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Impact of volcanic processes on the cryospheric system of the Peteroa Volcano, Andes of southern Mendoza, Argentina☆

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ABSTRACT

Soil temperatures of the active Volcanic Complex Peteroa situated in the Cordillera Principal between Chile and Argentina at 35°15′ S and 70°35′ W (approximately) were monitored in the area, and local geomorphology (periglacial geomorphology, presence of permafrost, and cryoforms) was studied. The present contribution also resulted in a comparison of two consecutive analyses of the volcano peak carried out with special thermocameras (AGEMA TVH 550, FUR P660) in order to study the thermal range of different *hot* and *cold* sites selected in 2009. The thermocameras were used ascending by foot and also during flights with a Cessna 180. A night expedition to the volcanic avalanche caldera, at up to 3900 m asl (approximately), completed the monitoring activity of 2010. *Hot* zones were associated to present volcanism and *cold* zones to the presence of glacier ice and shadowy slopes with possible presence of permafrost. Identifying and mapping uncovered and covered ice was possible with the help of monitoring and geomorphological interpretation related to the upper englacement, which is severely affected by volcanism. Glaciers are retreating toward the north or approaching the rims of the volcanic avalanche caldera leaving islands of ice associated with superficial permafrost. The cryogenic area with slope permafrost was identified through active protalus and sedimentary cryogenic slopes. Craters have undergone considerable thermal changes in comparison to the year 2009; and new, much more vigorous fumaroles have appeared in *hot* areas detected in 2009 following a tendency toward the west. New subaquatic *heat columns* that appeared in crater 3, crater walls, and glaciated areas vanished, supplying cold water and thus contributing to the formation of a new lake in crater 4. A possible post-seismic shift of the volcanic activity may provide geodynamical evidence of the changes registered in other areas after the earthquake of 27 February 2010.

1. Introduction

Various authors have analysed the relationships between active volcanoes and glaciers for the Northern Hemisphere, although bibliography is scarce (see Bleick et al., 2013). In terms of permafrost still less references are to be found (Palacios et al., 2007; Abramov et al., 2008). These authors studied the loss of ice mass, the formation of lahars, jökulhlaups, ground thermal properties, or the ice lost in history. Such details may be a useful tool to predict potential eruptive activity. In South America, this topic has hardly been studied (Tormey, 2010).

In 2004 the Geocryology unit of the IANIGLA began the inventory and mapping of cryogenic landforms of Andean key sites, including sampling and analyses of selected pedological and stratigraphical profiles that are affected by cryogenic and volcanic processes. For this purpose the Volcanic Complex Planchón–Peteroa–Azufre (now called the Volcanic Complex Peteroa VCP) was chosen, and a multidisciplinary research project began financed by the International Center for Earth Science (ICES) in Malargüe, Argentina. The inventory of periglacial landforms and detection of permafrost occurrences were included in detailed cartography as part of the geocryological South American mapping project. A monitoring programme of ice bodies was also launched.

In order to support the hypothesis that, presently, volcanism is the most important driving force for changes – and most likely also had been many times in the past – the processes of the cryospheric system of the volcanic complex, thermal analysis of the area with craters, and monitoring of the eastern slope of the VCP help to prove the high temperatures in the subsoil, which interact with the ice of the summit and also with nearby glaciers studied by Espizúa and Pitte (2009).

In 2004 periglacial geomorphological studies of the peak and slopes of the volcanic avalanche caldera of the volcanic complex began. But it was not until 2008 that the first thermal soil temperatures could be collected after surface drilling inside the volcanic avalanche caldera. The first air temperatures were collected at the same time. Since 2008

☆ *Yokul. Ce mot veut dire “glacier” en islandais, et sous la latitude élevée de l'Islande, la plupart des éruptions se font jour à travers les couches de glace. De là cette dénomination de Yokul appliquée à touts les monts ignivomes de l'île.* (Voyage au Centre de la Terre, Jules Verne, 1856)

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preliminary results have been presented at different congresses (see Trombotto et al., 2009, 2010a,b for example).

In addition to periglacial geomorphological studies of the area, the aim was to analyse the evolution of soil temperatures at a specific monitoring site in order to explain the presence of permafrost detected in 2006. By consecutive studies and through permafrost mapping of the volcano peak, applying special thermocameras, different superficial *hot* and *cold* sites were identified and monitored.

Calvari and Pinkerton (2004) are among the first using infrared thermography (FLIR) to detect instability of volcanic structures. They worked on the upper slopes of Mount Etna in summer 2001 when the onset was also with phreatomagmatic activity. Airborne high resolution visible and thermal infrared (TIR) imaging was also used for monitoring of low temperature thermal features and for detecting subtle changes over time (elevated temperatures at summit ice melt holes) in Alaska at Redoubt Volcano during the 2008–2009 unrest and eruption (Wessels et al., 2013).

The volcanic complex Peteroa was overflown several times with a monomotor Cessna equipped with a thermosensitive camera. The purpose of these inspection flights was to analyse the temperature of the volcanic avalanche caldera at inaccessible sites and of the summit, which displays volcanic activity and glaciation and neoformation of permafrost at the same time. The intention was to register the surface temperature at the summit and to distinguish different thermal areas with uncovered or covered ice, in the shade or exposed to solar radiation, as well as to calculate the temperatures that are indicating permafrost geomorphologically and to identify areas of maximum temperatures linked to present volcanic activity.

During these studies an increase of volcanic phreatomagmatic activity with expulsion of ashes, steam, and sulphur reaching heights of several hundred metres and columns of up to 3 km on 11 March 2010, which affected the regions, was observed (Fig. 1).

The present contribution seeks to find additional precursors of increased volcanic activity through thermogeomorphological monitoring linked with post-seismical processes of the Chilean earthquake of 27 February 2010 and to give geodynamical evidence of the registered changes. A new monitoring of terrestrial fieldwork was carried out in summer 2013.

In fact, three important aims are to be pointed out: i) to know the cryospheric system of the VCP through its climate and geomorphology (glaciers and permafrost); ii) to develop a continuous monitoring of the climate parameters (air and soil temperatures, precipitation), of variations in the surfaces covered by glacier ice and permafrost of the VCP that allow a follow up procedure, and a comparison of volcanic activity during the studied period (2007–2013); and iii) to corroborate that the presence and the history of glaciers and permafrost are conditioned by volcanic activity.

At present, no studies of this kind have ever been made so far, neither in this region nor in other parts of the Andes.

2. Study area

The active volcano Peteroa (4010 m asl) is located in the Cordillera Principal (Late Cenozoic Volcanic Arch) at 35°15′ S and 70°35′ W between the Argentine and Chilean border (Fig. 2). The volcano belongs to a complex occasionally called Planchón–Peteroa–Azufre, at approximately 90 km NW of the town of Malargüe and 65 km ESE of the town of Curicó. In Chile, the complex is simply referred to as Planchón–Peteroa. Tormey et al. (1989) also added the volcano Azufre (3448 m asl) in the southern part of the complex with a very large area of glaciated lava and pyroclastic sediments (30 km^3). Tormey et al. (1991) thought that the complexity in the petrology of the Southern Volcanic Zone of the Andes, between 33° and 42° S (including the Peteroa volcano region) depends on the thickness increase of the continental terrestrial crust; and so the author explained the evolution from basalt to basaltic andesite because of the crustal contamination. According to Tormey et al. (1995), the variations in the proportions and compositions of crustal components caused different lavas defined by geochemical trends that are also present in the VCP.

The volcanic structure comprises a round surface of 78.2 km^2 (approximately) and a maximum height of 4100 m asl at Cerro Peteroa. The volcanic avalanche caldera comprises 5 km^2 (approximately). It is a basaltic andesite–dacitic stratovolcano.

