

Mondaca Volcano lahar of December 3, 1762, Maule Region (35°28'S): one of the largest volcanic disasters in Chilean history

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ABSTRACT. The Mondaca Volcano comprises a thick rhyolitic lava-field and a dome of similar composition, located near the Lontué River Valley headwaters in the northern part of the Southern Andes Volcanic Zone. It reaches a total volume of $\sim 0.85 \text{ km}^3$ and it is formed by 4 subunits, named Mondaca 1, 2, 3 and 4, which correspond to successive rhyolitic blocky lava flows, emitted from a rounded dome structure. They present well-preserved flow structures and, in the surroundings, restricted to the south and east of the dome, pyroclastic fall, as well as block and ash deposits are also exhibited. Downstream, along the Lontué River, a laharic deposit is recognized. The lahar was produced after the collapse of an ephemeral $\sim 0.44 \text{ km}^3$ lake generated after the river obstruction by viscous lavas, during the 1762 first eruptive phase. Proximal lahar facies are well exposed between 5 and 30 km from their source. The profuse agricultural activity has completely obliterated the lahar's medium facies deposits along the Central Depression, but are well identified at the mouth of the Mataquito River, 180 km downstream, as a beige-coloured layer, interbedded within dark coastal beach-sands. The identification of overflows and super-elevation deposits formed during the debris flow emplacement along the Lontué River valley, allows to determine a high flow mobility, with estimated velocities that locally reached up to 114 km/h. Petrographic characteristics in addition to chemical composition of lavas from the volcano, pyroclasts and juvenile blocks of the laharic deposit, indicate that all they correspond to high K calcoalkaline rhyolites with subalkaline affinity. These backgrounds, together with the geographical continuity between the lavas and debris deposits along the Lontué and Mataquito rivers, verify facies correlation and common origin as the result of the 1762 Mondaca Volcano eruption complex evolution. Although it was a mainly effusive eruption that could not be observed from Curicó, the collateral consequences would have been catastrophic over a vast area to the south of that city, and evidences one of the largest volcanic disasters in Chilean history. Probably because of the low density population at that time, the consequences could have been minor.

Keywords: Mondaca Volcano, Lahar, Volcanic disaster, Southern Andean Volcanic Zone.

RESUMEN. El lahar del volcán Mondaca del 3 de diciembre de 1762, región del Maule (35°28' S): uno de los mayores desastres volcánicos en la historia de Chile. El volcán Mondaca está constituido por un campo de gruesas lavas riolíticas y un domo, emplazado en las inmediaciones de las nacientes del valle del río Lontué, en la parte norte de los Andes del Sur. Alcanza un volumen total de $\sim 0,85 \text{ km}^3$, y está conformado por 4 subunidades, denominadas Mondaca 1, 2, 3 y 4, que corresponden a emisiones sucesivas de lava riolítica de bloques, cuya fuente es un domo redondeado. Presentan estructuras de flujo bien preservadas y, en las proximidades, al sur y al este del domo, se observan depósitos piroclásticos de caída y de flujos piroclásticos de bloques y cenizas, con escasa extensión areal. Aguas abajo, a lo largo del río Lontué, se reconoce un depósito lahárico generado por la obstrucción del río y el subsecuente colapso del lago efímero de $\sim 0,44 \text{ km}^3$ ahí formado el año 1762, durante las primeras fases eruptivas del volcán Mondaca. Las facies proximales del lahar se encuentran bien expuestas y son reconocibles entre los 5 y 30 km desde su fuente. El profuso desarrollo agrícola ha obliterado completamente los depósitos de facies medias del lahar, cuyas facies distales se identifican en la desembocadura del río Mataquito, 180 km aguas abajo, como una capa de color bayo, intercalada en arenas costeras oscuras. El desarrollo de zonas peraltadas durante su emplazamiento a lo largo del valle del río Lontué permite deducir una alta movilidad del flujo, con velocidades estimadas que, localmente, alcanzaron 114 km/h.

Las características petrográficas y la composición química tanto de las lavas del volcán como de los piroclastos y bloques juveniles del depósito lahárico indican que corresponden a riolitas calcoalcalinas de alto K de afinidad subalcalina. Estos antecedentes, junto con la continuidad geográfica entre las facies de lavas y los depósitos de detritos a lo largo de los ríos Lontué y Mataquito, corroboran la correlación y origen como el resultado de la compleja evolución del volcán Mondaca, durante la erupción de 1762. Aunque fue una erupción fundamentalmente efusiva que no pudo ser apreciada desde Curicó, sus consecuencias colaterales afectaron una vasta zona de la depresión Central al sur de Curicó, lo que la califica como uno de los mayores desastres volcánicos en la historia de Chile. Probablemente, debido a la baja densidad poblacional en esa época, las consecuencias de esa erupción fueron menores.

Palabras clave: Volcán Mondaca, Lahar, Desastre volcánico, Zona Volcánica de los Andes del Sur.

1. Introduction

The Mondaca Volcano is a thick rhyolitic lava-field including a dome structure emplaced on the southern Lontué glacial valley, less than 20 km from its headwaters, in the northern part of the Southern Andes Volcanic Zone, Maule Region (35°28' S, Fig. 1). Together with the Teno River, both are tributaries of the Mataquito River, 10 km southwest of Curicó city. Based on historical chronicles, in addition to geographic and geological evidences, Naranjo et al. (1999) deduced that in 1762 AD a catastrophic

laharic debris flow event would have occurred along the Lontué River. The oldest reference related to such an event was made by Gómez de Vidaurre (1776) and taken by Molina (1788), who mentioned an eruption that occurred on December 3, 1762, which he erroneously attributed to the Peteroa volcano, located approximately 30 km northeast of the Mondaca Volcano. Thereafter, Barros Arana (1886) highlighted that, apparently, Molina (1788) was wrong, since he did not examine for himself the effects of the eruption that occurred in the area on December 3 of 1762, attributed to the Peteroa

