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THE PAIPA VOLCANO, EASTERN CORDILLERA OF COLOMBIA, SOUTH AMERICA : VOLCANIC STRATIGRAPHY.

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ABSTRACT

We recognized a Quaternary volcano in the Eastern Cordillera of Colombia between longitudes 73º9'4"W to 73º3'39"W and latitudes 5º40'28"N to 5º45'20"N. Paipa volcano has an eroded edifice that reaches 300 m above the Cundiboyacense high-plateau (2871 m.s.l), and a 3 Km caldera with several vents inside it. Volcanic products overlay sedimentary rocks of Upper Cretaceous age and cover a 31 Km2 area. Geologic field mapping, stratigraphy and petrography analysis has been made to establish eruptive units and pyroclastic transport and deposition processes in order to reconstruct volcanic activity history. Caldera outflow facies are ash fall deposits and ash and pumice flow tuffs interbedded with fluvial and torrential deposits. There are also several geothermal springs including CO2 vents northward the caldera. The inflow facies are lava-domes, ash and block flow tuffs and pyroclastic surge deposits interbedded with fluvial and lacustrine deposits. We defined 14 eruptive units within two eruptive epochs: the first one comprises the formation of a volcanic caldera and its collapse, while caldera resurgence took place during the second epoch. Single events ages are not well known because of lack of radiometric dating; 1.9 to 2.5 Ma K/Ar and Ar/Ar ages suggest a Pliocene and Pleistocene range for Paipa volcanism.

Key words: caldera, eruption unit, ignimbrite, domes, magmatic eruption, phreatomagmátic eruption, pyroclastic flow, pyroclastic surge.

RESUMEN

Reconocimos un volcán cuaternario en la Cordillera del este de Colombia entre las longitudes 73º9'4"W a 73º3'39"W y latitudes 5º40'28"N a 5º45'20"N. El volcán de Paipa tiene un edificio erosionado que alcanza 300 m sobre el alto-meseta Cundiboyacense (2871 m.s.l), y una caldera de 3 kilómetros con varios respiraderos dentro de él. Los productos volcánicos sobreponen rocas sedimentarias de la edad cretácea superior y cubren un área de 31 km2. El análisis geológico el mapa de trazado, estratigráfico y de la petrografía del campo se ha hecho para establecer unidades eruptivas y procesos piroclasticos del transporte y de la deposición para reconstruir historia volcánica de la actividad. Las faces de salida de la caldera son depósitos de la caída de la ceniza y tuffs del flujo de la ceniza y de la piedra pómez con los depósitos fluviales y torrenciales. Hay también varios resortes geotérmicos incluyendo respiraderos del CO2 hacia el norte la caldera. Las facies de la afluencia son lava-bo'vedas, incineran y bloquean tuffs del flujo y la oleada pyroclastic deposita interbedded con los depósitos fluviales y lacustrine. Definimos 14 unidades eruptivas dentro de dos épocas eruptivas: primer abarca la formación de una caldera volcánica y de su derrumbamiento, mientras que el resurgimiento de la caldera ocurrió durante la segunda época. Las solas edades de los acontecimientos no son bien sabido debido a carencia de fechar radiométrico; 1.9 a 2.5 edades del mA K/Ar y de Ar/Ar sugieren una gama pliocena y Pleistoceno para el volcanismo de Paipa

Palabras Clave: caldera, unidad, unidad de erupción, ignimbrite, bóvedas, erupción magmática, erupción reatomagmática ,flujo piroclástico, oleada piroclástica.

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INTRODUCTION

Between latitudes 5º40'28''N and 5º45'20''N, and longitudes 73º9'4''W and 73º3'39''W, in the central part of the Eastern Cordillera (EC) of Colombia (Figure 1), the Paipa volcano was recognized during the INGEOMINAS (Colombian Geological Survey) Geothermal Research Project.

Paipa volcanic rocks were first identified by Sarmiento (1941) and were first mapped by Renzoni et al. (1983) as Cenozoic volcanic andesites. Because Paipa town is well known by its geothermal springs it has been the focus of economic and scientific geothermal exploration projects since 1979 (ENUSA-IAN, 1979). With the exception of the research work titled 'Estudio de reconocimiento de los recursos geotérmicos de Colombia', written by Geotermia Italiana et al., (1981), and 'Feasibility study report of geothermal power plant for ICEL', written by JAPAN CONSULTING INSTITUTE (1983), there was a lack of volcanological studies in this area. Besides this two geothermal studies, several undergraduate and graduate theses at the Universidad Nacional de Colombia (Ferreira, 1998; Hernández & Osorio, 1990; Garzón, 2003) discussed Paipa volcanic rocks as intrusive bodies and domes.

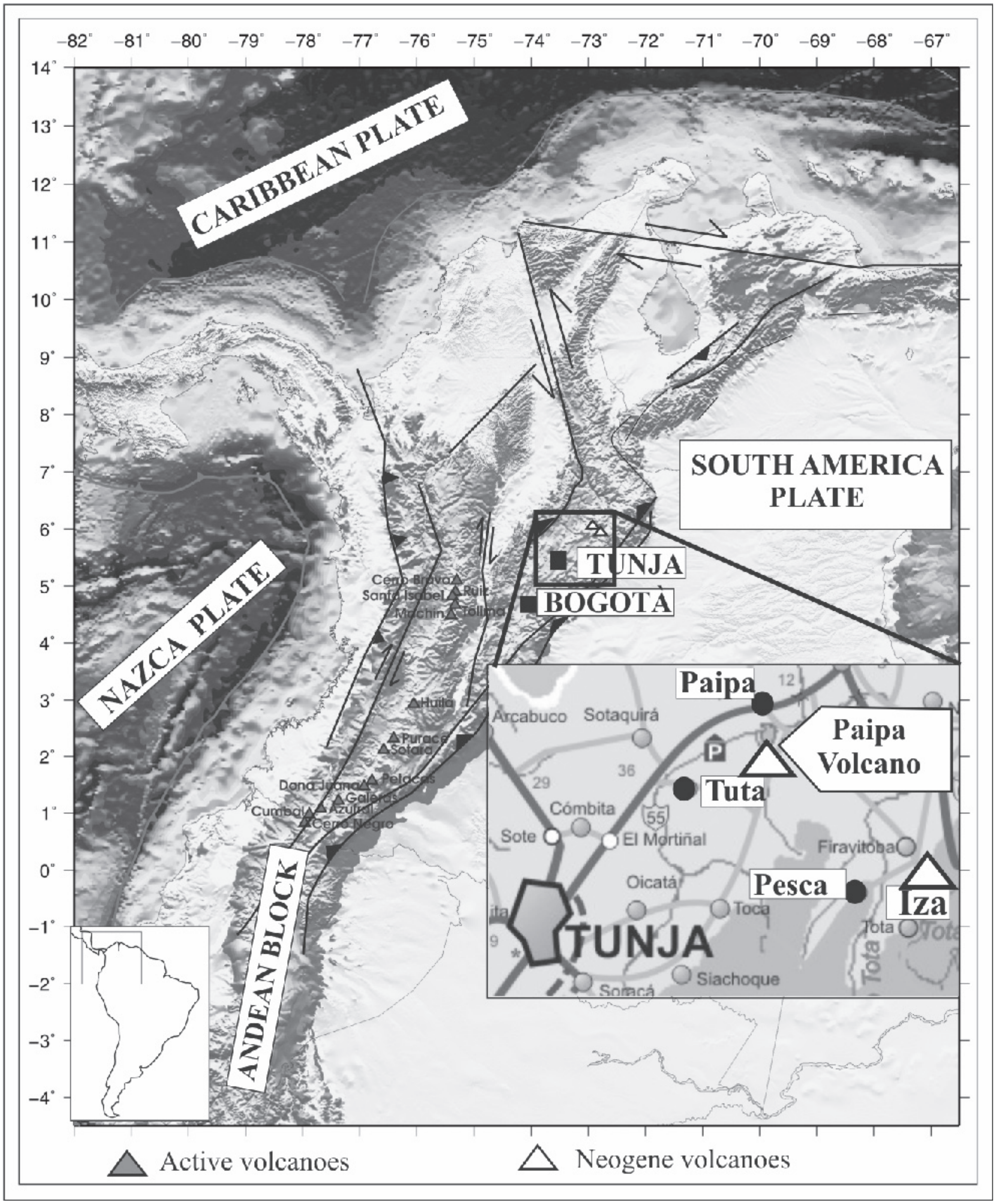

Figure 1. Paipa volcano is localized in the middle part of the Eastern Cordillera (EC) of Colombia.
General geotectonic framework of NW South America and spatial relation with active volcanoes are shown.

In 2003 a preliminary Geothermal Research study was completed by INGEOMINAS with the definition of a high-temperature geothermal system, the identification of a volcanic caldera and the definition of two eruptive epochs (in the sense of Fisher & Schmincke, 1984).

The purpose of this paper is to present part of the results obtained by Pardo (2004) on Paipa volcano, in collaboration with INGEOMINAS and the research on Neogene's volcanism of the EC done by the professor J.M. Jaramillo at the Universidad Nacional de Colombia. The paper presents a detailed geological map, based on 1:25000-scale field mapping, and the volcanic stratigraphy of Paipa volcano (Figure 2). On these bases we defined the transport and accumulation processes of the volcanoclastic material and reconstructed the eruptive history of the Paipa volcano.