Volcanism is expressed mainly by five large craters with fumaroles, solfataras, and emanations of sulphur and steam. A smaller sixth crater was observed when the authors overflew the area, but it did not show any signs of activity. The volcanic activity since its beginning has been described in various publications and may be analysed in the publications of Tormey et al. (1989), Haller et al. (1991, 1993), Naranjo et al. (1999), and Naranjo and Haller (2002). In conclusion, the structure called Peteroa–Azufre is composed by an old volcano from the medium lower Pleistocene. Toward the north, the volcano Planchón (3920 m asl

Fig. 1. Phreatomagmatic eruption with expulsion of ashes (to considerable height steams) and sulphur on 2010 October 20 (over 2 km, approximately).

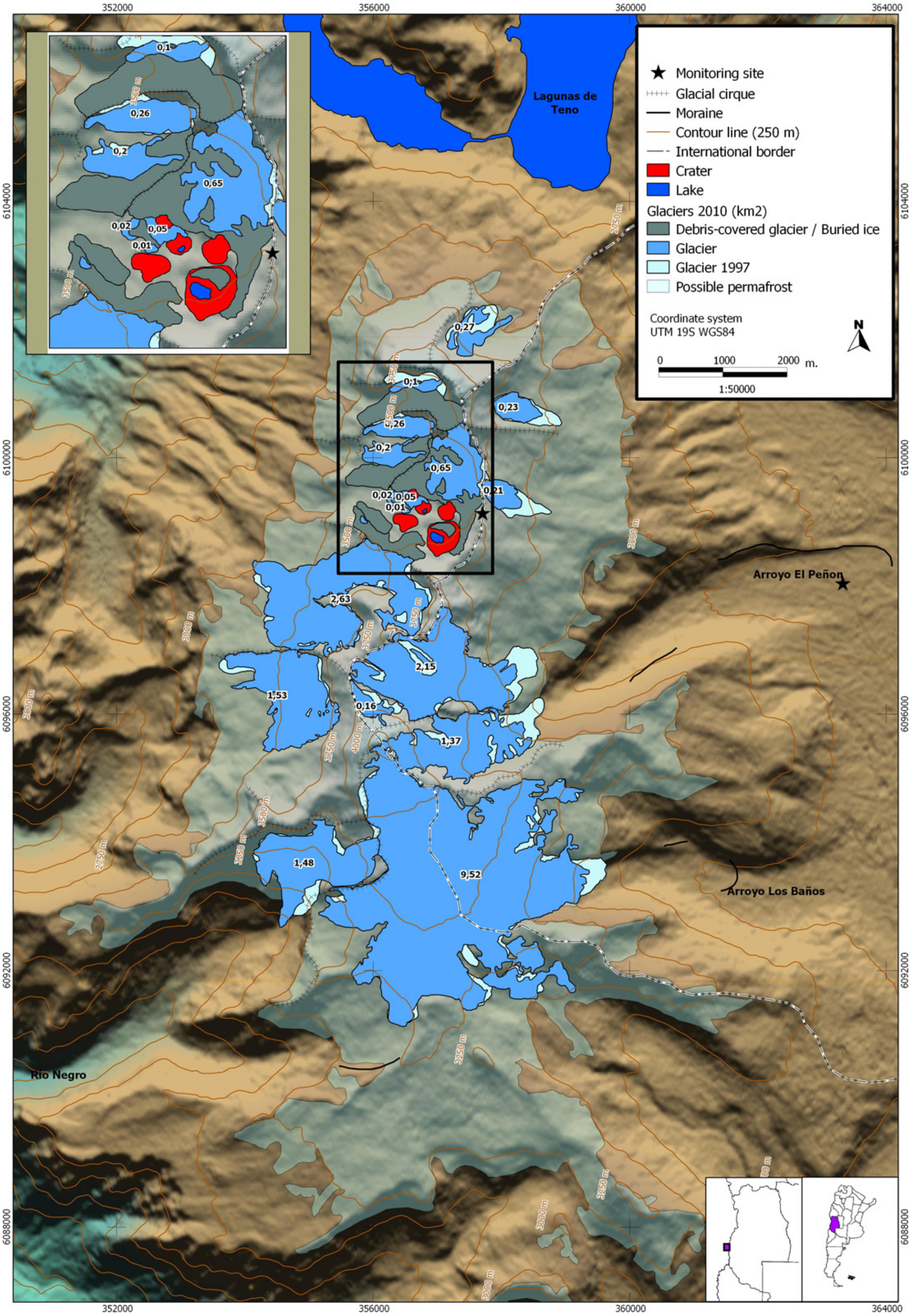

Fig. 2. Study area.

and Morro Planchón 3977 m asl) is superimposed to the structure of the complex of an initial Late Pleistocene. Tormey et al. (1989) emphasized a remarkable bimodality of the volcano Azufre and indicated that its lavas have shaped under low pressure and by fracture of a mixture with a high content of plagioclases. According to these authors, the lavas of the complex have two crustal profundities.

Post-glacial activity has mainly been explosive and has occurred in at least five craters. The latest important eruption took place in 1991 (creation of El Hornillo?). Another event was registered in 1998, but with a VEI (eruptive index) = 1. At present, signs of volcanic activity of the Peteroa are visible through numerous fumaroles on the bottom of two craters and also through superior fissures where the ice has disappeared and with a noticeable expulsion of sulphur gas (sulphur dioxide?) revealed by its smell. Lagoons and areas of melted glacial ice appear and disappear, infiltrating into the craters where the water is expulsed as steam and influences the eruptive explosions. These

Fig. 3. Periglacial environment on the slopes of the present volcanic avalanche caldera at the Volcanic Complex Peteroa. Diurnal Peteroa Flight 2010.

phreatomagmatic eruptions have been registered repeatedly in the last years. Another parallel volcanic activity is linked with the presence of thermal waters in different pits in the sulphur baths with varying temperatures.

On 2010 March 11 the VCP had a phreatomagmatic eruption with expulsion of ashes to considerable heights (over 2 km, approximately) and of steam and sulphur. The increase of activity was irregular, with important peaks and columns reaching a height of several hundred metres between 2010 and 2011.

The glaciated surface is characterized by 15 glaciers of different size that occupy part of the summit and its surroundings. The above-mentioned publications do not define the number of glaciers correctly. Naranjo et al. (1999) did however, mention the surface of four important glaciers and the significance of glaciations for eruptions or volcanic activity in order to explain phreatomagmatic eruptions or the formation of volcanic rocks (scoria bombs with cauliflower structure, palogonitic glass rings, and oxidation vesicles).

Neoglacial episodes with the advance of ice are described by Espizúa (2000) and may be associated with the ages indicated by Mercer (1982) for his Holocene glacier variations in southern South America, although Espizúa does not mention the important restriction that the volcano's internal geodynamics imply when trying to relate glacial advances with permanent activity of the VCP, which relativises the ages and the altitudes of the moraines.

3. Material and methods

Geomorphology characteristics in general and periglacial geomorphology as well as the ice cover of the volcano in particular were elaborated with the help of aerial photographs from 1997. Later on, landforms

Fig. 4. Covered glacial ice on the top of the caldera of a volcanic avalanche in the Volcanic Complex Peteroa.