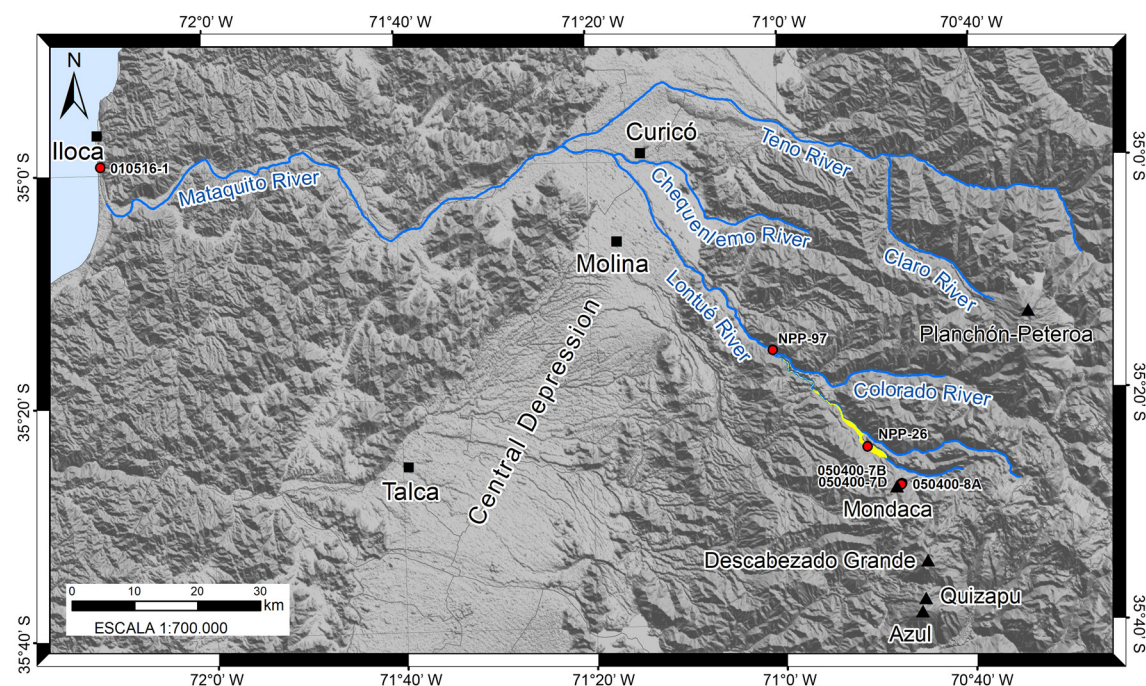


FIG. 1. Location of the Mondaca Volcano in the Lontué River valley, southeast of Curicó city, in relation to the main volcanoes and rivers in the area. Red circles indicate the location of samples to which chemical analyses were performed. In yellow, distribution of the proximal facies of the lahar of 3 December 1762.

volcano. According to Barros Arana (1886), Molina would have limited himself to record the news that reached his ears, but he wrongly added that Molina “confused the Lontué River with the Teno River”. The later instead is located 15 km north of Curicó and discharges the Planchón-Peteroa Volcanic Complex (PPVC) basin (Fig. 1). In addition, Barros Arana (1886) indicated that more detailed investigations of this phenomenon were necessary. However, having been a prominent phenomenon, no other chronicles of the effects of the eruption have been found, probably because of the low population density at that time.

During a detailed study of the geology and hazards of the PPVC, Naranjo *et al.* (1999) concluded that, according to the places mentioned, Barros Arana (1886) had also misinterpreted Molina’s (1788) error, maintaining that the aforementioned eruption had occurred at the Peteroa volcano. In fact, the geological evidence, as the presence of remarkable fresh-looking debris flow deposits along the Lontué valley, indicates that the Mondaca Volcano (unknown in 1762) lava emplacement was responsible for a dammed lake and its subsequent collapse, which originated the December 3, 1762 debris flow (Fig.1). This conclusion is also supported by Domeyko (1903), who indicated that, approximately in the mid-nineteenth century, on the southern shore of Mondaca Lake, beaches with abundant pumice pebbles were recognized, where thermal waters still sprouted that were used for medicinal purposes. This author also pointed out that the plains arranged upstream of Mondaca Lake “formed an elliptical valley that took the place of some ancient lake”.

During a 1:500,000 geological mapping, González and Vergara (1962) assigned the Mondaca Volcano to the Current Volcanic Cones unit, calling it as the “Lengua de Vulcano”, which dammed, towards the east, the present Mondaca Lake, to the north of the Descabezado Grande volcanic group. According to these authors, it corresponds to a “vitreous flow of andesitic-dacitic lava, generated in a monogenetic eruption that dammed the current lake”. They also argued that, “due to their fresh morphological features, the Lengua de Vulcano would correspond to a very recent eruption, probably occurred during historical times”.

From a petrological point of view, Ruprecht *et al.* (2012) suggested that the magmatic diversity in the area around the Quizapu volcano is mainly

controlled by the mixture of primitive and evolved magmas, such as those found in the basaltic volcanoes Los Hornitos-La Resolana, and the rhyo-dacitic lavas of the Mondaca Volcano, separated by 20 km. Finally, Osorio (2014) made an undergraduate report on the geology of the Mondaca Volcano and distinguished rhyolitic lava lobes, both to northeast and northwest, along the Lontué River valley, in addition to minor volumes of pyroclastic density current (PDC) deposits.

The purpose of this work is to provide the physical and chronological description of the different evolutionary stages of the Mondaca Volcano and its products, as well as the characteristics of the laharc debris flow and its impact. Although the historical references of the process are scarce and confusing, based on its characteristics and distribution, this work also aims to provide the geological and geographical background that allows it to be associated with the so-called “eruption of December 3, 1762” (Molina, 1788).

2. Methodology

The methodology comprises field work to identify the distribution of volcanic units (mapping) and sampling, petrographic studies and chemical analyses, and compilation of historical background.

Following the antecedents presented by Naranjo *et al.* (1999) for the Planchón volcano, located 35 km northeast of the Mondaca Volcano, the available historical data related to this area were reviewed. Sectors around the Mataquito River mouth and Iloca beach where visited (Fig. 1). In these places, black sand deposits derived from metamorphic rocks, contrast with beige coloured sand deposits composed of pumice and crystal fragments, including lapilli and large clasts of pumice bombs. Subsequently, a selection of potential sources for these pumices was made by a detailed on-site review of the volcanic deposits located along the Mataquito River tributary valleys (Claro-Teno and Barroso-Colorado rivers, from the PPVC; Lontué River, from the Mondaca Volcano). The eastern side of the Mondaca Volcano dome, lava-flow and pyroclastic deposits, as well as the distal western lava flow front were also visited on the ground. In addition, during the field survey, a selective sampling of the Mondaca Volcano products (lava flows, debris flow deposit and pyroclastic deposits) was

carried out. Consequently, thin-section petrography was described, and whole rock chemical analyses of the collected samples was made to complement the stratigraphy of this eruptive center. Detailed geological mapping carried out on high-resolution satellite images available on Google Earth platform allowed us to determine the morphostratigraphical relationships of the lava flows (overlapping lobes) and to establish a stratigraphic-evolutionary scheme for the Mondaca Volcano. Finally, lava flow volume estimations together with debris and pyroclastic flow deposits distributions were made.