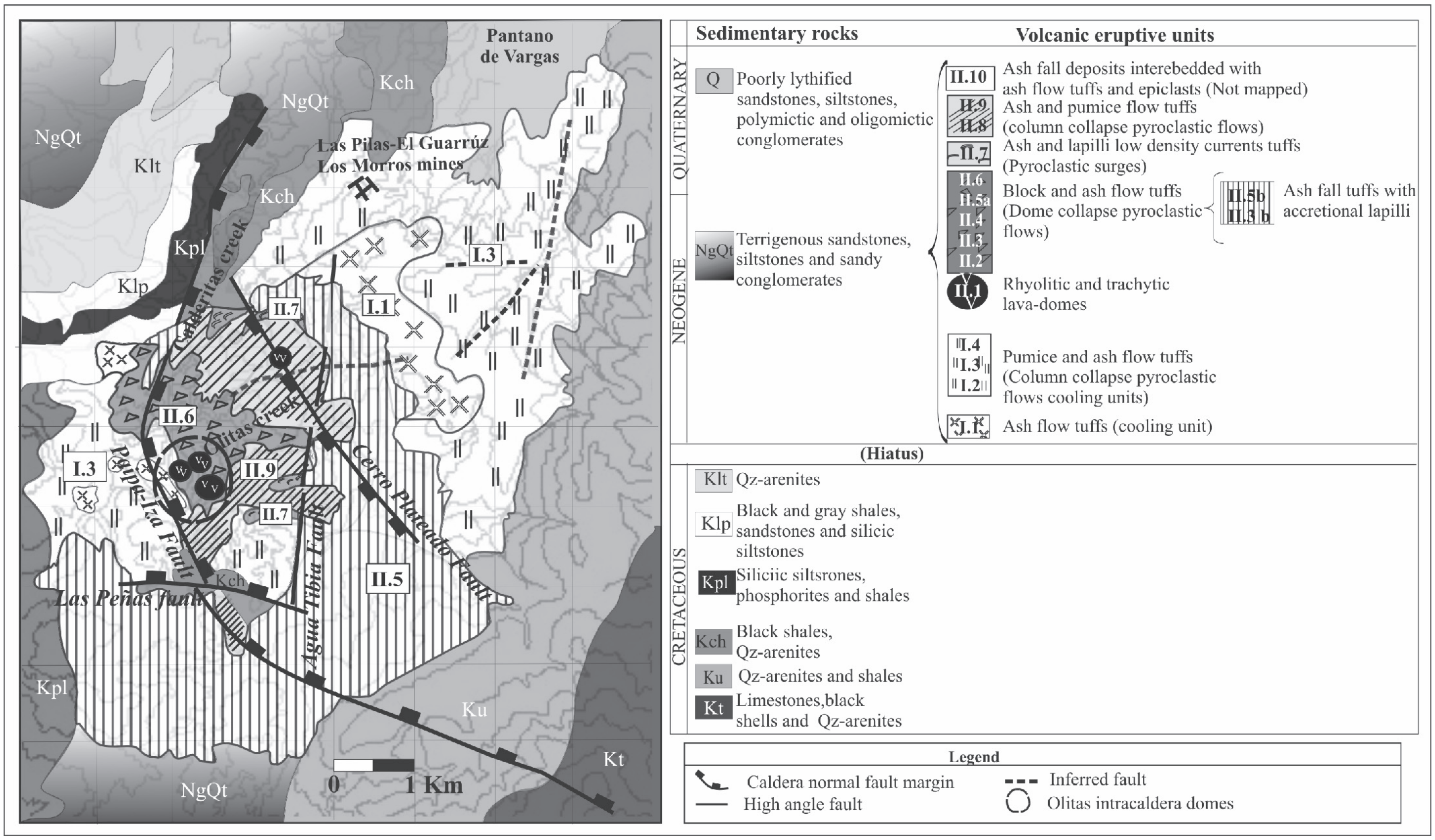

Figure 2. Paipa volcanic rocks follow a NE-SW depositional trend over a 31 Km2 area and unconformally overlay upper Cretacic sedimentary rocks. Ignimbrites outcrop as far as 6 Km away from the original edifice while domes, block and ash flows and surges are confined to the volcanic caldera and are related to intracaldera vents. Paipa Volcano Geologic map. Pardo (2004)

GEODYNAMIC FRAMEWORK

Eastern Cordillera geological history has being the result of a complex interaction between the Caribbean and Nazca plates with the South America plate (Pennington, 1981; Cooper et al., 1995; Trenkamp et al., 2002). Its genesis is related to the convergence of an ancient island arc (Serranía del Baudó-Panamá) that, accordingly to Kroonemberg et al. (1990), approached to the NW part of South America during the Neogene until it collided with the continent seven to three million years ago; Fabre (1983 a, b) registered intense folding during the Miocene and the greatest uplift during Pliocene and Quaternary.

Based on seismotectonic analysis, Taboada et al., (2000) suggested a subduction angle increment for the Caribbean Plate under the Eastern Cordillera at 4ºN latitude, with a segment that gets into the lower mantle. On the other hand, Nazca Plate descends under the paleo-Caribbean Plate segment at an angle of 35º which increases until it overturns in the lower mantle.

Taboada et al., (2000) model has been the only one published that takes into account data from the National Seismological Network (Red Sismológica Nacional) in correlation to the alkaline volcanism present in the Eastern Cordillera, reported by Martínez (1989) in Iza town (Boyacá Department). Based on this data, Early Quaternary EC volcanism has been related to Caribbean Plate subduction under South America (Jaramillo & Rojas 2003). However, the geodynamic environment of the NW corner of South America is still controversial. Paipa volcanic rocks chemistry suggests other hypothesis concerning back-arc volcanism and crustal delamination processes in a transpressive tectonic regime identified in the EC. Slip and normal NW trending faults interact with inverse NE trending regional structures and possibly create the volcanic conduits for trachytic to rhyolitic magmas of alkaline affinity (Cepeda & Pardo, 2004).

STRUCTURAL GEOLOGY

In the studied area there are NE trending inverse faults parallel to the regional structures of the EC and NW trending normal fractures, parallel to the lineaments that Ujueta (1991, Figure 3) proposed to link volcanic and intrusive rocks, such as Cretacic basalts and gabbros, alkaline intrusive bodies and high temperature geothermal springs. We think that the Neogene volcanoes of Paipa and Iza could be also related to this NW faults. The main NW structures are (a) Cerro Plateado Fault (normal), and (b) a fracture that links Paipa volcano to Iza volcano, which suggest also a tensional behavior allowing magma upward flow. Together with the E-W Las Peñas fault and the NE Agua Tibia fault, these four lineaments are the caldera margins (Figure 2) suggested by Pardo (2004), Cepeda et al. (2004) and Cepeda & Pardo (2004).

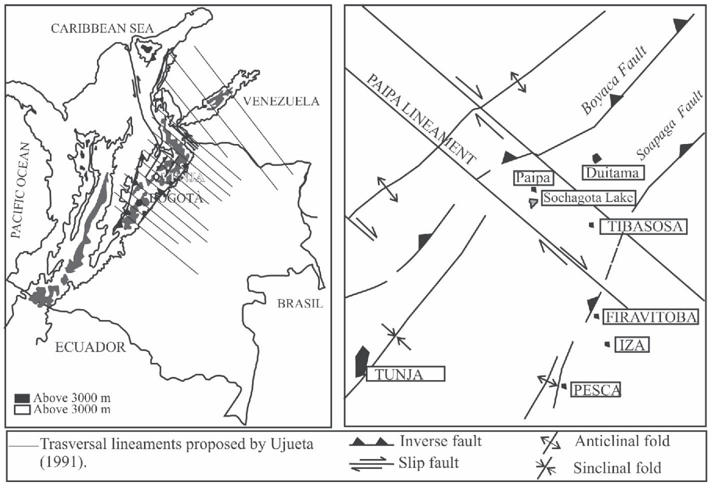

Figure 3. Transversal NW lineaments proposed by Ujueta (1991) and their interactions with the NE structures.

METHODOLOGY

The present work comprised intense literature review, analysis of aerial photos, a 25-days field work, petrography and chemical analysis. We prepared a 1:25000 scale geological map and 13 stratigraphic sections following Cas & Wright (1987), Fisher & Schmincke (1984) and Wohletz & Heiken (1992) recommendations. The term "bed" was used for thickness between 3 cm to meters and the term "laminae" for thickness less than 3 cm (Fisher & Schmincke 1984). Pyroclastic sizes were determined according to Schmid classification (1981 in Wohletz & Heiken 1992), and Fisher & Schmincke (1984) classification of pyroclastic rocks. In each deposit the relative proportion of different fragment types was determined (juveniles, accessories and accidentals). In addition to the petrograhy and chemical analysis (Pardo 2004; Cepeda & Pardo, 2004), two samples were sent to the University of Sao Paulo (Brasil) for Ar/Ar and one to Canada (ACTLABS laboratory) for K/Ar radiometric age dating.

The detailed stratigraphic field work (1:100 to 1:20 scale) and the 1:25000 scale field mapping allowed us to identify different eruptive units (in the sense of Fisher & Schmincke, 1984) formed by tephras, non- lithified pyroclastic deposits, pyroclastic rocks, lithified deposits, and epiclastic deposits. Based on this, we inferred the transport and accumulation processes and we reconstructed the Paipa volcano eruptive history.

VOLCANIC STRATIGRAPHY

The Paipa volcano (Figure 4) has an eroded edifice which reaches 280 m over the Cundiboyacence High-Plateau on the Eastern Cordillera, 2780 m above the mean sea level. The Paipa volcano has a caldera with a maximum diameter of 3 km and there are several vents inside it as indicated by the existence of lava-domes and by the lateral facies variation in pyroclastic deposits. The Volcanoclastic deposits cover a 31 Km2 surface and unconformally overlay older Cretacic sedimentary rocks (Figure 2).

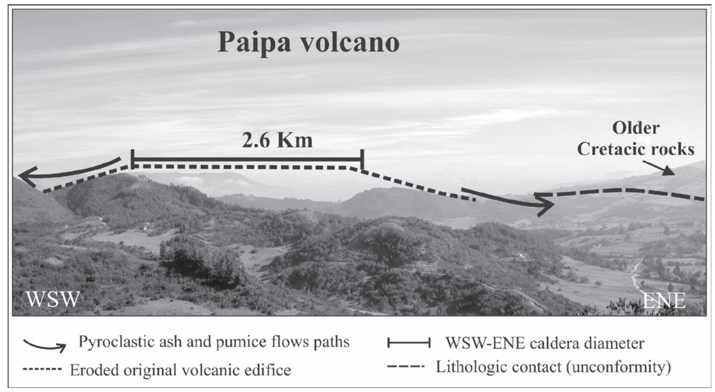

Figure 4. Panoramic view of the Paipa volcano eroded pyroclastic edifice (foreground). Older Cretacic rocks appear on the background and surrounding Paipa volcano.

We defined 14 eruptive units; their nomenclature is given by a roman number that denotes the eruptive epoch (I for the first eruptive epoch, FEE, and II for the second one, SEE) and by a natural number which states the depositional order:

Unit I.1 (Figure 5a): it is a pyroclastic flow cooling unit formed by welded, poorly sorted pyroclastic rocks, with less than 5% of accidental block-size lithics, chaotically distributed in a glassy matrix with 20-40% of 1 mm to 2 mm crystals. The thickness of this unit varies accordingly to the paleotopography; the maximum measured thickness was 150 m but it must be thicker because we could not observe the base of the unit in several places. These rocks were classified as alkaline rhyolites crystal-vitric tuffs, with aligned sanidine, anorthoclase, hastingsite and sphene crystals in a glassy matrix (Pardo, 2004). The accidental lithics are phylites, chert, phosphoric and silicic siltstones. The phylite accidental lithics are probably from the Paleozoic basement which outcrops to the NW of the volcano, while the sedimentary accidental lithics are samples of the cretaceous cover that outcrops around the volcano; the co-magmatic accessory fragments are altered pumice and oxidized volcanic rocks derived from the volcanic conduit.

Facies associations suggest deposition by pyroclastic flows originated by continuously collapsing columns and accumulation near the vent.

Correlation: Unit I.1 outcrops at the foothill of El Mirador hill and at Alto Los Volcanes high, westward Honda Grande Creek; it also form the Alto Los Godos hill, at the east of Honda Grande Creek, where it reaches the greatest thickness (>150 m without basal outcropping), where is greater the content and the size of accidental lithics and where the hydrothermal alteration is more evident (adularia-trydimite-illite). From Alto Los Godos hill toward the NE and from El Mirador hill toward the SW matrix/clast relation increases while average thickness and hydrothermal alteration decrease. This unit forms the paleotopography for all other younger volcanic deposits; fragments of these rocks are common as accessory lithics in overlaying units (Figure 5b).