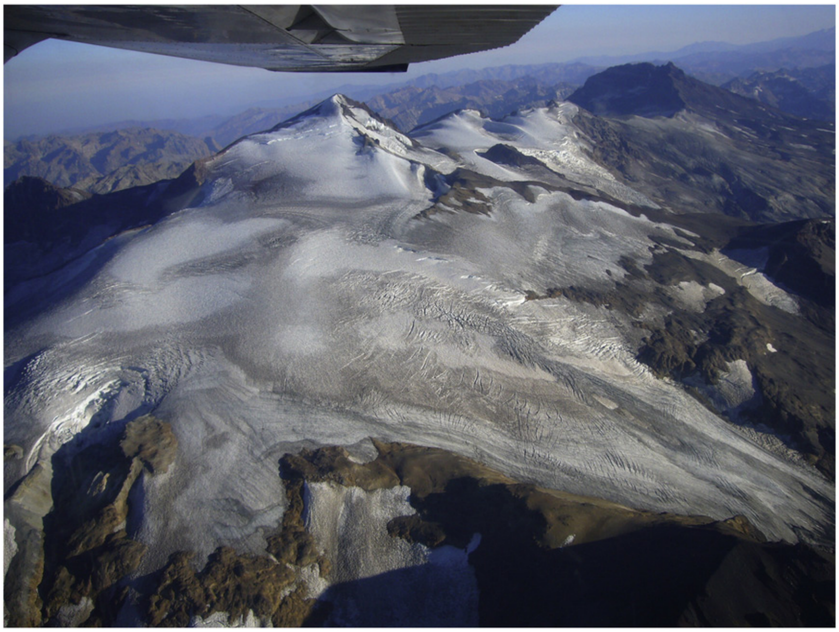

Fig. 5. Southern glacier of the Volcanic Complex Peteroa. Diurnal Peteroa Flight 2009.

were determined and permafrost occurrence corroborated with Google Earth and field work. This identification inventory and mapping of land and cryoforms was begun in 2003.

The georeferencing of the image map made by Trombotto et al. (2009) allowed the digitalization of the glaciers for the year 1997 and thus with a partial control of the field, it was possible to obtain the limit of coverage of *possible permafrost*.

The methodology applied in the following, for mapping the glaciers of the Planchón–Peteroa–Azufre volcano complex, was based on the spectral analysis of satellite images obtained by the Aster sensor by the end of March 2010 and during fieldwork in the area of the volcanic avalanche caldera throughout all summer seasons until 2013.

Once the ice bodies and their borders had been identified, they were corrected on the basis of the fieldwork data, which allowed, to distinguish those ice bodies that were covered and therefore had not been captured by spectral analysis, as well as observe isolated ground ice disconnected to the glaciers, which adds to the permafrost zone.

Permafrost was determined wherever *possible* (Fig. 2) with the help of an imaginary limit drawn on the basis of field and profile observations, findings of covered ice and frozen ground detected next to glacier tongues during each summer of various field trips (2003–2013), and considering the front of protalus, protalus ramparts, and other active cryoforms (Fig. 3).

In order to carry out a continuous monitoring of soil temperatures, a monitoring site close to the rim of the volcanic avalanche caldera but not reached by volcanic activity was chosen and duly equipped. Soil and air temperatures were collected to describe the evolution of the temperatures in the subsoil. Sensors used were data loggers type UTL (accuracy = ±0.1 °C; resolution = 0.27 °C (8 bit); average frequency = 4 h), built at the University of Bern (Switzerland). At site Peteroa (3360 m) – on the border of the volcanic avalanche caldera – the thermistors were installed at following depths: −0.20, −0.45, and −0.80 m depth during 2007–2013. A data logger at +1.20 m was also installed to calculate the mean annual air temperature. These data are being collected each year in summer.

To measure precipitation, a totalizator was installed at the foot of the VCP (35°15′05.4″ and 70°30′08.5″, 2449 m asl, see Fig. 1). This simple equipment allowed, to know the total precipitation each year. In winter the site is inaccessible.

On the other hand, thermocameras were used to analyse surface temperature in different areas: in- and outside the volcanic avalanche caldera, in periglacial, glacial, and volcanic areas. These tasks were carried out in 2009 and 2010. The camera used in 2009 was an AGEMA TVH 550, with a resolution of 320 × 240 pixels (76,800 detectors). In 2010 a more sophisticated camera, a FLIR (Forward Looking InfraRed)

Table 1
Monitoring site Peteroa.

Monitoring site	Coordinates	Altitude (m)	Method
Peteroa	35°14′27″ S and 70°33′50″ W UTM zone 19 South WGS 84: 6,099,128.20 m; 357,705.99 m	3489	Data logger and borehole

Table 2
Comparison of glacier areas, 1997 and 2010.

Uncovered glacier	Area 1997 (km^2)	Area 2010 (km^2)	Difference	New data 2010 (km^2)
Azufre Glacier	−1.44	1.37	*−0.07*	
Azufre Superior Glacier	−0.9	0.16	*−0.03*	
El Peñón Glacier	−1.98	2.15	0.17	
Este Alfa Glacier	−0.32	0.23	*−0.09*	
Este Beta Glacier	−0.29	0.21	*−0.08*	
Norte Glacier	−0.33	0.27	*−0.06*	
Oeste Delta Glacier	−1.27	1.53	0.26	
Oeste Gamma Glacier	−2.42	2.63	0.21	
Sudoeste Glacier	−1.2	1.48	0.28	
Superior Alfa Glacier	−0.44	0.65	0.21	
Superior Beta Glacier				0.08
Superior Norte Alfa Glacier	−0.18	0.1	*−0.08*	
Superior Norte Beta Glacier	−0.24	0.26	0.02	
Superior Norte Gamma Glacier	−0.19	0.2	0.01	
Sur Glacier	−8.49	9.52	1.03	
Total area	−18.98	20.76	1.78	0.08

Italicized numbers indicate that the difference is negative.

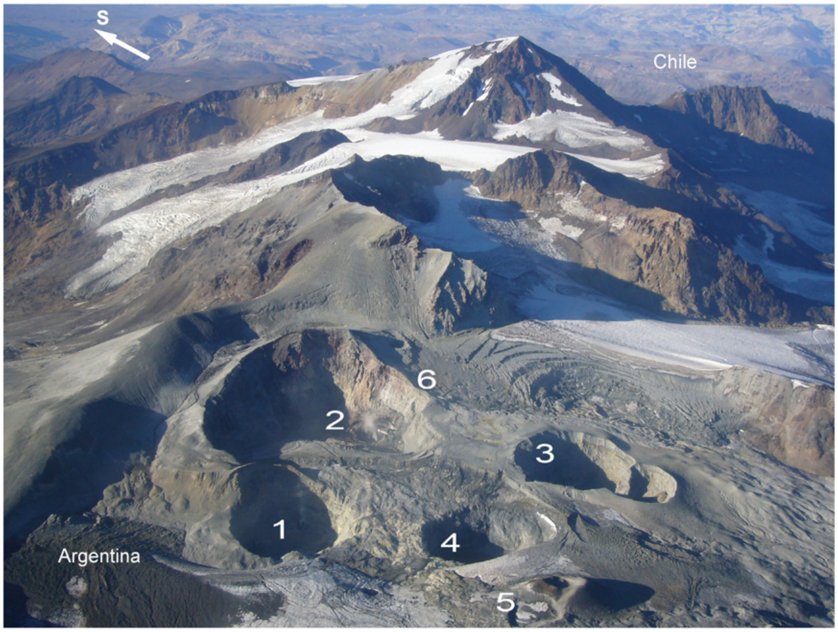

Fig. 6. Present volcanic avalanche caldera of the Volcanic Complex Peteroa. Diurnal Peteroa Flight 2009. Clockwise craters1, 2, 3, 4, and 5, crater 6 separate.

P660 with a resolution of 640 × 420 pixels (268,800 detectors), with an integrated digital camera of 3.2 megapixels and GPS system was used.