Regarding the whole rock major elements chemistry, six selected Mondaca lavas and laharic boulders samples collected during at least 3 field seasons were analysed in the chemical laboratory of Sernageomin's by atomic absorption spectrometry (AAS).

3. Geology of Mondaca Volcano

There have been identified different eruptive products for the Mondaca Volcano. They include lava flows, a dome, laharic flows, tephra-fall and block and ash PDC deposits, which are described as follows.

3.1. The lava field

It is located approximately 1,900 m a.s.l. on the left (south) slope of the Lontué River valley at 14 km NNW of the Descabezado Grande volcano (Fig. 1). The Mondaca Volcano corresponds to a rhyolitic lava-field, which reached a total volume of $\sim 0.85 \text{ km}^3$ (Figs. 1 and 2). In this sector, the bottom of the Lontué glacial valley is located at a height of 1,450 m a.s.l., and presents between 1.5 and 3 km wide. For the Mondaca lava-field, 4 sub-units were identified, called, in chronological order, Mondaca 1, 2, 3 and 4, which features are detailed in table 1 (Fig. 2). They correspond to successive lava emissions, sourced at a rounded dome structure, which occurs in continuity with the lava flows, except for its western flank, where it develops a slope on one of the lava flows (Figs. 2 and 3A, B).

The lava flows are rhyolitic blocks distributed around the dome, with blocks reaching 0.5-8 m in diameter and locally up to 15 m (Fig. 3A-D). On the surface, lava shows well-preserved flow structures, such as central channels with the development of transverse ridges and levées, on which they form longitudinal ridges of more than 1 km in length. On lateral scarps, 1 to 2 m thick subhorizontal joint structures are observed

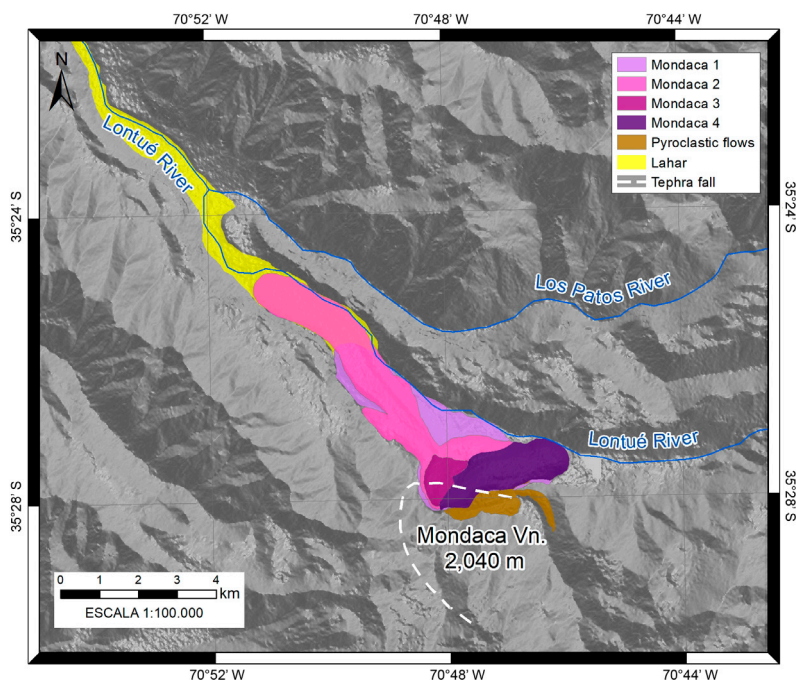


FIG. 2. Geology of the Mondaca Volcano in the Lontué River glacial valley. Mondaca subunits 1 to 4 overlap successively. The western lobe of the Mondaca 2 lava was placed on the proximal facies of the lahar deposit.

TABLE 1. SUMMARY OF THE DESCRIPTIVE CHARACTERISTICS OF MONDACA VOLCANO LAVA SUBUNITS.

Subunit	Lobe number	Flow direction and length (km)	Distribution, stratigraphy and outcrops	Thickness (m)
				Area (km ²) Volume (km ³)
Mondaca 1	2	NW (~5) and NE (~3)	Isolated outcrops in the northern, eastern, and western parts of the lava field, beneath flows from later stages. Longitudinal orientated ridges are observed parallel to flow direction.	10-60
				9.2
				0.32
Mondaca 2	2	NW (~8) and NE (~2.5)	The NW lobe is the largest in the lava field, ~8 km long and up to ~1 km wide above Mondaca 1 flow, and is completely confined to the Lontué valley. It developed extended, ogival curved ridges (~1.1 km in length and ~300 m in width), as well as others with wider curvature (450 m in length and 350 m in width), in addition to well-marked levées and a central channel; it developed a sublobe that overspilled its eastern levée. Second lobe to the NE.	80-185
				8.82
				0.31
Mondaca 3	1	N (~1.7 km exposed)	It was shed as a discrete lobe (coulée) to the north for ~1.7 km length.	<20
				0.86
				0.013
Mondaca 4	1	NE (~3.6)	Corresponds to the last lobe and flowed for 3.6 km directed towards the NE; it is 1.1 km maximum wide.	<115
				3.13
				0.2

and they tend to form ramp structures toward the upper part (Fig. 3C). Lavas exhibit diverse textures, from black massive obsidian to highly vesicular light brown pumice, with reddish colour oxidised layers. Occasionally these lavas show flow banding texture.

Under the microscope, slightly fractured and fragmented phenocrysts of plagioclase, pyroxene, biotite, with scarce amphibole and Fe-Ti oxides are observed, immersed in a vitreous ground mass, locally highly fractured, including spherulites. Also, these lavas exhibit varying amounts of vesicles (up to 1 cm in diameter), plagioclase microliths, and pyroxene and amphibole microcrystals. In addition to the aforementioned textures, they develop intersertal, cumulitic, glomeroporphic and sieve textures in plagioclase.

3.2. Laharic deposits

3.2.1. Proximal facies

Along ~25 km of the Lontué River, between the front of the Mondaca 2 lobe and the junction with

the Colorado River (Figs. 1 and 2), a conspicuous laharic debris flow deposit outcrops covering an area of ~7 km². Proximal facies present similar characteristics at 5 and 30 km down-river from the source (Figs. 2 and 4A-E). It corresponds to a terraced debris flow deposit up to 5 m thick that, locally, shows superelevation deposits up to 9 to 13 m high around channel bends.