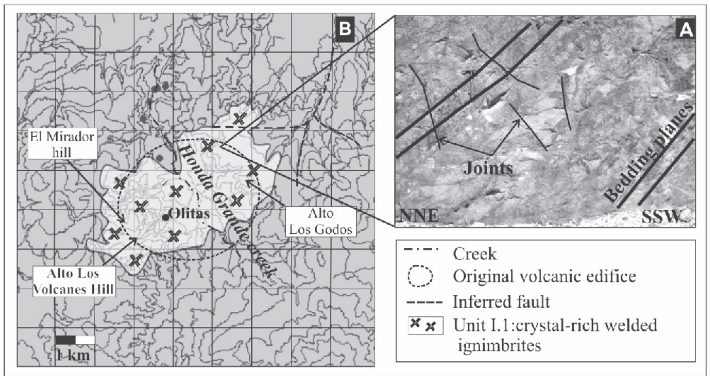

Figure 5. (a) Unit I.1 is a poorly sorted and welded ash flow tuff with Kfs crystals up to 1,5 cm and accidental metamorphic lithics in a fine ash and pumice matrix. (b) Distribution of eruptive unit I.1.

Unit I.2: it is a pyroclastic flow cooling unit deposited over an erosion surface at the top of the unit I.1 (Figure 6a). It consists of very poorly sorted pumice and ash flow tuffs, with pumice juvenile fragments and very angular phylites, quartzites and sandstones accidental lithics up to 30 cm, chaotically distributed in a yellow-brown pumice and ash matrix. At the top there are deep incisions as 10 m deep grooves which suggest an erosive domain after deposition. Rocks are high-K calcalkaline rhyolites, vitric-crystalline flow tuffs dispersed along paleovalleys (Pardo, 2004). Its textures and composition indicate pyroclastic flows originated by collapsing eruptive columns.

Correlation: in the type-section (in Las Pilas-El Guarrúz puzzolana mines; Figure 6b), it reaches the greatest thickness (100 m) without showing the base. Thickness is controlled by the topography. The unit is well exposed from Alto Los Godos hill to the NE, E and SE directions, getting thinner in those senses while fragments size decreases and particle roundness increases; therefore, deposits range from pumice and ash flow tuffs to ash and pumice flow tuffs with distance from Alto Los Godos hill to the NE and E.

Unit I.3: it was deposited over an erosion surface and overlays unit I.2 in El Guarrúz and Las Pilas mines (Figure 6). It is a very poorly sorted ash and pumice deposit, with 25 % of very angular accidental blocks in a cream ash and pumice matrix. Accidental lithics are block-sized (up to 40 cm) fining-upward while pumice juvenile fragments are coarsening-upward. The main characteristic of the unit is the high content (30%) of armored lapilli up to 25 cm in diameter (Figure 7). Rock samples are high-K calcalkaline rhyolites, vitric-lithic flow tuffs (Pardo, 2004) with 15%-25% of accidental phylites, red, yellow and green sericite-bearing siltsones and mudstones, quartzites, chert and green sandstones. Accessory lithics are mainly crystalline-vitric ignimbrite fragments from unit I.1. The strong topographic control in dispersion and thickness variation, the poor sorting, the flow textures and the composition suggest a pyroclastic flow cooling unit formed by the accumulation of single flow units originated by collapsing columns that were not differentiated in this study because paleo-soil horizons lack lateral continuity.

Correlation: it covers a 31 Km2 surface (Figure 7b) being the most extended deposit. Its thickness varies accordingly to topography and it reduces from Alto Los Godos hill towards the NE and from El Mirador and Alto Los Volcanes hills towards the SW; lithic content, sizes and angularity decrease in the same directions. Maximum thickness was measured in Las Pilas-El Guarrúz mines, where it reaches 30 m (Figure 6).

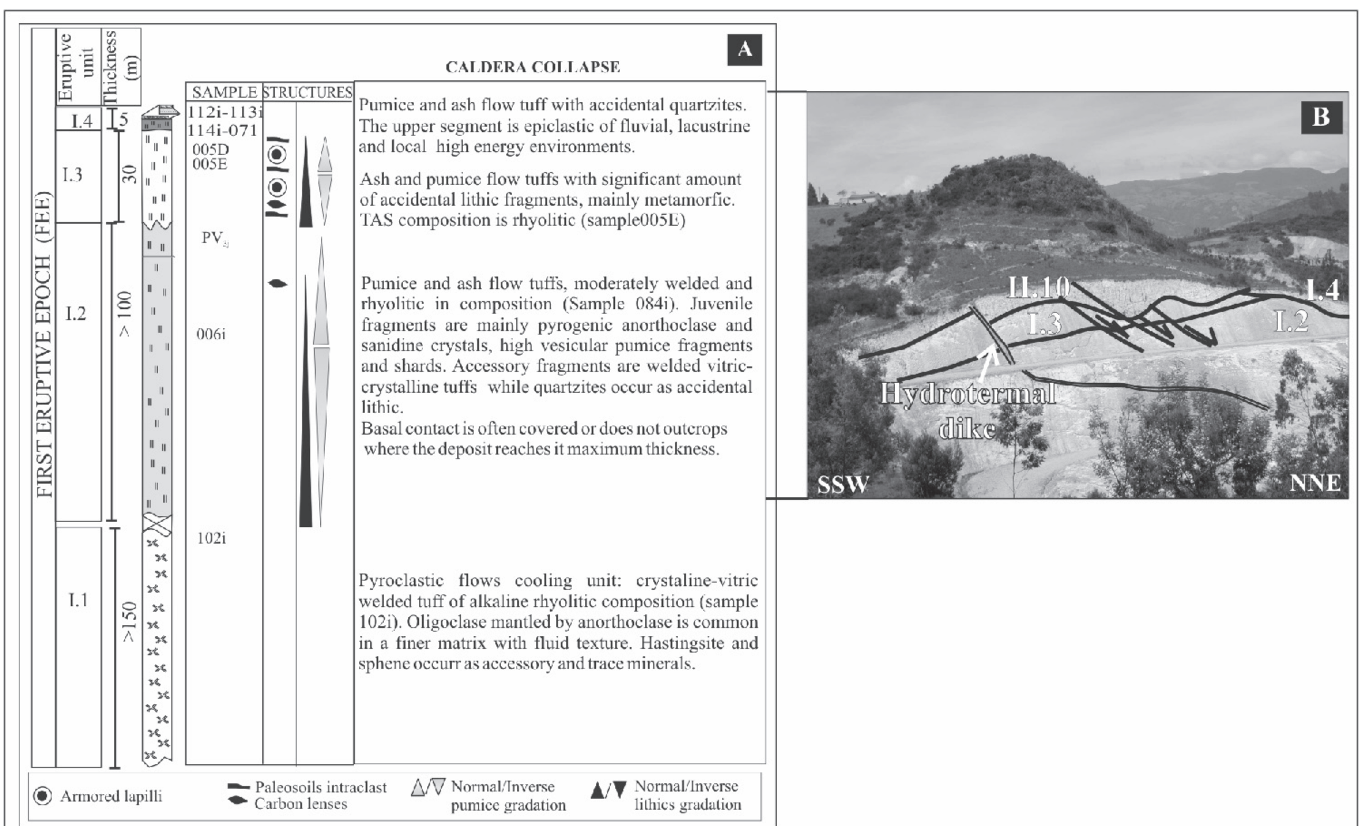

Figure 6. (a) General Stratigraphic section showing the four eruptive units deposited during the FEE. B) The stratigraphic type section of the FEE is located at the NE, at the puzzolana mines Las Pilas-El Guarrúz-Los Morros, where the total thickness of the ignimbrites was estimated in 285 m.

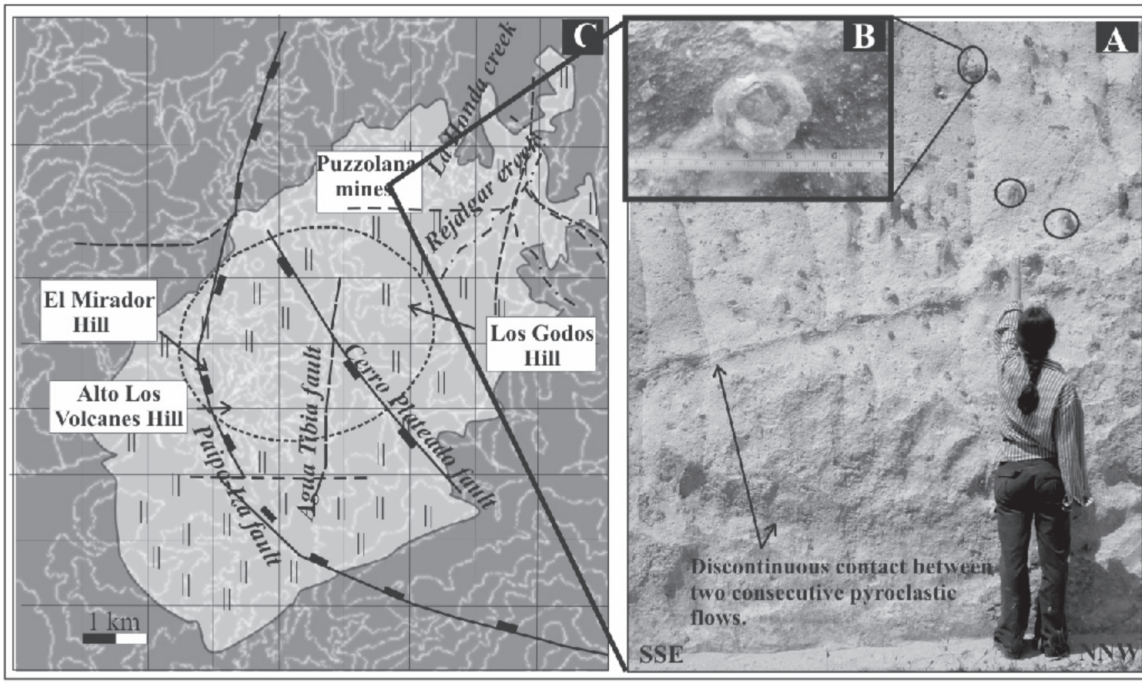

Figure 7 (a) Unit I.3 is a pyroclastic flow cooling unit where the abundance of armored lapilli, together with a significant content of accidental lithics suggests a phreatomagmatic mechanism. (b) Close-up on armored lapilli. (c) Spatial distribution of eruptive unit I.3. Thickness variation, granulometry, texture and compositional variation show evidence of a nearby central vent.

Unit I.4: the lower segment is mainly pyroclastic and the upper segment is mainly epiclastic. The former fills paleovalleys and it was not found over more than a 1 Km2 surface area, with a maximum thickness of 4 m (in Los Morros mine; Figure 6). It is a white poorly sorted deposit, highly vesicular pumice and ash flow tuff, with quartzites and phylites blocks in a vitric-clastic matrix. Vitric-crystalline ignimbrite fragments are the main accessory lithics. Those rocks are modal alkaline-feldspar trachytes with anorthoclase and sanidine crystals in the matrix (Pardo, 2004). Poor sorting, topographic control, nature and composition suggest deposition by pyroclastic density currents. Its high spatial restriction could be due to a strong erosive period after accumulation or due to the origin of the flow. The evidence of high degasification, the absence of co-ignimbrite ash fall deposits and the restriction of crystals to the matrix while they're absent in pumice fragments, could signify a boiling over process, but it could also be the result of a small column collapse.