The objects emit infrared radiation, which depends on their temperature and on emittance. Terrestrial and aerial monitoring with thermocameras allows us, to detect anomalies and local temperature changes and their variations. That is to say it is able to indicate an increase of volcanic activity, expansion or not of hot zones and alignments, or consecutive orientation of certain surfaces where volcanic activity is observed. This method was applied for different volcanic phenomena (see Spampinato et al., 2008). In order to process data, the proceeding (as indicated by Spampinato et al., 2011) was followed as well as the indications of the manuals for this type of thermocamera.

The thermocameras were used while overflying the area with a unimotor Cessna 182 in daytime. In 2010, a night expedition to the volcanic avalanche caldera, to a height of 3900 m asl (approximately) completed the monitoring programme with the FLIR P660. Photographs were taken and films were also made in order to support the interpretation of the sites made with the results of the thermocamera. The thermocameras take both visible and infrared photographs.

The temperature scale of this measuring can be chosen from a menu of thermal ranges within which the camera calibrates itself automatically and results in a better lecture. In this case, the range was −20 to 150 °C. Once the camera is supplied with measuring parameters such as emissivity (property of each material), temperature range, reflected or environmental temperature, relative humidity, and distance, it auto-calibrates for adjustments of an attenuation of air temperature caused by vapours, dust in suspension or the presence of gases. The minimum resolution of the cameras is ±2% of the lecture respectively.

4. Results

4.1. Geomorphology

The glaciers of the Central Andes retreat in different ways and to different extents. In the case of the Piloto glacier situated at the Argentine–Chilean border at 32°37′ S, the 1979–2003 cumulative mass balance is equivalent to a mass loss of 10.5 m of water and shows a general process of retreat (Leiva et al., 2007). At 33°58′ S the glacier Echauren Norte in Chile (DGA, 2009), displays a cumulative mass balance of −7.87 m water equivalent for the period 1975–2009. At the Aconcagua massif, variations of glacier fronts measured in metres (which is another method to register glacier withdrawal) such as in the case of the glaciers Güssfeldt at

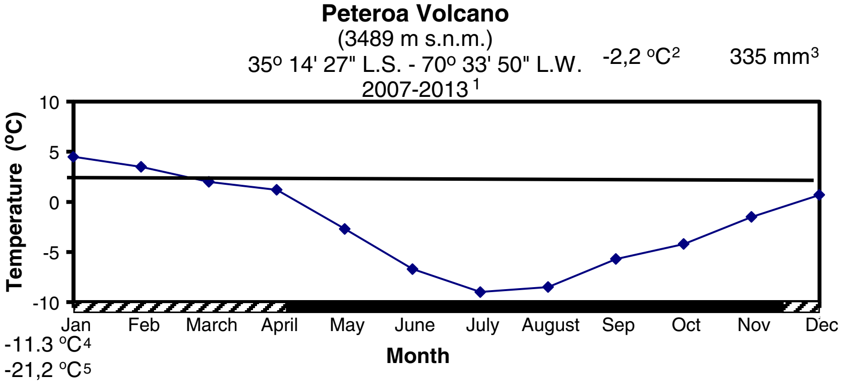

Fig. 7. Walter-Lieth diagram of the site called Peteroa S at 3489 m asl (1) period of time considered (with interruptions), (2) mean annual temperature, (3) annual precipitation, (4) mean value of the daily minimum of the coldest month, and (5) absolute minima.

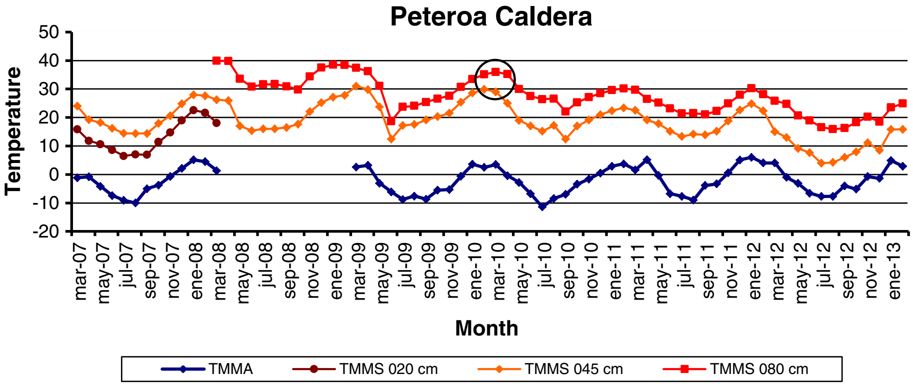

Fig. 8. Mean monthly soil temperature (MMST) at 20, 45, and 80 cm of depth. MMAT is the mean monthly air temperature. The circle indicates the initialization of a major event of volcanic activity (March 2010).

32°61′ S and Vacas at 32°55′ S it was estimated to be −20 up to −400 m in each case in the year 2007 and compared to the period 1929–2005 (ICSU et al., 2012).

Monitoring the area and studying its geomorphology allowed us to identify and map uncovered and covered ice associated with the upper glaciated area of the volcano strongly affected by volcanism. Glaciers are retreating toward the north or toward the rim of the volcanic avalanche caldera – depending on their location – because of volcanic activity and a high geothermal gradient. *Islands* (isolated spots) of ice are remaining, associated with surface permafrost (Fig. 4).

According to the images taken in 1997 and 2010, the glaciated surface comprises 20 km^2 approximately (Trombotto et al., 2009, 2010a, b) which is considerably less than the surface registered by Gonzalez and Vergara (1962) (in fide Naranjo et al., 1999) who mentioned a glaciation of 30 km^2 for the volcanic complex Peteroa–Azufre. These dimensions, would then always vary because of volcanism and the characteristics of the complex to generate and contain glaciers. The superior uncovered ice body, in the volcanic avalanche caldera, is <1.3 km^2, but many islands of covered ice have been cut off from glacial tongues in motion. The sedimentary cover displays irregular thickness (generally > 25 cm).

A sharp reduction in the superior glacial ice thickness suggests a maximum thickness of 20 m that remains in small areas such as the zone between craters 4 and 5. To the south of the complex, the largest ice body is found with a surface of over 8.49 km^2 in 1997 (Fig. 5), but 9.52 km^2 in 2010. The 1997 data is also approximate because the images are not georeferenced.

Table 2 shows the variations obtained comparing the image map of 1997 with that of 2010.

Notably, the areal variations of the detected ice bodies were generally insignificant. The glacial tongues of those glaciers facing east toward Argentina, however, have shortened considerably. During fieldwork it was possible to observe the changes of the glaciers on the summit (informally called superior glaciers) and to identify them according to the orientation of their respective tongues. The remarkable reduction of the ice thickness on the summit makes us assume that other local glaciers also lost thickness—despite little visible changes in the images, and the exact dimensions are unknown. Some lateral variations of the ice bodies that do not correspond with one another ought to be considered as mistakes made by the authors.

Table 3
Apparent temperatures and their respective zones.

Apparent temperatures (°C)	Zones
41.0–13.6	Water inside the crater
37.7–26.7	Zones with fumaroles[a]
20.8	Zones without visible ice in sun[b]
17.4–5.0	Covered ice in sun[c]
9.2–(−10.3)	Areas without visible ice in shade[b]
−3.8	Uncovered ice in sun
−2.4–(−10.3)	Covered ice in shade
−10.2–(−13.8)	Uncovered ice in shade

[a] Low temperatures are associated with the presence of ice.
[b] Positive high temperatures are associated to the walls of active craters.
[c] Ice is either dirty or covered by dark volcanic sediments of varied thickness.