The lahar deposit occupied the entire valley width (0.86 km) and was carved by braided rivers and current river deposits (Figs. 4A, B). This is a pumice and lithic rich deposit which contrasts with local pumice block-free fluvial deposits. It presents coarse debris (M=0.5 m), including angular-subangular grey lithics (exceptionally up to 2.5 m), and few granitic boulders, with about 10% fibrous lapilli-sized pumice (and little obsidian), with up to 30 cm diameter, rounded, beige-coloured boulders, with plagioclase, pyroxene, scarce to none biotite phenocrysts. Debris flow deposits exhibit up to 2 m high levées (Figs. 4B-E).



FIG. 3. **A.** Mondaca Volcano as seen from the WNW on the southern slope of the Lontué River glacial valley. The Mondaca 2 lava is observed above Mondaca 1 lava and beneath Mondaca 3 lava. In the background, the Descabezado Grande, Quizapu and Azul volcanoes. **B.** Aerial view looking to the northwest, showing the lateral scree of Mondaca 2 lava above Mondaca 1 lava. **C.** Aerial view to the northwest. Present Lontué River gorge, exhibiting Mondaca 2 lava lateral cut with conspicuous ramp structures, above Mondaca 1 lava flow. **D.** Mondaca 2 lava front above laharc debris flow deposits, produced by the collapse of the original Mondaca Lake; **E.** Aerial oblique view to the WNW. Mondaca 4 lava lobe on the Mondaca 1 lava; dome structure and block and ash PDC deposits on the left.

Profuse agricultural development in crop fields, starting at the apical part of the Lontué River gorge alluvial fan and over the Central Depression to the west, has completely obliterated the lahar medial facies deposits. In fact, such alluvial fan exceeds 15 km wide, between the Chequenlemono river to the north, and the town of Molina to the south, and covers an area of approximately 300 km² on the Central Depression (Fig. 1). Instead, radial ridges that could resemble boulder alignments as debris flow levées remnants, are recognised on satellite images.

3.2.2. Distal facies

A ~15 cm thick, matrix-supported gravel layer, with rounded pebbles of dark reddish and grey lava, is recognized 8 km to the north of the Mataquito River mouth, 180 km down-river from the Mondaca Volcano source (Fig. 1). The deposit also shows coarse rounded pumice sand of a beige colour with few quartz crystals matrix (Fig. 4F). That gravel layer is at ~50 cm depth interbedded within dark beach sands (derived from metamorphic rocks), which are related to lagoon-like deposits. In addition, few sub-rounded to rounded pumice fragments of up to



FIG. 4. **A.** Aerial oblique view to the west. Braided rivers in terraced deposits of proximal lahar facies of December 3, 1762, downstream Mondaca 2 lava front. **B.** Close-up of these facies, showing metric grey colour blocks of accidental lava and beige colour rhyolites from that eruption, in a matrix of pumice sands. **C, D, E.** Deposits of the 1762 lahar at 28 km from the source. Angular to subangular grey lithics are observed, including $\geq 10\%$ lapilli-sized pumice, aligned along up to 2 m high levées. **F.** Distal facies corresponding to a 20 cm thick, matrix supported conglomerate (between segmented lines) with rounded pebbles of reddish to dark grey lava, in a matrix of pumiceous coarse sand, interbedded in lagoon-like deposits at the mouth of the Mataquito River.

15 cm in diameter were also observed. This deposit would correspond to the most distal facies of the lahar, whose proximal facies were previously described.

3.3. Tephra-fall deposits

About 0.3 to 1 km immediately to the south and southeast of the Mondaca Volcano, the main isolated tephra-fall deposits crop out, which proximal tephra dispersion envelope is indicated in figure 2. They show little areal extension and reach up to ~ 20 m of exposed thickness, restricted to the source

surroundings. These deposits are light brownish to grey in colour and are arranged as subhorizontal banks of 30 cm to 1 m thick, with well-marked parallel stratification (Figs. 2 and 5A, B).

3.4. Block and ash deposits

A 30 m thick succession of block and ash type pyroclastic flow deposits were shed up to 3 km to the east on the eastern flank of the Mondaca Volcano dome (Figs. 2 and 5C). At its foot, block and ash deposits show inclinations of up to $\sim 20^\circ$

to the ENE (Fig. 5D). They consist of 5 to 50 cm layers of grayish-pale brownish, ash-rich and fine to medium lapilli pumice alternating with dark grey, clast-supported 10 to 25 cm, medium to coarse lapilli with a higher content of angular obsidian lithics (Fig. 5E, F). Well-defined parallel stratification is observed and, in some sectors, diffuse crossed

or wavy stratification is also present where surge facies occur. Some layers are subrounded pumice rich, occasionally with inverse and normal grading (Fig. 5F). Bomb-size fragments are highly abundant toward the stratigraphically higher sections, some of which being prismatic jointing and bread crust bombs of up to ~30 cm, and lithics that, exceptionally, reach

