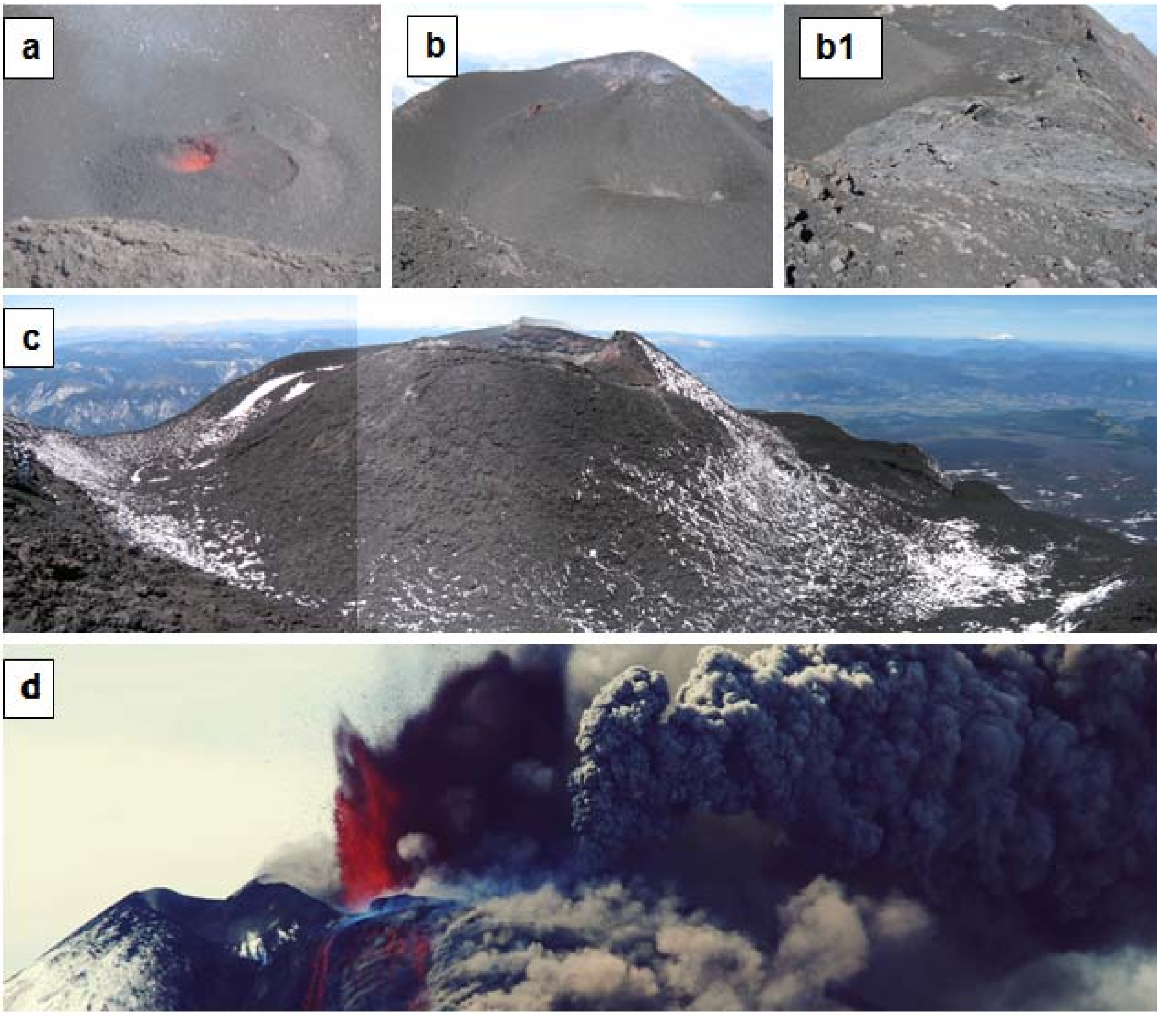

Figure 3. a Scoriae and spatter cones on 16 January 2008, Daniel Basualto. b View from SE of the nested craters on February 27, 2008 by Alex Koller. The Figure b1 shows annular cracks and lava flow respectively. Figure c. Panoramic view from N of the crater's complex by February 2009, Marco Millar. Figure d. General view of the main vent and the whole nested crater on April 2009. Daniel Basualto.