The upper segment is formed by heterolithologyc well stratified set of sedimentary beds, well exposed along Agua Tibia fault (Figure 2). Those are mainly fining upward feldspar fine-grained sandstones, (Atv facies) and white fine-laminated siltstones (Lmc facies) that suggest moderate-energy fluvial currents and very low-energy environments in which finer particles could settled down. The base is not well exposed, deposits are entirely folded and faulted, beds are vertical and siltstones are crenulated (Figure 8). In the same stratigraphic position there are polymictic poorly sorted conglomerates lenses with random angular gravels locally imbricated, which reflect very high-energy deposition environments where deposition occurred as slope changed. Those deposits outcrop outside the structural polygon defined by Agua Tibia fault, Cerro Plateado fault, Paipa-Iza fault and Las Peñas fault, while Atv and Lmc facies outcrop along these structures and inside the polygon.

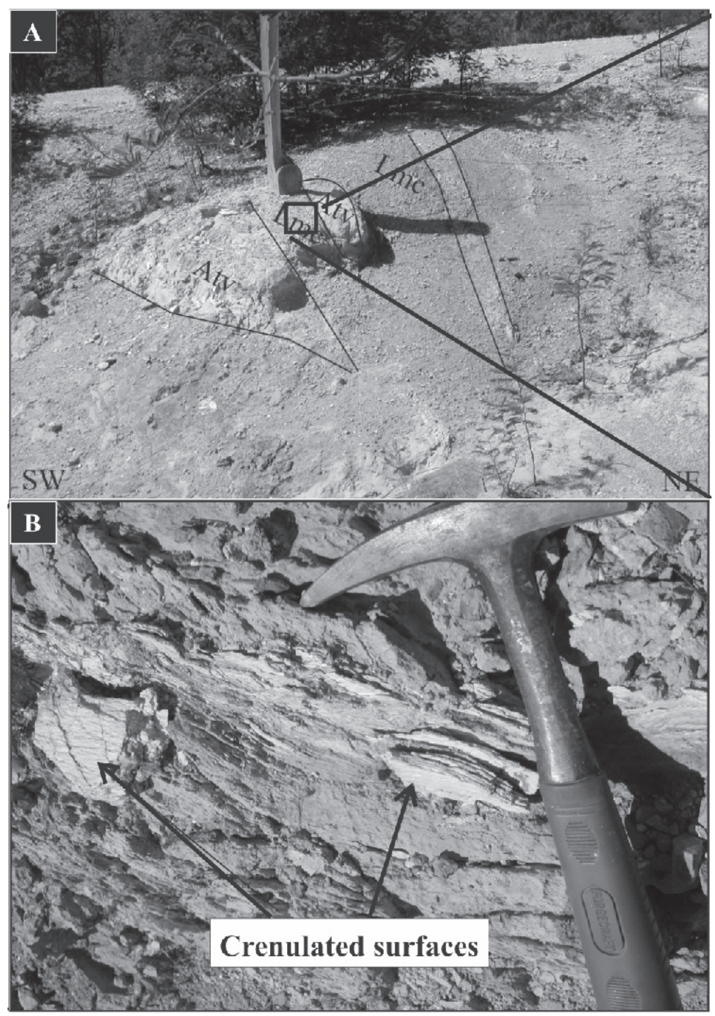

Figure 8. The upper segment of the eruptive unit I.4 is composed of poorly lithified epiclastic sandstones and siltstones which suggest fluvial and lake-environments at the end of the FEE. Structural deformation and fracture of these deposits, which outcrop along Cerro Plateado and Agua Tibia faults, resulted from structural collapse and the formation of a caldera in the volcanic edifice.

Facies association indicates a quiescence period in volcanic activity, during which more than 3 m thick sedimentary beds were deposited in a fluvial-lake environment, and long enough for a structural event to occur, responsible for local deformation and fracturing. This event allow us to distinguish two (2) eruptive epochs (FEE and SEE), suggested also by the spatial configuration of the following deposits that reflect a change in the eruptive style (Figure 9). Three (3) types of volcanic products characterize the SEE: (a) lava-domes and (b) block and ash flow tuffs confined into the structural polygon; (c) ash fall deposits inside and outside de structural polygon, mantling previous topography.

Unit II.1: porphyritic lava-domes outcrop at the head of Olitas Creek, associated to Paipa-Iza fault (Figure 9). Those are hypocrystalline alkaline trachytes and rhyolites (Pardo, 2004), that suggest that volatile release was continuous through the permeable conduit walls while magma rising occurred. Eruptions were rather effusive than explosive. Near the intersection of Agua Tibia fault and Cerro Plateado fault there is another rhyolitic dome (Figure 9b). However we lack of radiometric data to clearly correlate it to Olitas domes.

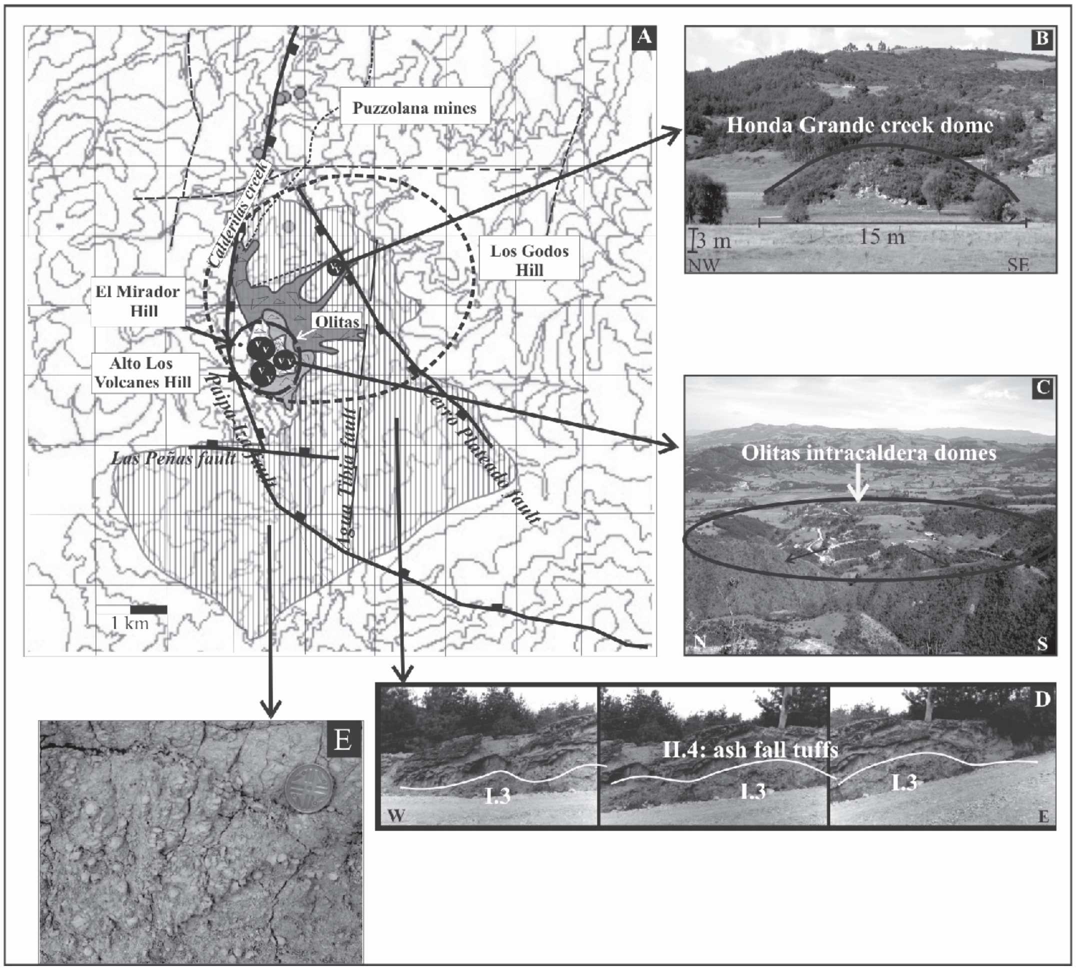

Figure 9. (a) Distribution of intracaldera domes and first SEE deposits. (b) Honda Grande Creek rhyolitic dome. (c) Facies lateral variation, the domes and the hydrothermal alteration show evidence of an eruptive intra-caldera vent at the head of Olitas Creek, related to Paipa-Iza fault. Younger eruptive units II.2 to II.6 consisted in block and ash flows caused by dome collapse. (d-e) Contemporaneous accretional lapilli rich ash fall deposits were deposited outside caldera margins, mantling previous topography.

Over lava-domes (Figure 10) there are five (5) pyroclastic block and ash flow units: the first two (2) units (II.2 and II.3) show the least transport since fragments have the greatest sizes (up to meters) and angularity. Those are restricted to Quebrada Olitas stream along which there is a gradation from block and ash flow tuffs to ash and block flow tuffs towards the E. Those deposits are monolithologic, composed of dome fragments and without juvenile pumice. Their thickness varies accordingly to topography: a maximum of 43 m was estimated for unit II.2 and 30 m for unit II.3. The strong topographic control, the crude sorting and composition suggest pyroclastic density currents originated by dome-collapse.

Over the unit II.4, which is a small flow tuff with pumice, there are other two (2) dome-collapse flow units confined to Quebrada Olitas valley and Quebrada Calderitas valley, along which thickness and grain sizes reduces towards the north along Quebrada Calderitas valley and towards the east along Quebrada Olitas valley. Unit II.5 is 6 m thick and it has the greatest proportion of accessory dome fragments and accidental metamorphic lithics (schists, phylites and quartzites). Unit II.6 is 42 m thick and it contains juvenile and accessory lava-dome fragments in a finer red to cream matrix with sanidine and biotite ash-size crystals.

All these units have a polymodal size distribution (Figure 10); dense dome fragments possibly gave high density and low mobility to the flows, therefore, those deposits are restricted to the first 3 Km from the vent, located at Olitas headstream (Figure 9).