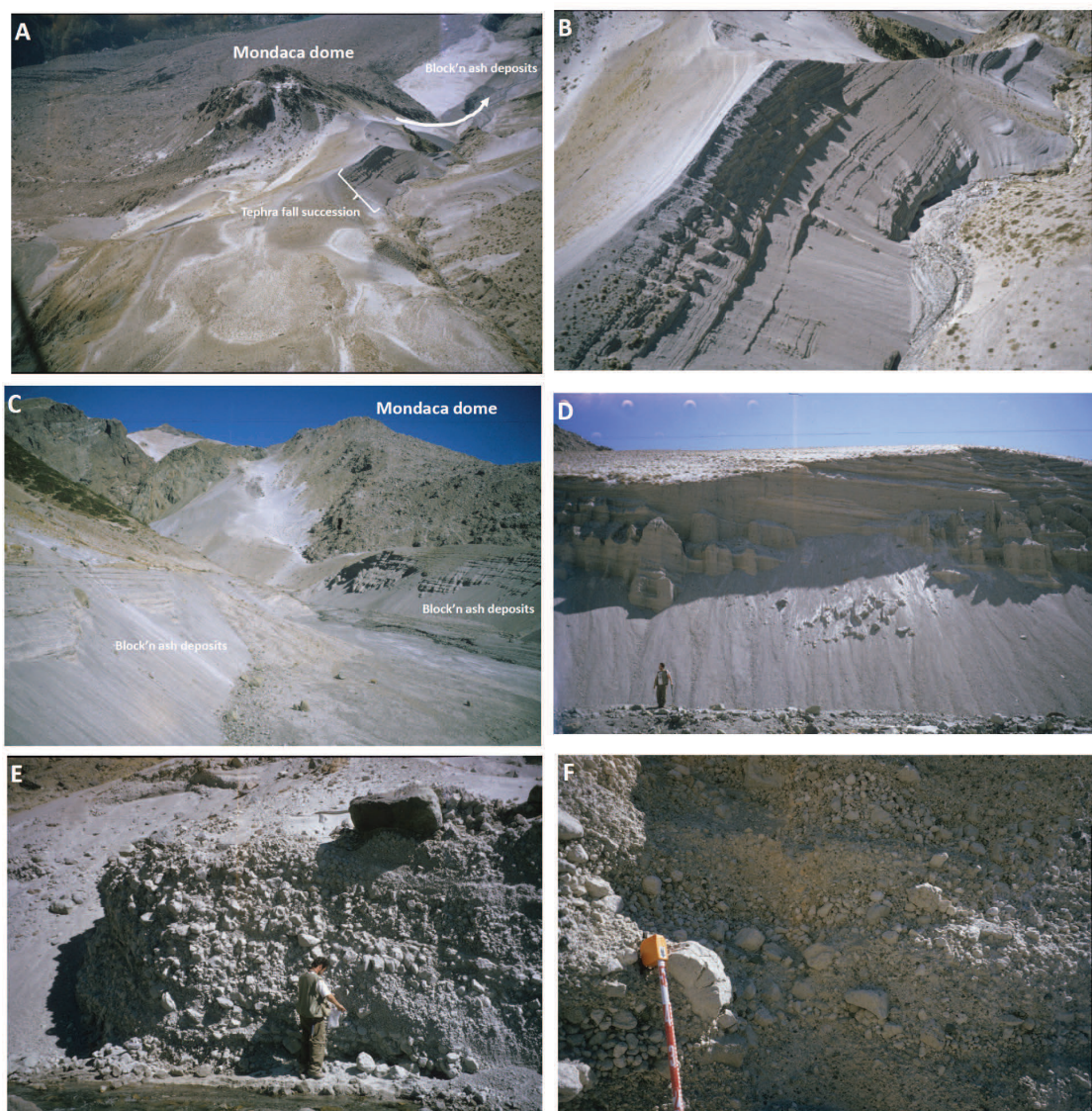


FIG. 5. **A.** Aerial view to the NNE showing a 20 m thick succession of tephra-fall deposits, immediately south and southeast of the Mondaca dome. White arrow indicates block and ash flow direction. **B.** Detailed aspect of the tephra-fall sequence. **C.** View to the west, block and ash PDC deposits east of Mondaca Volcano. **D.** Pyroclastic surge deposits alternated with block and ash deposits, 750 m to the east of the eruptive source; **E.** Block and ash deposits at the eastern foot of the Mondaca Volcano dome. **F.** Detail of block and ash deposits showing normal gradation, with juvenile bread crust bombs, pumice lapilli and ashes.

2 m in diameter. The matrix consists of vitreous and pumice juvenile lithic fragments, of ash and lapilli size (Fig. 5E, F). Both, dense and pumice juvenile fragment petrography is similar to the previously described lava.

3.5. Petrography and major element geochemistry

The selected rock samples from the Mondaca Volcano are characterized by having porphyritic texture, in addition to vesicular (pumice), intersertal (lava) or vitrophiryc (dense juvenile fragments with prismatic fracturing or PJB) texture, depending on their origin and evolutionary stage of this eruptive center.

Whole-rock chemical analyses of six samples associated to different eruptive products of Mondaca Volcano are exhibited in table 2. Three of them correspond to pyroclastic flow deposit bombs in the eastern sector of the volcano, one from the western Mondaca 2 lava front, and two were obtained from the laharic deposit, one of proximal facies and the other from the Mataquito River-mouth deposit at Iloca (Figs. 1 and 2). In addition, two analyses were published by Ruprecht *et al.* (2012) and two others were performed in the Sernageomin Laboratory that were reported data by Osorio (2014). All these results allow these rocks to be classified as high-K calcoalkaline rhyolites with subalkaline affinity, except for the juvenile fragment immersed in the debris flow deposit that is slightly alkaline (Figs. 6 and 7). Compared with rhyodacitic white colour pumices from the 1932 Quizapu volcano eruption, located 19 km to the SSE of the Mondaca Volcano, the latter's beige colour rhyolites, systematically show lower Fe, Ca and Mg contents.

The samples from the Mondaca Volcano are rhyolites that exhibit a very restricted interval in silica content (70-72 wt%, anhydrous values) (Fig. 6) with an evident dispersion in K₂O content (3.7-4.7 wt%), which makes it easy to distinguish them from Descabezado Grande and Quizapu volcanoes pumices (Fig. 7), being these the least evolved pumice in the area. The physical, morpho-stratigraphical and geographical distribution of the Mondaca lahar pumices preclude the nearby Loma Seca and Altos de Las Mulas rhyolites (71 and 72 silica wt%, respectively; located to the north of Descabezado Grande Volcano, Fig. 1) as possible sources.

4. Discussion

4.1. Facies correlation and origin

Petrographic and geochemical characteristics of the lavas and juvenile fragments, in addition to the geographical continuity between the lava facies and debris-flow deposits along the Lontué and Mataquito rivers, unequivocally indicate that they are the result of the complex eruption that gave origin to the Mondaca Volcano. Indeed, other rhyolitic pumices in the area, such as those of the Descabezado Grande volcano (2 analyses) and the tephra-fall deposit of the Quizapu 1932 Plinian eruption (1 analysis, in addition to the data published by Hildreth and Drake, 1992) (Fig. 6) differ in colour, texture and petrography, with respect to those of the Mondaca Volcano. The latter is beige coloured, with phenocrysts of plagioclase, pyroxenes, biotite and scarce amphibole and Fe-Ti oxides, against the light gray colour and plagioclase, amphibole, orthopyroxene, magnetite, ilmenite and clinopyroxene for the Quizapu, whereas Descabezado

TABLE 2. MAJOR ELEMENT CONTENT OF SELECTED SAMPLES OF MONDACA VOLCANO.