6. Effects of eruptive activity

During the January 1 2008 and April 3 2009 large events, immediate glacial melting produced 2 main powerful lahars over Captrén and Calbuco rivers (N and W respectively, and 3 smaller ones by April 2009. Boulders of 10-80 tons were transported and then mixed with ash and ice blocks. Close to the vent area, several meters of glacier were melted down, and in the base of Llaima W flank 10m a gully was produced by erosion derived from glacial melting. Giant "ice spines" where molded by hot lahars.

Activity in Jan 2008 at Llaima volcano forced evacuation of 246 tourists and 545 people from adjacent localities and authorities determined establishment of yellow alert to Cunco, Vilcún, Melipeuco and Curacautín communities (Onemi 2008). No environmental damage has been caused by ash of this eruption [13].

7. Conclusions

In this work we provided a short chronology on the evolution of 2007-2009 eruptions at Llaima volcano using easy tools and widely accessible materials. A large number of sequential photos (around 10.086 daily images) were collected and fast-reproduced to recognize volcanic activity. As we did in our work, Moreno *et al.* (2009) identified 10 distinctive eruptive phases in this eruption using seismic and visual analysis. Their research shows similar eruptive phases in comparison with our work. In this case, the use of combined remote sensing tools permits us to know with very exact precision chronology of events, its characteristics and extension.

As was observed in all the eruptive events, activity was clearly preceded by seismicity, thermal increase and minor explosions. Using sequential photography was possible to observe that, in most of cases, explosions were preceded by fumarolic increase at main vent. Also, as Bathke et al. (2011) reports, the full eruptive cycle started after an inflation period. It indicates that those signals are very important to predict future eruptions (not only in this volcano, could be in any one), and shows that surface precursory activity is directly linked with inflation periods and possibly reflects deformation resultant of magma ascent. These signals will be very useful to know the proximity of a new eruptive event at Llaima volcano in future events.

The 2007-2009 eruptive process of Llaima volcano consisted in 9 distinctive eruptive phases, two of them paroxysmal, in January 2008 and April 2009, with the emission of mostly lava and pyroclastic basaltic rocks. The close-vent accumulation of those products formed initially three scoriae nested cones inside main crater, which grew, unified and partially collapsed after the eruptive cycle. Lava effusion melted N and W flank glaciers producing lahars, more destructive on January 2008, forcing 545 people evacuation and transporting ~80 tons blocks. These lahar floods were not largely extensive, maybe because they affected W flank of volcano, which is less populated than other flanks as southern, last one directly connected to Melipeuco town. If is clear that activity didn't caused deaths and environment hasn't been contaminated, duration and intensity of activity has been compared to 1944-46 and 1955-57 eruptions (Moreno et al. 2009), which were larger than usual eruptions. However, last eruption didn't finish into a large paroxysm as was observed in those cases.

This paper tryes to record volcanic activity in use of non-expensive tools that also contribute to the remote observation and reduction of human presence and exposition at the field. Maybe, this technology does not record all the events that could be in process at the eruption, as example shock waves or short episodes, and also is limited by weather conditions that sometimes makes not possible to observe the volcano. Those limitations must be solved in future recording with more advanced technologies because they deteriorate the chronology reconstruction. Anyway, this way to study volcanic events in real time is absolutely helpful for understanding the volcanic behavior and also could be applied in civil protection for reducing people risk and exposition or alert promptly to authorities in case of hazardous phenomena.

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Glosary

AA Lava = Type of lava flow formed by a central fluid hot mass covered externally by scoriae pieces of cooler lava

Composite-Shield = A volcano of shield morphology formed by alternating lavas.

Hawaiian eruption = Volcanic eruption with abundace of fluid lava, scarce gas and without explosivity

Lava bombs: Rock projectiles emitted by a volcanic explosion.

Pahoehoe = Type of fluid lava flow forming an special texture of strings and lobules

Paroxysm = Is the climax of an eruption phase or event.

Phreatomagmatic eruption = Eruption of water interacting with magma, highly explosive
POVI= Proyecto de Observación Volcán Villarrica (y Llaima).

Pyroclastic = Rock high-temperature fragments expulsed from a volcano during an eruption

Pyroclastic flow = Incandescent mass of gas, ash and rocks which flows down from the eruption vent

Stratovolcano = Volcano composed by alternating pyroclastic and effusive materials

Strombolian activity = Eruption with minor explosivity and abundance of lava and particles

VEI = Volcanic Explosivity Index. Is a scale proposed by Newhall & Self with the objective of classify volcanic eruptions combining intensity and magnitude of volcanic events.

Vent = place or aperture where the volcanic products are emitted

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