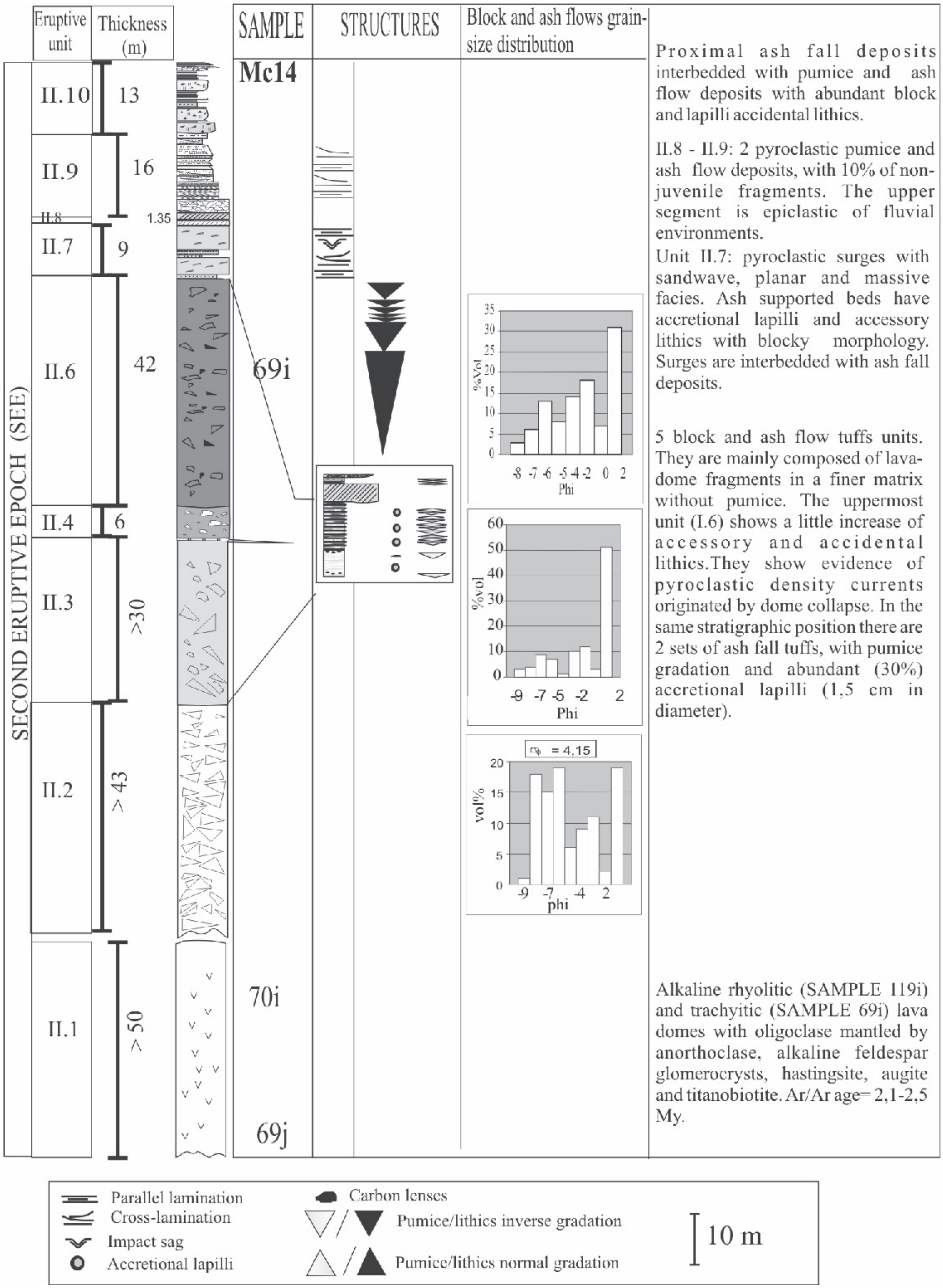

Figure 10. General stratigraphic section showing the 10 eruptive units accumulated during the SEE during caldera resurgence.

In the same stratigraphic position respect to units II.3 and II.5 there are two (2) sets of ash fall tuff beds in distal zones (Quebrada Calderitas valley, Quebrada Agua Tibia valley and Pastorero village). Ash fall beds mantle the topography (Figure 9d) and their thickness tend to increase towards southwest. They are depleted in pumice, lack of internal structures, and contain about 25-20% of 1,5 cm- diameter accretional lapilli (Figure 9e). Deposits suggest accumulation from the column umbrella region and their dispersion indicates wind directions from the northeast. Geochronology is needed to confirm their correlation to block and ash flow proximal facies of units II.3 and II.5.

Unit II.7: this unit covers a 2,5 Km2 surface area (Figure 11 a) and overlies an oxidized crust there lies a well stratified deposit. The proximal facies (Figure 11 b) are massive, iron stained (orange), poorly sorted, with juvenile pumice, mixed composition pumice blocks and accidental metamorphic lithics in an ash and pumice matrix. Four (4) eruptive phases were distinguished in the medial zone where it reaches 10 m thick (Figures 11 c): two sets of planar and sand wave facies typical of surge deposits, fine-grained and cross-laminated beds with sand wave facies containing accretional lapilli. Between them there is a multiple laminated ash fall deposit with impact sag structures (Figure 11 d) and a well stratified deposit where ash and pumice beds are interbedded with lapilli beds that contain aligned juvenile and accessory dome fragments finer than 1 cm, with prismatic fracture, probably deposited by a blast density current. At the top of the unit there is a 15 cm thick bed of massive purple mudstones with oxidized laminae and sporadic carbon lenses that outcrops all over the studied area (Paleosoil Ps1). The stratigraphic column is shown in Figure 10 e.

Correlation: the distal facies are volcano-sedimentary sets in which coarsening upward sandstones in fining upward subsets are interbedded with very well sorted ash fall beds (Figure 11 f).

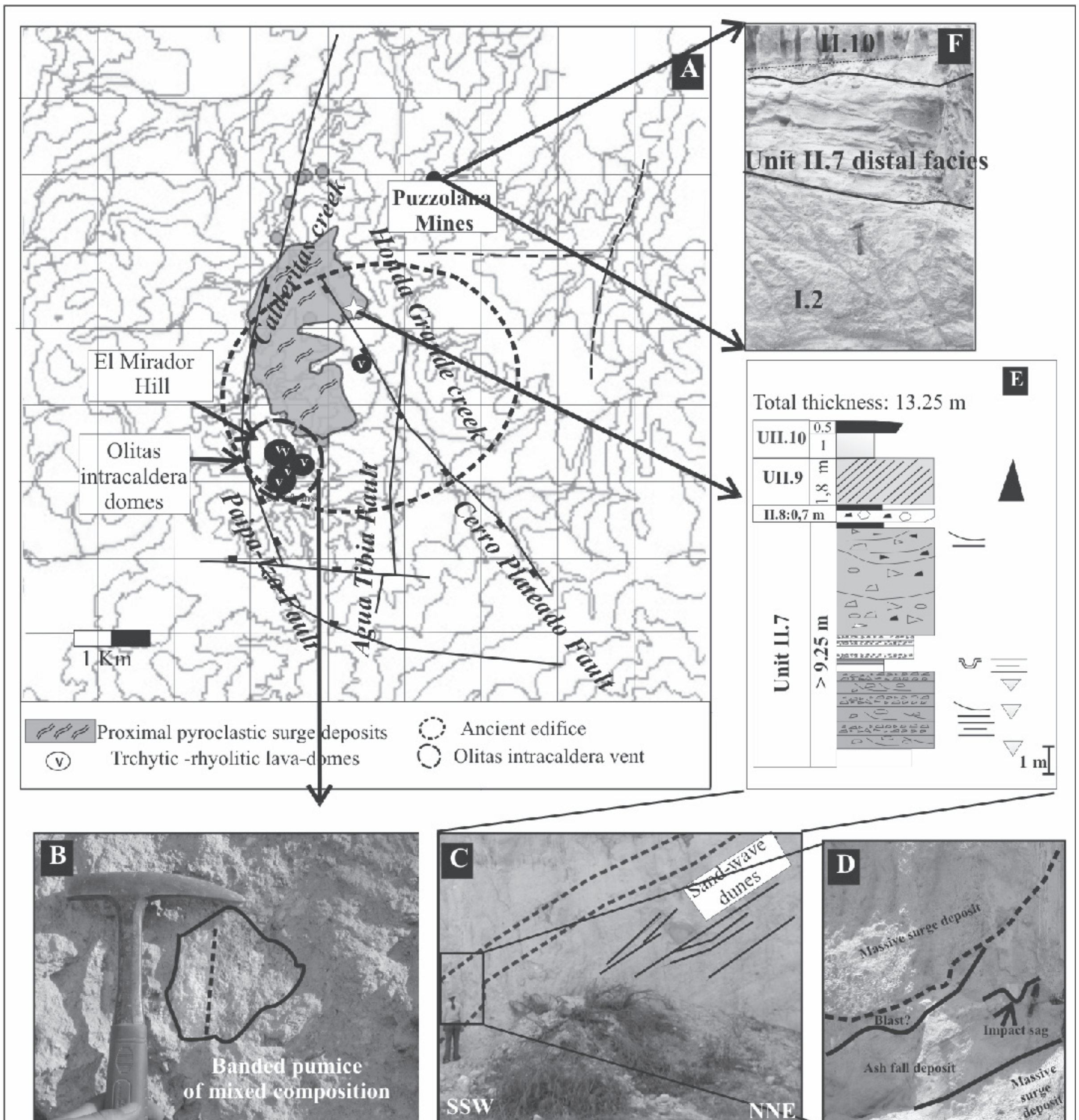

Figure 11 (a) Spatial distribution of proximal surge deposits. (b) Proximal facies are less well stratified, poorly sorted, with rare pumice fragments of mixed composition. (c) Medial deposits show sand-wave structures, planar facies and massive facies in regular to well sorted beds interbedded with very well sorted ash fall deposits. (d) Close-up on ash fall deposits with impact sags. (e) Stratigraphic section of medial facies. (f) Distal facies are epiclastic sandstones interbedded with ash fall deposits.

Facies association suggest that, while pyroclastic surge deposits remained restricted to the structural polygon, erosion and transport processes occurred in distal regions outside it. Surges are wet-type, since there are abundant massive facies in proximal zones, accretional lapilli in sand-wave facies (medial zones), plastic deformation in ash fall beds (impact sags) and there is significant content of accidental lithics. In general, fragments have prismatic fractures and blocky morphologies.

Over paleosoil Ps1 and separated by another brown-purple paleosoil (Ps2), there are units II.8 and II.9 (Figures 10, 11 e, 12) which are two poorly sorted ignimbrite deposits with accidental phylites and accessory fragments. Each one has a maximum thickness of 1m, but it varies accordingly to topography. Thickness, lithic content and clast angularity decrease from Alto Los Volcanes and El Mirador relieves towards N, E and S directions. These deposits overlay a minimum area of 6 Km2 (Figure 12 a). In distal zones we identified reddish beds of pumice and ash tuffs with accretional lapilli in the same sratigraphic position, but granulometric and radiometric age determinations are required to define if those deposits are coeval co-ignimbrite ashes or distal facies of the same ignimbrites.

In proximal zones, at the top of the unit, there is an epiclastic segment of slope and high-energy fluvial environments (Figures 10, 12 b-c). It is up to 14 m thick and is mainly composed of clast-supported conglomerates, poorly to moderate sorted coarse sandstones and well sorted sandstones at the top.