Sample	Lithology	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	CaO	MgO	MnO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O*	Total
050400-7B	Juvenile PJB	70.03	15.07	0.30	2.37	1.55	0.53	0.08	5.15	4.13	0.13	0.50	99.34
050400-7D	Juvenile BCB	69.75	15.57	0.34	2.46	1.59	0.54	0.08	5.12	4.03	0.16	0.14	99.64
050400-8A	Pumice	71.49	14.62	0.20	1.89	1.06	0.35	0.06	4.79	4.48	0.11	0.97	99.05
NPP-97B	Juvenile lahar block	69.46	14.76	0.34	2.20	1.36	0.48	0.06	5.16	4.58	0.11	1.36	98.51
NPP-26A	Lava flow	70.59	14.39	0.51	2.19	1.48	0.50	0.06	4.86	4.15	1.04	0.18	99.77
010516-1	Pumice	70.92	14.18	0.33	2.44	1.44	0.78	0.07	4.47	3.59	0.08	1.42	98.29

PJB: Prismatically jointed block; BCB: Bread crust bomb. H₂O* correspond to volatiles content (H₂O, S, CO₂). Contents in wt%.

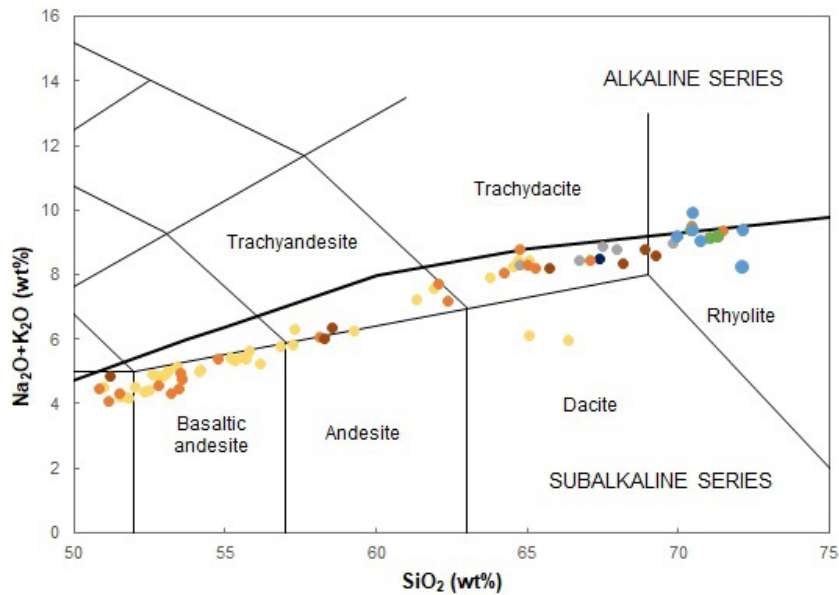


FIG. 6. TAS diagram (Total Alkalies versus Silica; Le Maitre *et al.*, 2002) of selected rocks of Mondaca Volcano (light blue circle) and other neighbouring eruptive centers (**gray**: pumice of 1932 Quizapu volcano eruption; **orange**: Descabezados Group; **gold**: Planchón-Peteroa volcanic complex (PPVC); **brown**: Los Baños PPVC pumice; **blue**: Descabezado Grande volcano pumice; **green**: Mondaca Volcano from Ruprecht *et al.* (2012) and Osorio (2014)).

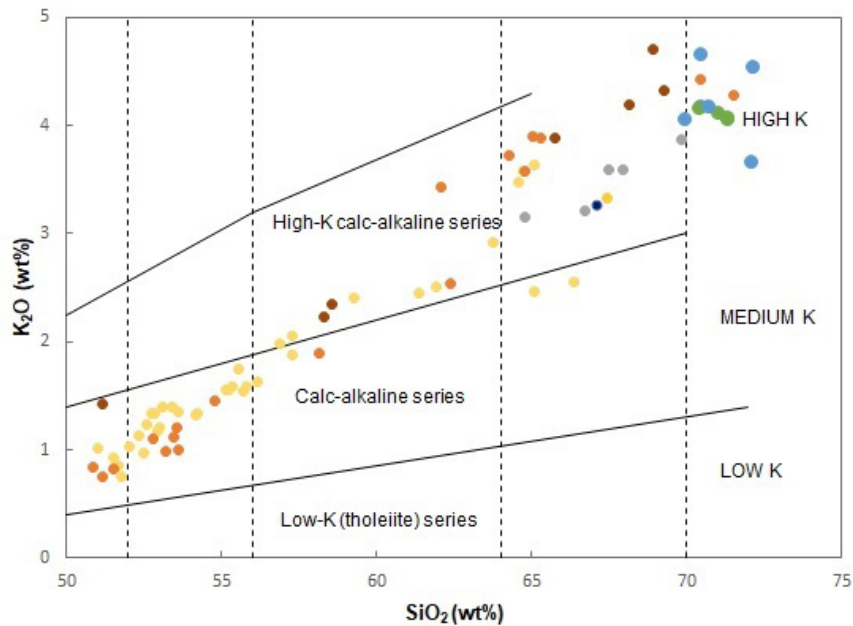


FIG. 7. K_2O versus SiO_2 diagram (Peccherillo and Taylor, 1976) of the selected samples of Mondaca Volcano showing different series: Low-K, calc-alkaline and high-K calc-alkaline (circles colours are the same as figure 6).

Grande pumices are typically yellow coloured and remarkably fibrous.

Although the Mondaca eruption was typically effusive, with low emission rates of viscous rhyolitic lava, the collateral consequences were catastrophic. The eruptive phases were low in magnitude, with pyroclasts generation restricted to the source area and the Lontué valley flanks, therefore, the volcano could not be identified from the Central Depression, where Curicó city is located, between Teno and Lontué rivers. The river headwaters of the first correspond to the CVPP, whose building stands out in the mountains and is clearly visible from Curicó, 65 km to the ESE. On the other hand, Descabezado Grande, Cerro Azul, as well as Mondaca volcanoes stand out where the sources of Lontué River are located, approximately 82 km southeast of Curicó (Fig. 1). This city was founded in 1743, that is only 19 years before Mondaca erupted. Thus, given these geographical conditions, it is reasonable that both Molina (1788) and Barros Arana (1886) had confused the origin of the debris flow on December 3, 1762 as coming from the PPVC, the closest volcano to Curicó.

4.2. Mondaca Volcano evolution: volumes and eruptive rates

After decent at least 450 m from 1,900 m a.s.l. on the southern slope of the Lontué River valley, the first effusive phase that gave rise to the Mondaca 1 lava-lobe took place, completely filling the valley and reaching 5 km long. A second *ca.* 3 km long lava-lobe to the east was formed as the viscosity (by cooling and/or lower emission rate) increased (Fig. 8A).