South of an avalanche caldera, a covered glacier of 0.42 km^2 decreased significantly according to field observations in 2013 (see Fig. 2) as a consequence of the latest activity that clearly affected the Chilean side of the avalanche caldera. The increases (see Fig. 2 and Table 2) are associated with errors (Sur Glacier, Oeste Gamma Glacier, Oeste Delta Glacier) or areal variations caused by the increase of geothermal heat because of the activity of the volcano (Superior Norte Beta Glacier, Superior Norte Gamma Glacier).

The decrease of ice thickness (accumulated on the summit during times of less volcanic activity) seems to gain more importance than the retreat of the tongues on the sides, as far as interaction with geothermal heat is concerned. Notice, that on the western slope this phenomenon becomes more evident. No significant changes are observed, because the VCP is inclined toward this slope; it is also the direction of the volcanic avalanche caldera. The eastern slope is much steeper, there the variations at the accumulation zone are more significant.

The cryogenic area with cryogenic processes and permafrost on the slopes was identified through isolated ice bodies covered by volcanic sediments, active protalus lobes, and protalus ramparts, small rock glaciers, nivation hollows, gelifluction terraces, and cryogenic sedimentary slopes (Fig. 3).

The peak of the VCP coincides with the altitudinal level of *quasicontinuous* permafrost in the classification by Garleff and Stingl (1986), although the observations of periglacial geomorphology and the presence of ice on the slopes of the volcanic avalanche caldera lower the altitudinal mountain permafrost level down to 2900–3000 m asl (approximately). Permanent volcanic activity and the retreat of glaciers cause neoformation of permafrost that is only concentrated to the interior of the volcanic avalanche caldera, today in most of the cases interrupted or separated from the main glacier bodies (Figs. 2 and 4). This phenomenon has been corroborated during consecutive expeditions in the area. Possible permafrost in the volcanic avalanche caldera and its surroundings has been calculated to be 74 km^2 (approximately; Fig. 2; Trombotto et al., 2009, 2010a,b).

At first, five craters were identified during flights and diurnal ascents inside the volcanic avalanche caldera; however during the last flight (2010) another small vent without clear signs of volcanic activity was detected (Fig. 6).

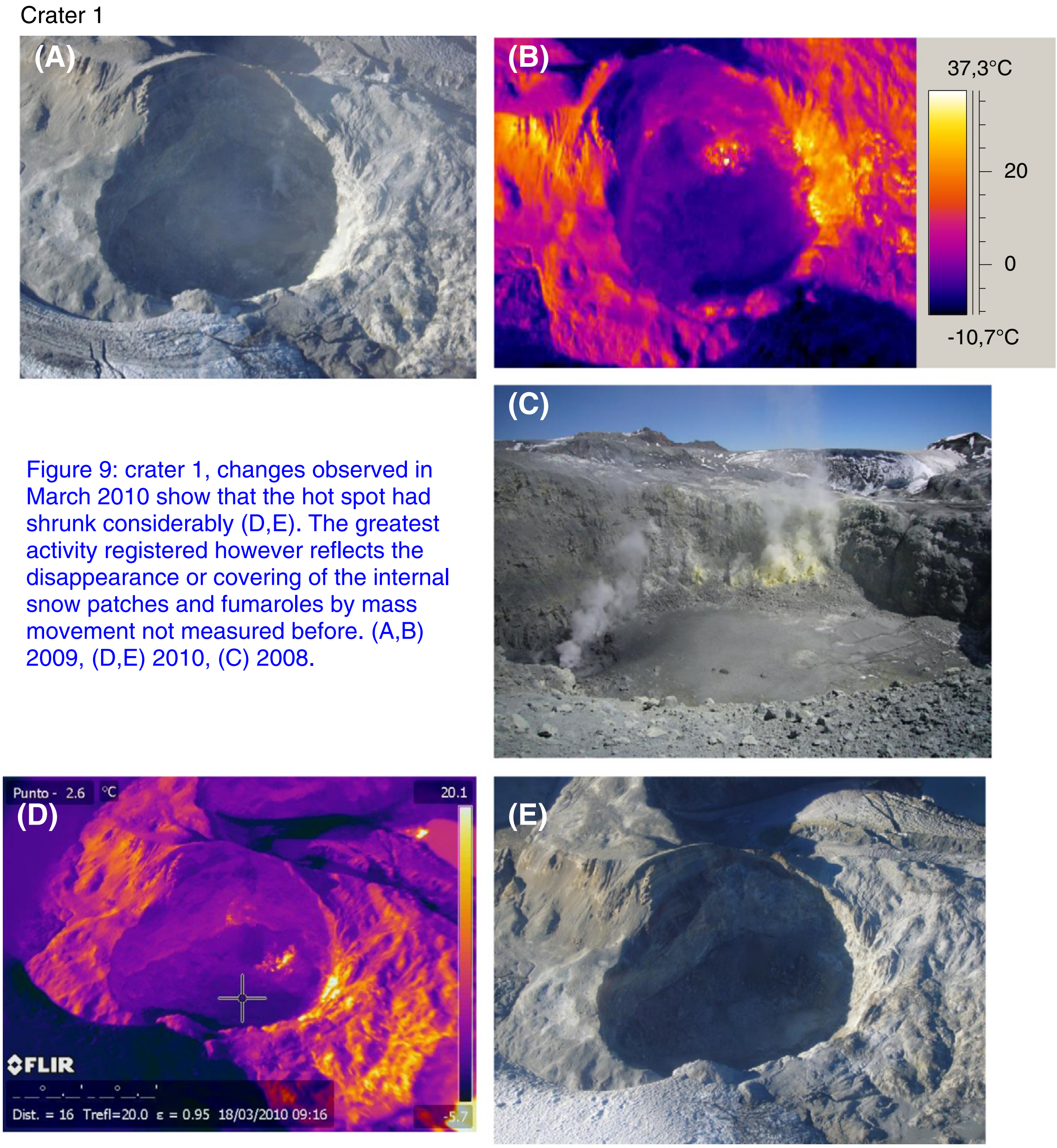

Figure 9: crater 1, changes observed in March 2010 show that the hot spot had shrunk considerably (D,E). The greatest activity registered however reflects the disappearance or covering of the internal snow patches and fumaroles by mass movement not measured before. (A,B) 2009, (D,E) 2010, (C) 2008.

Fig. 9. Crater 1 changes observed in March 2010 show that the hot spot had shrunk considerably (below). The greatest activity registered, however, reflects the disappearance or covering of the internal snow patches and fumaroles by mass movement not measured before. Upper part 2009, lower part 2010; on the middle and right image of 2008.

4.2. Registered meteorological characteristics and thermal subsuperficial soil monitoring

The climate of the site is Andean tundra corresponding to that of an altoAndean region (Trombotto, 1991) of the most southern part of the Central Andes. According to the modified Köppen climate classification (Peel et al., 2007), the study area would belong to an ETH climate, a polar tundra climate in high altitude, characterized by no or very little excess of water, little seasonal variations in terms of hydrical efficiency with the longest periods of evapotranspiration in summer, little precipitation in summer and with presence of permafrost. Local seasonal changes are observed.

Within a year a period of thawing and a period of freezing, with air temperatures below 0 °C, can be distinguished. Westerly winds and the South Pacific cyclone prevail with intense snowfalls in winter. The air temperatures presented below and the data of total precipitation were obtained from a monitoring site installed in 2007.

The mean annual air temperature (MAAT) registered at the site called Peteroa (Table 1) on the edge of the volcanic avalanche caldera of the volcanic complex Peteroa at a height of 3489 m asl between 2007 and 2013 was −2.2 °C (approximately), that is to say the mean annual temperature favours permafrost occurrence.