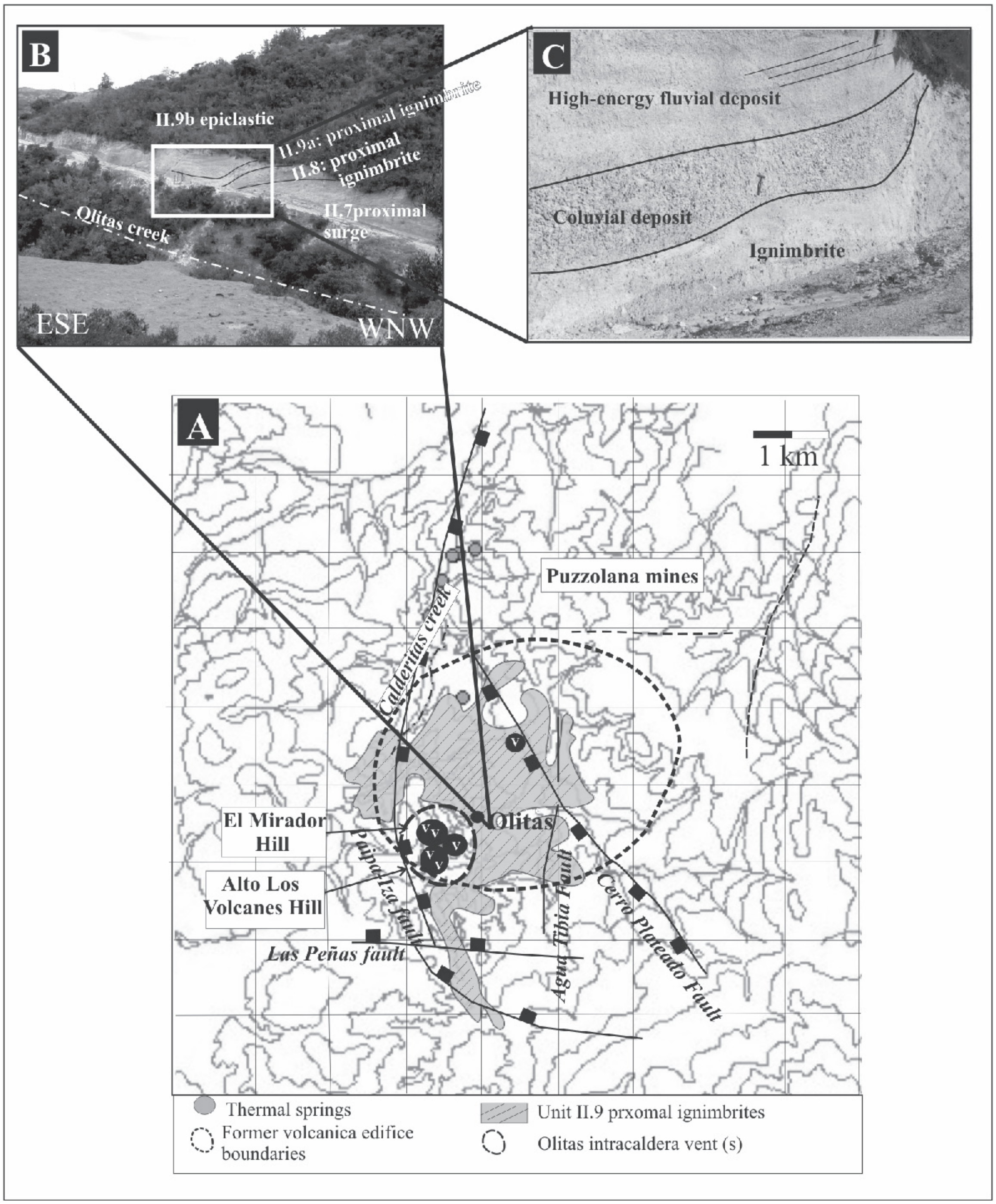

Figure 12 (a) Unit II.9 ignimbrite spatial distribution. (b) In proximal zones massive facies are separated by erosion surfaces and coarse grained epiclastic deposits overlay older pyroclastic deposits. (c) Close-up of (b).

Unit II.10: The lower segment of this unit is mainly composed of pyroclastic rocks while the upper segment is mainly composed of epiclastic rocks (Figure 13 a). It is formed by well stratified sets of well sorted gray and purple ash beds, with cyclic gradation of pumice, interbedded with tabular massive and poorly sorted pumice, lapilli and blocks beds; most of the fragments being accidental and intensely altered. 13 of these pyroclastic sets are separated by dark gray laminated siltstones beds and laminae (Figure 13 b). Gradually epiclastic rocks begin to increase upward, consisting of heterolithologic sandstones, conglomerates and siltstones (Figure 13 c). At the top of the unit there is a brown non lithified and very well stratified ash tuff bed with 80% of angular sanidine and plagioclase. Where it has not been cut by erosion, it is up to 30 cm thick (at El Guarrúz mine). It represents the last eruption known for Paipa volcano.

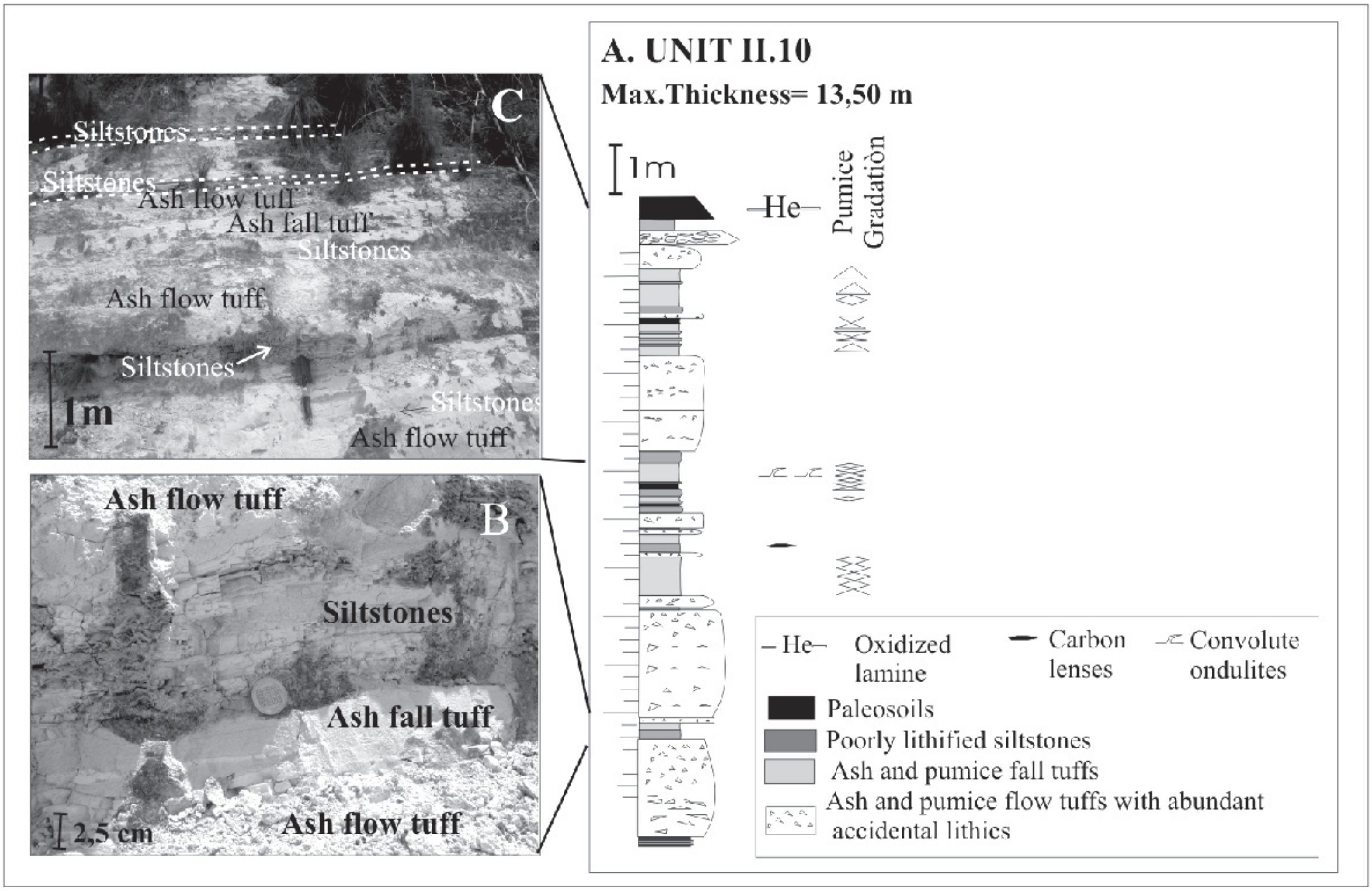

Figure 13 (a) Stratigraphic column of proximal deposits of unit II.10. Multiple layers of ash fall deposits are interbedded with pyroclastic pumice and ash flow tuffs and fine laminated siltstones shown in b and c.

In that way, well stratified massive ash beds suggest deposition as ash falls from umbrella region of unstable columns, often collapsing and generating pyroclastic flows represented by the massive poorly sorted pumice and lapilli deposits. The volcanic activity decreased gradually leaving place to reworking by fluvial processes.

Correlation: The pumice and lithic lapilli lenses that outcrop at the eastern margin of a Honda Grande creek and in El Guarrúz mine are always restricted to paleovalleys. Ash beds can be found all over the studied area mantling the paleotopography and alternated with purple mudstones. Their thickness increases towards the NNE, until Cruz de Murcia village, where those have been interpreted by Renzoni (1967) and Renzoni et al. (1983) as Tilatá Formation without palinological criteria.

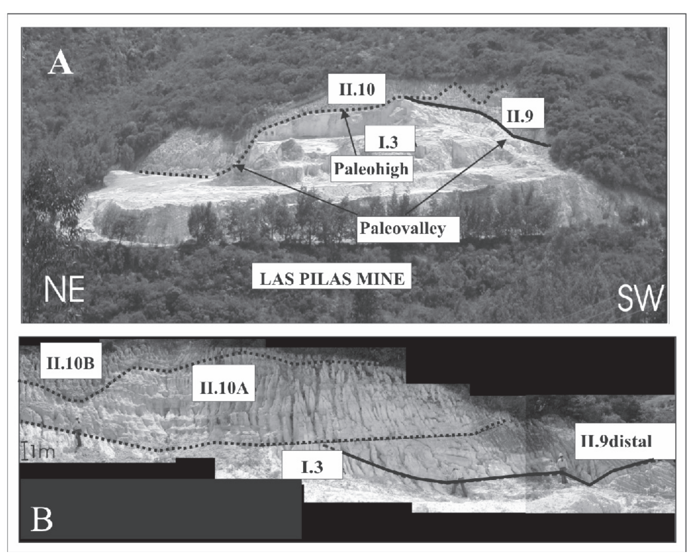

Figure 14. Artificial cuts made for mining the volcanic material for puzzolana cement (a) in distal zones deposits are very fine with sedimentary deposits of epiclastic origin prevailing over ash fall tuffs.

Type of volcano: Based on the field work and facies analysis described above, we conclude that the Paipa volcano was a pyroclastic edifice that was partially destroyed by a caldera formation. The volcanic products show a typical caldera facies association. Outflow facies are represented by ignimbrites (units I.1 to I.4), accretional lapilli rich ash fall deposits (distal facies of units II.3 and II.5), ash and pumice fall deposits (Unit II.10), epiclastic torrential and fluvial sandstones and conglomerates. Outside caldera margins, represented by normal and high-angle faults, and near them there are several geothermal water springs and CO2 gas seeps. Inflow facies are represented by rhyolitic and trachytic lava domes, most of them confined between El Mirador and Alto Los Volcanes highs, related to the SW margin of the caldera (Paipa-Iza fault) and an isolated-one placed near the NE limit (Cerro Plateado-Agua Tibia faults). Confined into the caldera depression there are block and ash flow tuffs, pyroclastic surge deposits and fine-graded ash fall tuffs interbedded with fluvial and lacustrine deposits together with local slope deposits. Geologic map (Figure 2) shows actual deposits distribution without the geology of the youngest eruptive unit II.10 that occurs discontinuously in isolated outcrops. Grain-size, thickness and lithic-content lateral gradation suggest a central vent from which products of the FEE could form; thickness and grain sizes tend to decrease towards the NE and the SW, while they increase towards Quebrada Honda Grande alluvial valley, which is a morphologic depression located where the former central vent must be placed. No epiclastic deposits suggesting strong erosion are founded, nor evidence of ignimbrites removal by fluvial agents; therefore, greatest thickness must be under the actual depression. Together with the eruptive units already described and the existence of normal faults and high-angle slip faults bordering the depression, facies association suggests the existence of a volcanic caldera. In that way, several intracaldera vents were originated during the SEE as resurgence occurred, most of them located at the head of Quebrada Olitas stream where domes ad coarser deposits occur (Figure 15).