The Mondaca 1 lava, which reached a volume of 0.32 km³, occupied the entire valley, and caused the obstruction of the river giving rise to an early Mondaca Lake (Fig. 8B). The dam was caused by the encounter of the lava against a ledge of the north valley slope that, at an approximate maximum level between 1,520 and 1,550 m a.s.l., constituted the true right barrier of the lake. In that sector, the current Lontué River shows an abrupt descent of 100 m along only 300 m of horizontal distance.

Considering the current flow of the Lontué River, measured between the confluences of Los Patos and Colorado rivers (Fig. 8C), and that it is 25 m³/s on average (SNIA-DGA, 2020), it can tentatively be

estimated that the early Mondaca Lake came to cover 7.33 km², with a water volume of 0.44 km³, which accumulated in a minimum time of 7 months, before collapsing. Given the possible variations in the river water flow, especially during the eighteenth century, we must assume that the resulting values are only an approximation. The overflow and rupture of such natural dam gave rise to the lahar of 3 December 1762 (Fig. 8C).

According to morphostratigraphical relations, the second phase (Mondaca 2) was also developed in two lobes showing conspicuous lateral scarps on the Mondaca 1 lava, reaching a total volume of 0.31 km³ (Fig. 8D). Following the maximum slope, the northwest lobe reached 8 km and was probably originated as the emission rate increased, overpassing previous phase lava flows. Increasing cooling and viscosity of the phase 2 lava caused the secondary lobe flowing to the northeast, upstream of the Lontué valley (Fig. 8D).

The emission rate for the Mondaca 3 phase continued to decline, and generated a coulée lava overlapping Mondaca 2 lava, with a volume of only 0.013 km³, probably as a result of viscosity increase. Coulée flank collapses caused successive block and ash flows emplaced to the east (Fig. 8E). These pyroclastic flows continued to build on the same flank during the emission of Mondaca 4 phase, a single lava flow that was emplaced to the northeast due to the containment of previous lava phases. The lava of the last eruptive phase reached a volume of 0.2 km³ and covered phases 1 and 3 lava flows (Fig. 8F). This final phase originated as the result of an increase in the emission rate. In addition, block and ash flows continued to emplace to the east, eroding the fall deposits that had accumulated during the previous phases.

The materials erupted during the various phases of the Mondaca Volcano were emitted effusively, through a low-magnitude eruption, with subordinated pyroclasts production, since it was not observed from the Central Depression, 60 km to the west. The rate of viscous lava emission was also very low and, considering the duration for the lake formation associated with phase 1, it must have occurred over a period greater than seven months. Although there is no evidence to determine the end of the eruption, if Domeyko's (1903) testimony is assumed, the eruption was over by the mid-19th century.

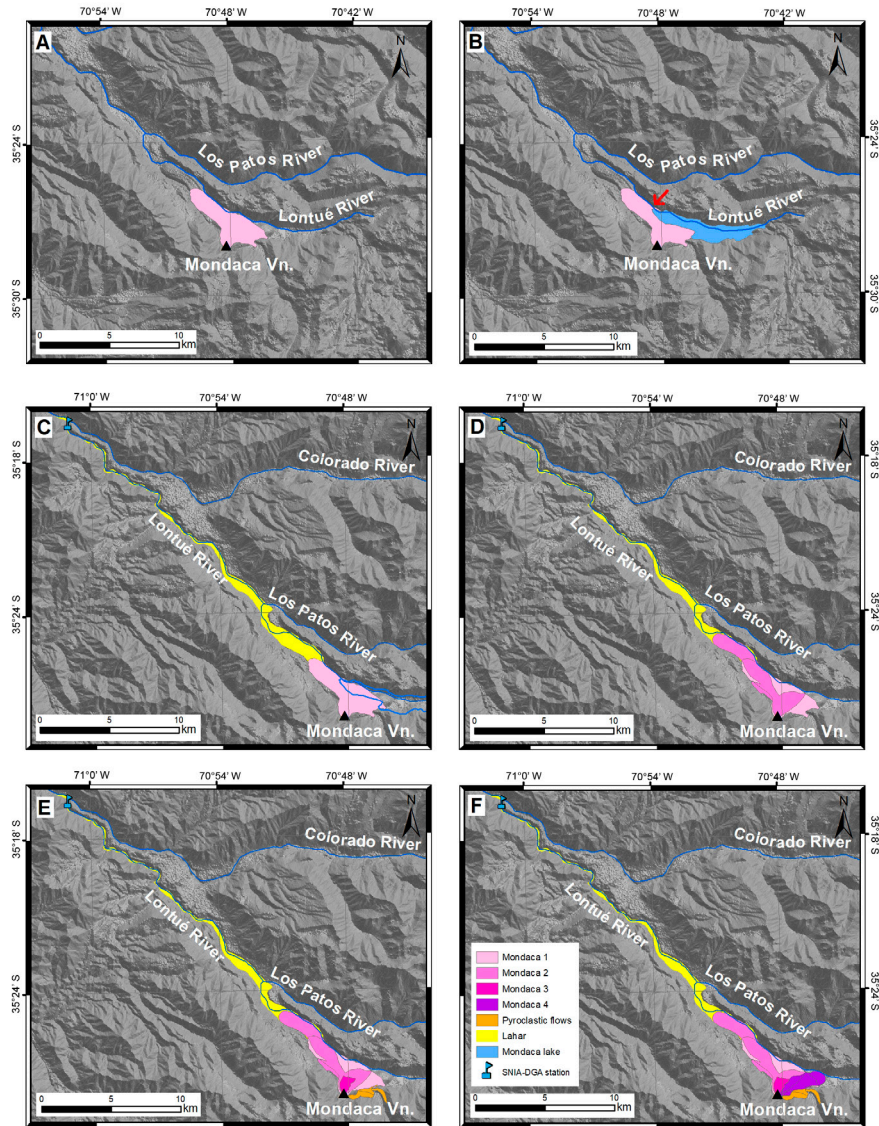


FIG. 8. Mondaca Volcano evolutionary stages. **A.** Northwest and east lava-lobes of Mondaca 1 phase. **B.** Formation of the ephemeral Mondaca Lake due to the obstruction of the river (red arrow). **C.** Sudden evacuation of the lake and emplacement of a laharic debris flow that covered the Lontué River valley to the northwest. **D.** Eruption of Mondaca 2 phase above phase 1 lava, with an extensive lobe to the northwest, covering the lahar deposit, and a smaller lobe to the northeast. **E.** Coulée lava emplacement corresponding to Mondaca 3 phase and block and ash PDC to the east. **F.** Mondaca 4 phase lava flow to the northeast.