July is the coldest month with a MAAT of −8.9 °C between 2007 and 2013. The coldest year of the considered time period was 2010 with a mean daily minimum of −12.8 °C and a mean value of maximums of −8.5 °C. This fact favours the superficial freezing of the ground for a prolonged time during winter although at little depth. The absolute minimum registered was −21.2 °C in August 2012. The absolute temperature below zero is important for the genesis of frost cracking in the ground and block breakage caused by cryoclastism. Between May and November, it can be expected that at this height the ground will remain permanently frozen (Fig. 7).

The mean monthly soil temperatures follow the general tendency of the mean monthly air temperatures. In the year 2009, the temperature

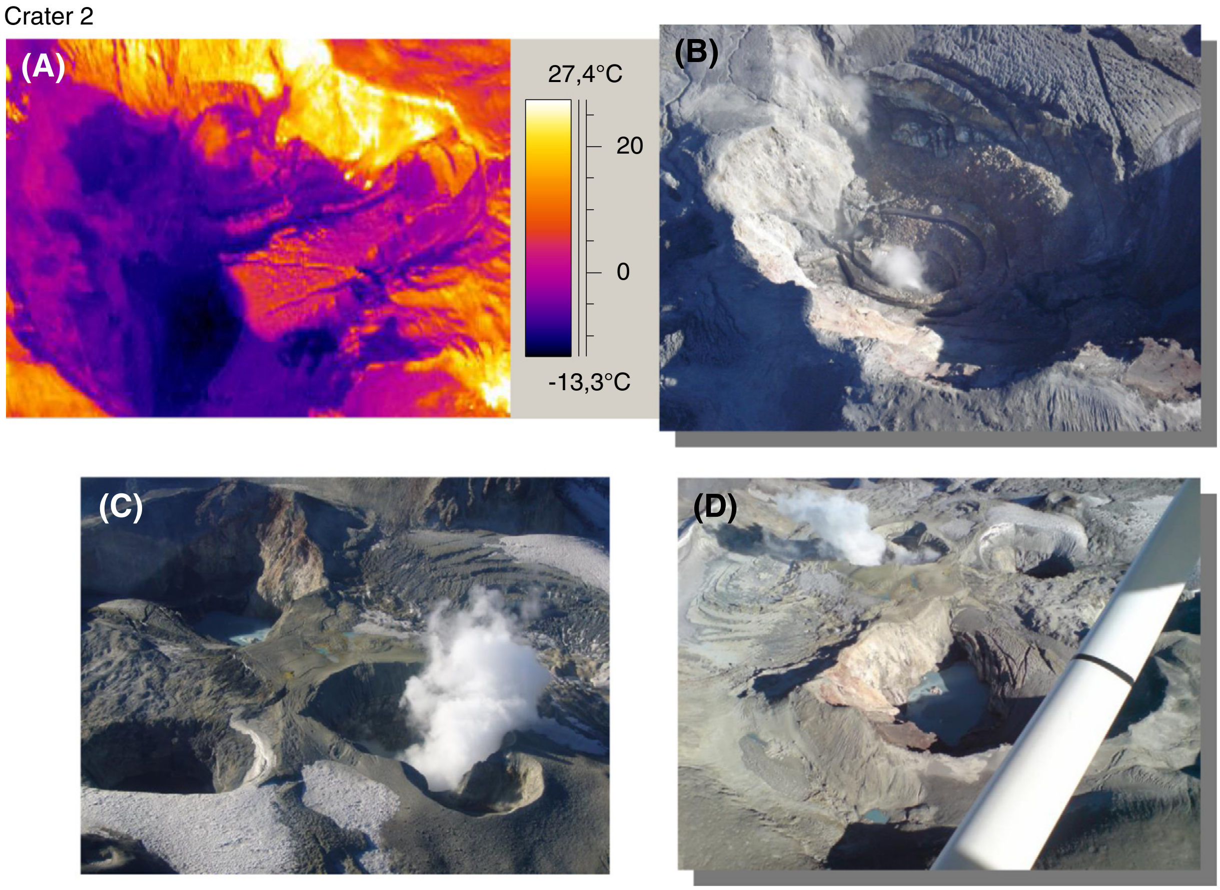

Fig. 10. Crater 2 shows the formation of the blue lake after the activity peak in March 2010. Above 2009 and below 2010.

in July was −8.8 °C and coincides with the temperature descent in the ground. However, although the mean monthly air temperature of July with −11.4 °C was lower than that of the soil, these temperatures are softened and do not correspond to the lowest temperatures. The lowest temperature peak in 2010, at a depth of 45 cm as well as at a depth of 80 cm was observed in September. This retarding might possibly be associated to an increase of volcanic activity. Overflying the area, an increase of volcanic activity was confirmed for September and October.

It strikes the eye (Fig. 8) that an increase of the difference between the curves of 45 and 80 cm expresses a reduction of the thermal gradient and documents a major incidence of geothermal heat. The mean monthly temperatures at a depth of 80 cm fell considerably since 2008, when the studies began, with a maximum descent of 10 °C in March (period 2008–2011) and a minimum of 3.5 °C in May (period 2008–2010). This phenomenon is observed after an increased volcanic activity, in March 2010, separating and increasing the temperature of the 80 cm curve. While in December 2009 the gradient is of 1 °C each 6.6 cm between depths of 45 and 80 cm, in April 2010 the gradient decreases at the same depth and temperature rise to 1 °C each 3.4 cm (April 2009 = 1 °C each 5.5 cm). The maximum is in July when the temperature rises 1 °C each 3.1 cm. Analysing these data, we may suppose that during the year 2008 there also was a major volcanic activity even though it has not been registered directly. 'A major volcanic activity over the last years' was observed by different inhabitants of the area (Amalia Ramires, affiliation, personal communication, 2012) without giving precise data.

New monitoring data collected between 2011 and 2013 showed that the minimum thickness for the thermal gradient was in winter (June–August) each time. We may suppose that at that time the region was covered by a thick layer of snow as is common in the southern Andes of Mendoza. Snow causes soil isolation and the direct influence of geothermal heat in the superficial soil layer. Under these circumstances it is better to analyse the thermal gradient without external heat influences.

4.3. Crater monitoring with thermocameras

Landforms and their surface temperatures were analysed with the help of thermocameras contrasting the results of visible images with those of infrared images. Results are shown in Table 3 that allowed us to classify subenvironments and associate them to the respective surface temperatures.

The FLIR P660 camera also allowed us to determine extreme temperatures. Each crater was photographed with the thermocamera and scanned.

Probable permafrost was detected with high certainty near the peak at 3950 m asl on the night descent in March 2010 and in contact with the perennial snow patch as expected (Trombotto, 1991).

The analysis of the craters located inside the volcanic avalanche caldera allowed us to observe notable variations between 2009 and 2010, which are described with detail in the following.

Crater 1, for example, changed its perimeter because of downfalls and the disappearance of all perennial snow patches discovered in its interior. It displayed fumaroles in 2009 and a remarkable hot spot (Fig. 9); in 2010 the apparent surface temperatures fell considerably (Fig. 9).

In crater 2, a great part of the glacigenic ice that had covered the crater melted and generated a blue lake (Fig. 10). It displayed visible strong fumaroles in 2009 that only remain as a poor and weak manifestation on the western margin.