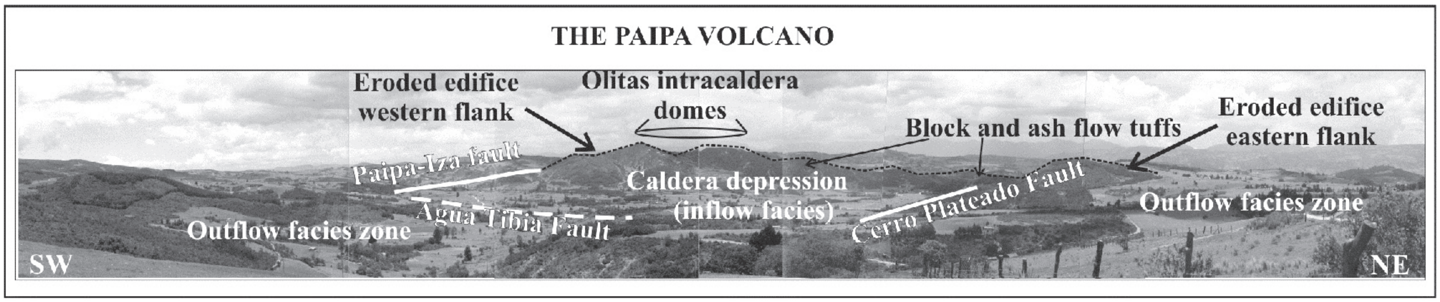

Figure 15: Paipa Volcano actual morphology. It has an eroded edifice formed by older ignimbrites, a 3 Km caldera with several vents inside it, most of them concentrated in Olitas headstream. NNW to NE faults and E-W faults are the possible caldera boundaries. NW Paipa-Iza fault and Cerro Plateado fault favored magma ascent to the surface.

RESULT SYNTHESYS: PAIPA VOLCANO ERUPTIVE HISTORY

Following Fisher & Schmincke (1984) terminology, we defined two eruptive epochs with 14 eruptive units separated by paleosoils and erosion surfaces: four ignimbrite units originated from a central vent took place during the FEE which ended with the caldera collapse; and ten units were formed during the SEE as a result of caldera resurgence.

The first eruption known for Paipa volcano was probably the result of magma interaction with external water, as suggested by phreatomagmatic shards, surface pitting and lack of juvenile fragments, reported in Cepeda & Pardo (2004). Unit I.1 suggests that explosive and thermodynamic conditions were unable to forming high eruptive columns but favored continuous column collapse. Pyroclastic flows produced in that way, built a pyroclastic edifice whose eroded walls still present (Figure 16 a). After a period of erosion or no deposition, system instability promoted by magma input, by volatile injection or by a sudden release of pressure, enhanced bubble formation, bubble coalescence and the transformation of the liquid-crystal and dissolved gases melt to a mixture of gases with suspended liquid drops and solid fragments; density reduction enhanced rapid acceleration outside the vent, producing a second eruption (Unit I.2). Apparently eruptive columns did not reach large heights and they collapsed to form pyroclastic pumice and ash flows from the vent towards northeast, filling the valleys and without exceeding distances greater than 6 km (Figure 16 b and c).

A third eruption unit was deposited after the probable explosive interaction between magma and water (phreatomagmatic mechanisms), as suggested by the accidental lithic content, by armored lapilli (Figure 16 d), by the presence of blocky and pyramidal shards, together with implosion cracks, hydration cracks and pitting (Pardo 2004; Cepeda & Pardo, 2004). Column collapse promoted the generation of vitric-lithic pyroclastic flows that traveled from the central vent towards the NE and the SW, covering a 31 km2 surface area. During a quiescence period a 7 cm thick paleosoil was formed. Later, bubble nucleation, rapid gas release and expansion processes created foam in the magma until it spread out forming a small vitric flow lobe over the north-eastern edifice flank (possible boiling over process, Figure 16 e).

These four (4) eruptive units comprise the greater thicknesses and the greater surface area covered by Paipa volcano products, supporting the hypothesis of a possible evacuation of a considerable volume from the magmatic chamber (close to 6 Km3), which could enhanced its roof collapse and the formation of a 3 Km-diameter caldera at the end of the FEE. In the meanwhile, erosion and high-energy fluvial deposition occurred in the outflow zone, outside caldera margin faults; inside the caldera depression poorly lithified fine-grained sandstones and siltstones were deposited (Figure 16 f).

In the following graphic model (Figure 16) the eruptive columns are not represented at scale.

PAIPA VOLCANO ERUPTIVE HISTORY MODEL

FIRST ERUPTIVE EPOCH (FPE):

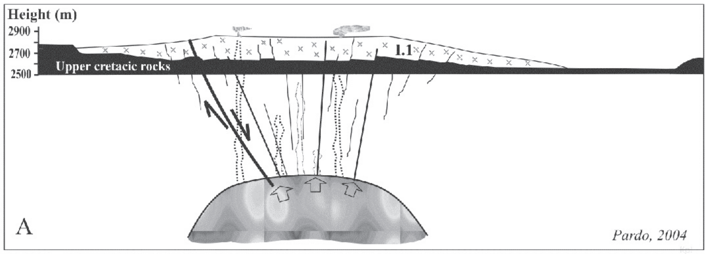

Figure 16 a. After the deposition of Bogotá formation (Paleocene), an eruptive center was originated in the middle part of Eastern Cordillera of Colombia, between 5°40'28" and 5°45'20" N UTM latitudes and 73°9'4" a 73°3'39" W longitudes. Viscous and highly explosive alkaline trachytes to rhyolites magmas and high-K calcalkaline magmas were erupted. Continuous deposition of ash pyroclastic flows originated by collapsing columns formed the pyroclastic edifice overlying older cretacic rocks.

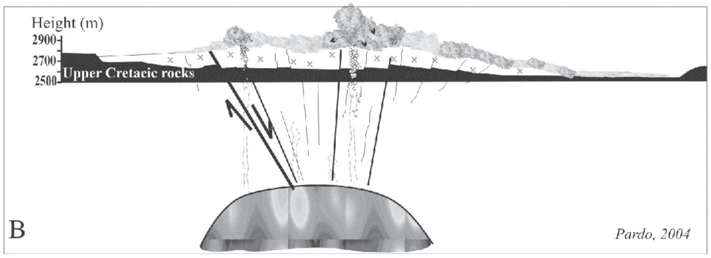

Figure 16 b. Explosive eruptions took place through one or several craters and ignimbrites were formed.

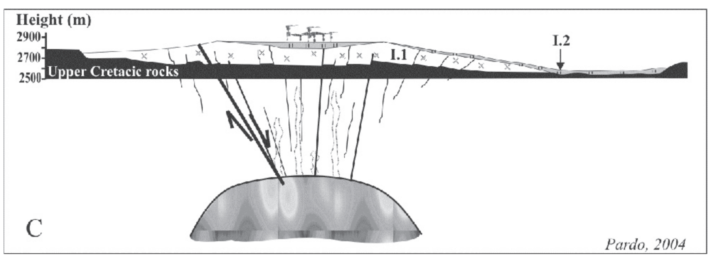

Figure 16 c. During a quiescence period volcanic relieve was eroded while torrential epiclastic deposits were deposited in topographic lows around the edifice.

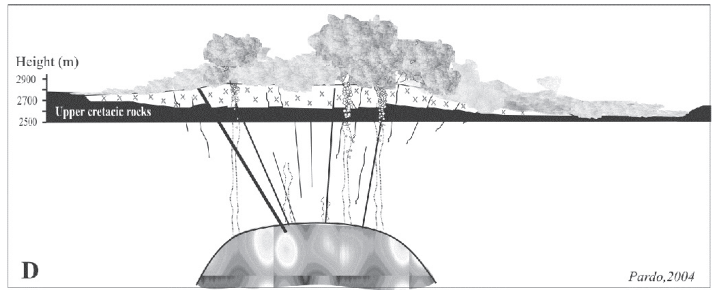

Figure 16 d. After a quiescence period the most intensive activity took place. Pumice and ash pyroclastic flows spread towards the SW and NE occurred by collapsing columns. Vesiculation and fragmentation was enhanced by explosive magma/water interaction, transporting basement metamorphic lithics outside the vent and forming agglutination structures around lithic lapilli and block-size nuclei (i.e. armored lapilli) which characterize massive and poorly sorted ignimbrites.

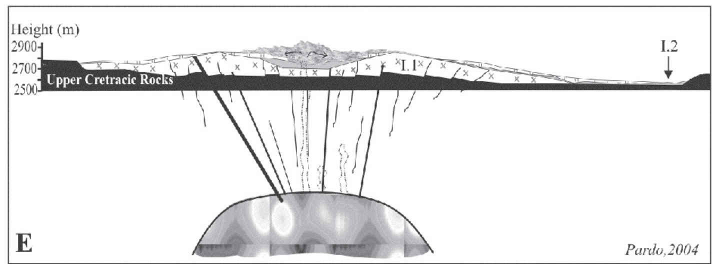

Figure 16e. After a non-deposition/erosive period a fourth eruption took place. It consisted of pumice rich pyroclastic flow emissions originated by possible boiling over.

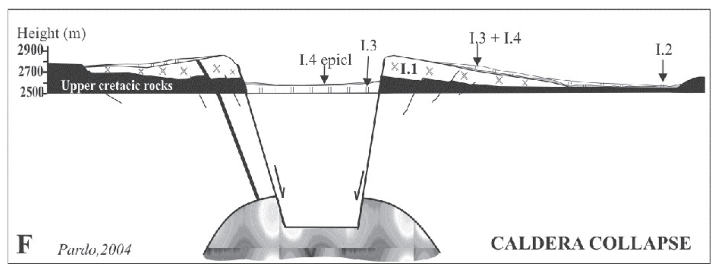

Figure 16 f. The evacuation of nearly 6 Km3 of pyroclastic material promoted collapse by lithostatic pressure over the empty space at magmatic chamber top. A 3 Km-diameter caldera was formed.