4.3. High impact effects of December 3rd, 1762 laharic debris-flow

The overlap of the Mondaca 2 lava flow over the laharic debris flow deposit demonstrate that the former $\sim 0.44 \text{ km}^3$ Mondaca Lake occurred as a direct consequence of the damming effect caused

by Mondaca 1 lava flow. The high mobility of the lahar flow is demonstrated when compared to the parameters that characterized the lahar flow produced by the Kelut volcano crater lake rupture during the 1919 eruption, Indonesia (Nawiyanto and Sasmita, 2018). Figure 9 shows the rate between the descending height (H) and

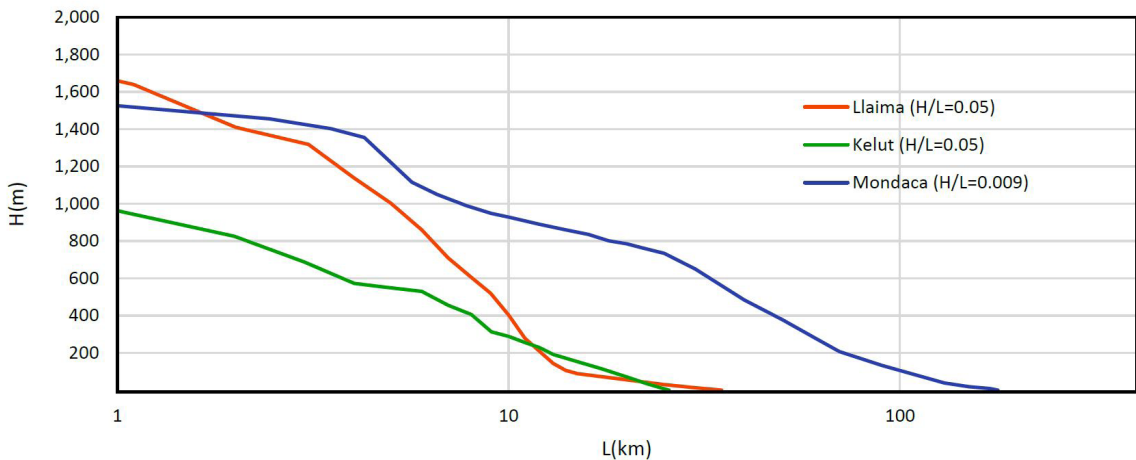


FIG. 9. Relationship (H/L , apparent coefficient of friction, U_i , 1983) between the descending height (H) and the distance travelled (L) of the lahar occurred on December 3, 1762 ($H/L=0.009$) as a result of the collapse of the ephemeral Mondaca Lake, compared to the H/L ratio of the 1919 eruption of Kelut volcano in Indonesia ($H/L=0.05$) and the jökullhaup generated to the south of Llaima volcano during the eruption of 1640 A.D. ($H/L=0.05$).

the distance travelled (L) by the Mondaca lahar, from 3 December 1762, the lahar associated with the Kelut volcano in 1919, and the lahar produced by the glacier outburst (jökullhaup) to the south of Llaima volcano during the 1640 AD eruption, one of the largest lahars in the Chilean Southern Andes in historical times (Petit-Breuilh, 1996¹; Naranjo and Moreno, 2005). The H/L ratio was defined by U_i (1983) as the “apparent coefficient of friction”, and ranges between 0.18 to 0.06 for volcanic dry avalanches. Consequently, we suggest that, with a coefficient of friction of 0.009 and a travelled distance of almost 180 km, the lahar generated by the emptying of the ephemeral Mondaca Lake is one of the largest volcanic disasters originated during history in Chile (Fig. 9).

As far as the debris flow velocity is concern, field evidences are shown at different sectors along proximal facies. Lahar flow mobility was significantly high as the flow runout deposited sediments in elevated areas around bends where it generated well-developed lateral trimlines. The flow also climbed topographic obstacles perpendicular to the flow direction, depositing material between 5 and 42 m higher than the flow base. These debris flow superelevation, generated at some bends, allow to have velocity estimations, using the formula given by Pierson and Scott (1985, and references therein),

which takes into account geometric features of such curves:

$$U = (g\Delta h r_c / b)^{0.5}$$

where U is mean fluid velocity, g is gravity acceleration (9.8 m/s^2), Δh is elevation difference between mudlines on the inside and outside of the channel bend, r_c is river-bend radius of curvature, and b is channel width. Velocity estimates computed from this equation are minimum values because frictional energy losses are not taken into account, but the computed values are assumed to be within 15% of actual velocities (Pierson, 1985). We have estimated an average velocity of $\sim 50 \text{ km/h}$ for the laharc debris flow, based on nine measurements along Lontué River between 15 and 30 km downstream from the source. These values varied in the range of 20 and 114 km/h, which could be minimum and maximum local flow velocities, due to variations in the width and depth of the river bed, curvature radius and local river slope.

One of the main lahar effects took place on the alluvial fan from the Lontué valley apex over the Central Depression (Fig. 1). From there, it is estimated that it would have been emplaced over a *ca.* 300 km² area with great agricultural potential, thus constituting the largest and most disastrous impact of the eruption.

¹ Petit-Breuilh, M.E. 1996. Cronología eruptiva histórica de los volcanes Planchón-Peteroa y Copahue, Andes del sur. (Inédito), Departamento de Asuntos Humanitarios, Programa de las Naciones Unidas para el Desarrollo (DHA), Proyecto Piloto de Monitoreo de los volcanes Planchón-Peteroa y Copahue: 44 p.

5. Conclusions

The Mondaca Volcano consists in a 0.85 km³ rhyolitic blocky lava field and a dome with similar composition, located in the vicinity of the Lontué River Valley headwaters, formed by 4 sub-units or eruptive pulses. During the early stages, the lavas blocked the river waters and caused a dam that, upstream, formed a 7.33 km² and 0.44 km³ lake, which accumulated water during a ~7 month period. The collapse of the natural dam triggered a highly mobile laharic debris flow, which, on December 3, 1762, flowed westward 180 km along the Lontué River, to the sea through the Mataquito River at an estimated average velocity of ~50 km/h. Petrographic and geochemical characteristics of the lavas and juvenile fragments of the lahar debris flow deposit, in addition to their geographical continuity along these rivers, indicate, unequivocally, that they were the result of the complex eruption that gave rise to the Mondaca Volcano. The distribution along the Lontué-Mataquito rivers and the high mobility of the lahar indicate that this eruption produced one of the largest volcanic disasters in Chilean history and affected an area estimated in 300 km² in the Central Depression, although its effects were only indirectly documented.

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