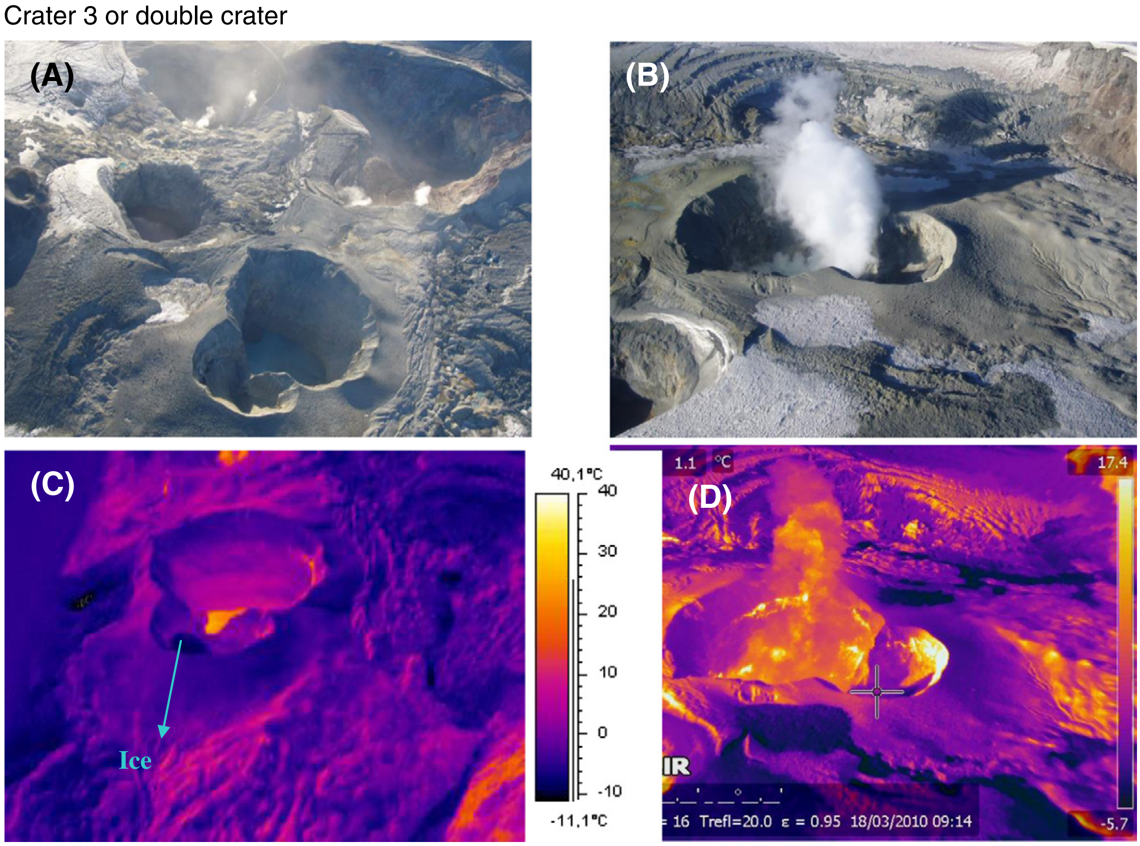

Fig. 11. Crater 3 or double. On the left digital/visible image and infrared (IR) from 2009 and on the right images turned toward the east (Argentina) visible and IR from 2010.

It was crater 3 situated in the western part of the volcanic avalanche caldera called *double* that displayed the most intense volcanic activity with strong fumaroles and splashes of boiling hot water observed during the expedition in March 2010 (Fig. 11), that is to say it looked completely different than in March 2009 (Fig. 11). The ice had disappeared almost completely (one little snow patch still remained on the NW wall). The images taken in 2009 showed a few spots with high surface temperatures and reduced surface (Fig. 11) and no visible fumaroles at all. It strikes the eye that the high temperatures indicate the internal lake and that already an important thermal indicator at the western wall is building up in layers.

The crater baptized informally as crater 4, or crater with the red lake, showed a thermal spectrum that in 2009 was very different from the one in 2010. At this crater, heat fumaroles could be clearly distinguished that affected a great part of the crater, including various penetrations below the water surface level (Fig. 12). An important heat fumarole was identified below the water surface indicating a real intensification of temperature not detected so far and concentrated in the west (Fig. 12).

Crater 5 showed signs of activity not registered before below the ice that covered the entire hole; today it is already broken apart and with emanations of heat on the margins (Fig. 13) as well as below the ice.

A sixth crater, called *crater 6* – adventice of crater 2 (Fig. 6) – was detected in 2010. It had no visible activity at that time and was covered by ice almost entirely, but when the glaciated area changed because of the enormous subterranean heat, it showed clear signals of fumaroles and solfataras. The surrounding area, however, which was strongly glaciated in 2009, had already undergone remarkable changes until the summer 2010. This area with *volcanic thermokarsts* allows us to assume a big hot spot below the ice of one of the glaciers informally called *superior* above the volcanic avalanche caldera, which might be the reason for the concentric shape of the glacier body with its concentric stepped fissures. This glacier announced a reduction and a strong displacement in 2013 as a result of melting and loss of glacier ice, which was already moving in circles and steps or showed collapse structures (Fig. 14). The glacier melting also left a lake inside crater 2. New important circular collapse structures also appeared surrounding crater 3 in 2013.

5. Discussion

The glaciers of the VCP are strongly conditioned by the volcanic activity, and their changes can hardly be associated to climatic variations. The particular geomorphology of the volcano allows cold air to remain in the caldera favouring the presence of glacial ice.

Although it has been claimed that the glaciers of the Peteroa Volcano Complex are retreating and advancing because of climate and meteorological variations (Espizúa and Pitte, 2009), we must say that the VCP glaciers retreat because of thermal activity rather than because of climatic reasons. This is confirmed by their behaviour and by the thermal conditions of the subsoil (see Fig. 8). It is worth mentioning that it had already been indicated that the VCP magmas have developed at shallow crustal levels indicating a shallow level head source to promote ice melting (Tormey et al., 1995; Tormey, 2010).

The advances described by Espizúa and Pitte (2009) are, rather, associated to a subsoil with a high geothermal gradient than to the ENSO events described by the authors as possible forces. The advance between 1963 and 1990 described by the authors culminates with the phreatomagmatic explosions of the VCP in 1991, when ascending magma interacted thermally with rocks but also with glaciers. On the other hand, the slight advance of 2004–2007 is paired all the time with major volcanic activity, and in 2010 it culminated in another phreatomagmatic explosion. This volcanic activity has enhanced the melting of the glacier base, the production of subglacial water and *pseudoadvances*. The fact that the Azufre glacier shows a minor negative trend compared to the Peñón glacier is to be explained by its greater