Second eruptive epoch (SEE): The caldera resurgence began with the emission of alkaline trachytic and rhyolitic magmas near the caldera margins (Figure 16 g); most of the eruptions occurred at one or several intracaldera vents formed at the headstream of Olitas Creek (Figure 16 h) as suggested by the presence of domes. Then, four (4) block and ash flows occurred by dome collapse and dense pyroclastic masses flowed along Calderitas Creek towards the N and Olitas Creek towards the E and deposited over the first 5 km (Figure 16 i). While block and ash flow remained restricted inside the caldera, explosive fragmentation formed high plumes that transported ashes far away from the vents. Particles covered by a glass rim originated agglomerates by electrostatic forces and rapidly felt from the umbrella region, forming ash fall deposits with 10-25% of accretional lapilli (Figure 16j). Impact sags were formed in ash fall tuffs by plastic deformation of ash beds, probably due to wet conditions ad suggesting hydrovolcanic processes.
After a quiescence period represented by a 15 cm thick paleosoil, deposits of unit II.7 were originated. Wet pyroclastic surges, ash falls and a possible blast density current occurred ant their deposits remained confined to the inflow zone. Later, two (2) eruptions took place, forming ignimbrites by column collapse (II.8 and II.9 units), in which the massive appearance, the high content of accidental lithics and the preservation of accretional lapilli in distal facies support the hypothesis of a phreatomagmatic domain during the SEE. (Figure 16 k-l). After an intensive reworking and epiclastic deposition period, the unit II.10: very well sorted and very fine-grained grey and purple ash fall beds were accumulated even at short distances from Olitas vent (< 1 km), with pumice vertical gradation. Columns collapse formed interbedded pyroclastic flows tuffs suggesting unsteady eruptive columns (Figure 16 m). The last deposit was a brown, very well sorted ash fall tuff. Over the volcanic deposits there is nothing or just a small soil has been formed, which suggest strong erosion or not accumulation processes since the last eruption; today, we think that the magmatic chamber is the principal heat source of Paipa geothermal system and its thermal springs.

SECOND ERUPTIVE EPOCH (SEE): caldera resurgence

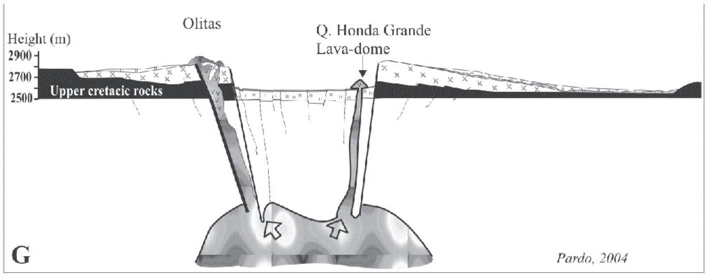

Figure 16 g. Caldera resurgence began with trachytic and rhyolitic magmas emission as intracaldera lava domes. Principal conduits were the Paipa-Iza fault and the Cerro Plateado fault.

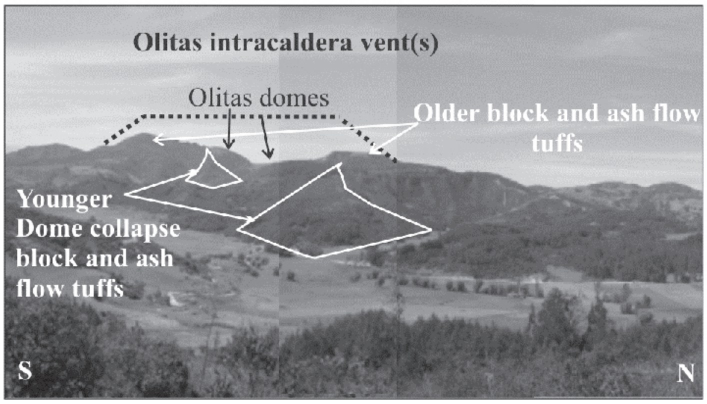

Figure 16 h. Panoramic view of Olitas intracaldera domes and proximal deposits accumulated during the SEE, which are mainly pyroclastic block and ash flow tuffs filling topographic lows and forming valley terraces.

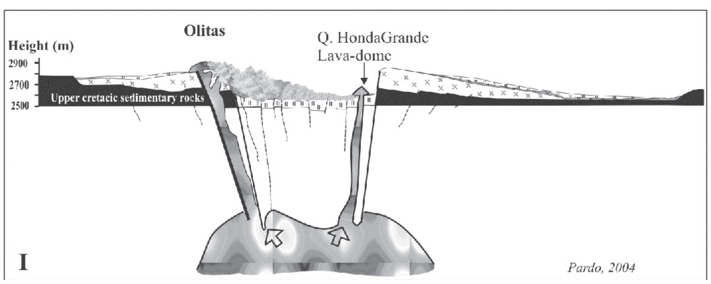

Figure 16 i. Domes collapse formed block and ash flows along Olitas and Calderitas valleys, which are the principal deposits filling the caldera depression during the SEE.

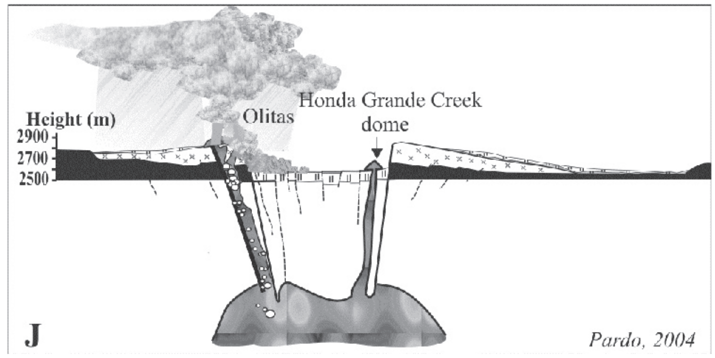

Figure 16 j. While dome collapse was occurring close to the vent, ash fall deposits enriched in accretional lapilli were deposited in distal zones from the umbrella region. Epiclastic high energy currents deposited torrential sediments on the edifice flanks while low energy environments were formed in topographic lows were clays and silts were deposited.

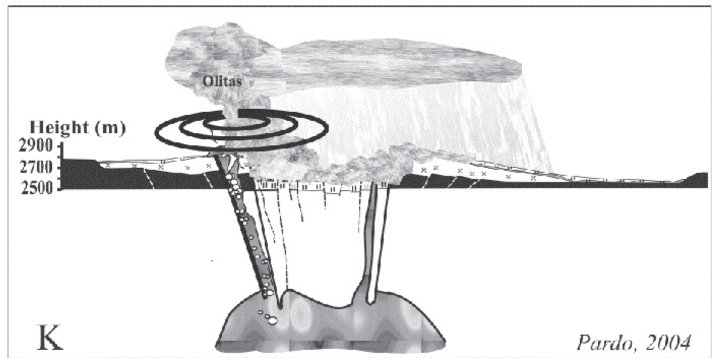

Figure 16 k. After a quiescence period pyroclastic surges transported ashes, pumice and accidental lithics in a NE direction; magma/water interaction resulted in explosive eruptions and the formation of high eruptive columns that deposited ash fall tuffs. Then, after a paleosoil was formed, two (2) pyroclastic flows occurred by collapsing columns, following topographic depressions and filling the caldera depression.

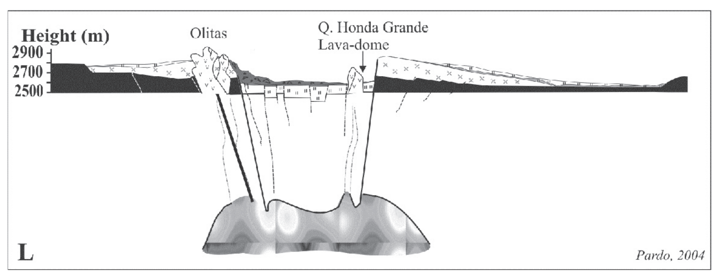

Figure 16 l. During posterior quiescence period, epiclastic processes and erosive denudation took place. Coarse-grained deposits occurred as product of high-energy fluvial processes in proximal zones (Olitas), while in the distal zones (outflow facies) erosion/no accumulation was dominant.

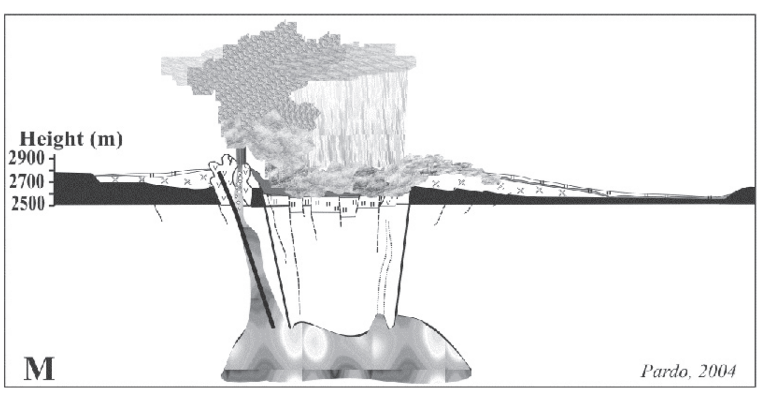

Figure 16 m. The last eruption comprises at least 13 eruptive phases of ash fall deposits accumulated from unsteady eruptive columns; column collapse enhanced pumice and ash pyroclastic flows. In the proximal zone each phase is separated from the other by a sedimentary bed of gray fine laminated siltstones that suggest local lake environments. The last eruption formed a very well sorted ash fall deposit. After that erosive processes have prevailed, locally a thin soil has been formed and there are several geothermal springs northward, outside the caldera margins.

DISCUSIONS AND CONCLUSIVE REMARKS

Geologic field mapping and volcanic stratigraphy evidence a caldera facies association for volcanic deposits placed between Paipa and Tuta municipalities (Boyacá, Eastern Cordillera of Colombia). Fourteen (14) eruptive units were defined as occurred during two (2) eruptive epochs. During the First Eruptive Epoch (FEE) a volcanic caldera was formed and nearly 6 Km3 of material were ejected from a central vent; the volcanic edifice is eroded and just the E and SW walls can be seen on the field. At the end of the FEE caldera collapse occurred along Paipa-Iza and Cerro Plateado normal faults, forming the depression along which Quebrada Honda Grande stream flows, over the place where the former vent must be located. Caldera resurgence took place during the Second Eruptive Epoch (SEE), with the formation of intra-caldera domes, block and ash flow deposits formed by dome collapse and surge deposits as inflow facies. Although exhaustive sampling, granulometry and electron scan microscope analysis are required, depositional structures and facies, such as accretional lapilli (25%) in ash fall deposits, the high content of accidental and accessory lithics in density currents deposits, soft-sediment deformation structures in ash fall debs, as well as very fine-grained ash fall deposits close to the vent, suggest a phreatomagmatic domain, particularly for the ten (10) eruptive units formed during the SEE. Until now, we just know a range of radiometric ages for Paipa volcanism, but a detail geochronology study has to be done; two Ar/Ar and K/Ar determinations indicate that volcanic activity occurred 2,4-1,9 Ma ago but stratigraphically over the rocks dated there lay the deposits of units II.7 to II.10, suggesting that volcanism continued during more recent times, possibly even during Pleistocene.

RECOMMENDATIONS

This article presents the first approach to Paipa volcanology and many questions still unsolved; radiometric dating is necessary to estimate recurrence periods and to estimate the duration of eruptions; single units electron scan microscope analysis is needed to get precision on fragmentation mechanisms; together with detail geochemical data and geophysical studies those tools could determine unknown quantitative aspects of Paipa volcano and provide information about the geotectonic environment.

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