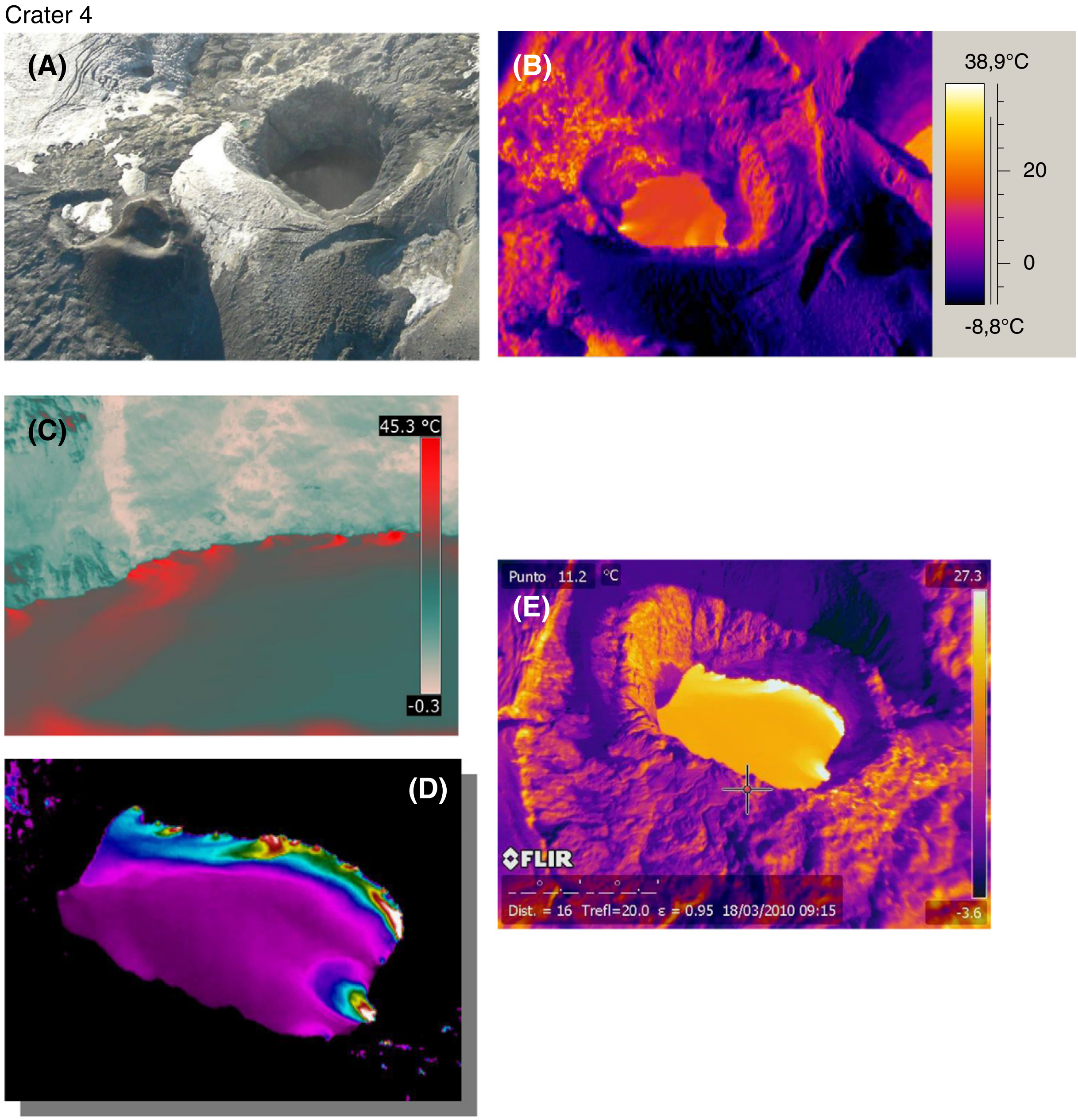

Fig. 12. Crater 4 or *crater with red lake*. Above 2009, below 2010. Intensification of heat on the western wall and heat spots not registered in 2009 below the water surface. Notice the huge heat fumaroles below the water surface and another important one in the NW part of the crater. The latest image already indicates the zonification and movement of the heat in the water.

geographical distance from the heat focus of the VCP, which is where the craters are today.

The existence of permafrost in the interior of the caldera is possible according to the hypothesis of Woodcock (compare Woodcock, 1974) for the Mauna Kea in Hawaii, where cold air with MAAT below zero is accumulated in the depression of the caldera and where evaporation and sublimation favour a cooling process as result of a thermodynamical phenomenon. In the case of the VCP however, it is an important superior glaciation that favours the existence and formation of permafrost.

Although it has been said that active temperate–zone rock glaciers are absent south of the volcano Planchón–Peteroa because of low topography, active volcanism, and increased humidity (Brenning, 2005), rock glaciers and protalus lobes are present in the VCP and as far south as the volcano Domuyo (36°36′). Their expressions are just minor and practically conditioned by volcanic activity, as these cryoforms directly interact in the soil and with its caloric balance. The origin and the persistence of the cryoforms is strongly conditioned by the geothermal gradient of the location. Whereas glaciers interact with the interphase (ice/soil) representing a *crustal* or superficial medium in this sense, which may subsist easier in the top of active volcanoes.

Although thermal soundings with thermocameras are carried out on the surface at only a few centimetres in the soil, temperatures below 0 °C in areas without visible ice allow us to suppose the existence of permanently frozen ground with a type of neoformation of permafrost (subterranean ice is observed), associated with glacier retreat and the interruption of areas with uncovered ice. At the same time, high temperatures on the ice and with tephras enhance the fast glacier retreat witnessed at present.

Glacier ice as relict ice remains and is visible in some parts of the volcanic avalanche caldera base. It displays intraglacial sediments mainly.

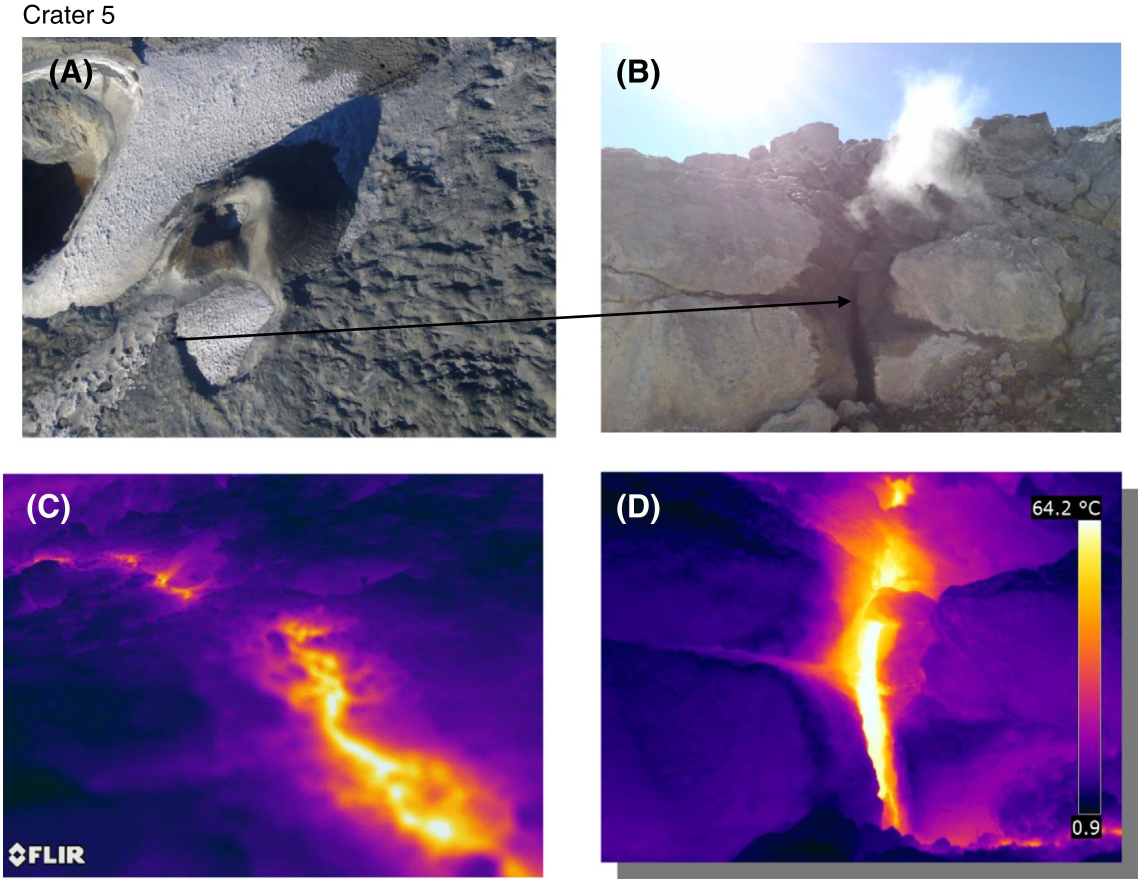

Fig. 13. Crater 5, left above 2009, right above and below fractures on the crater margins with important heat emanations. The heat flow expressed in the fissures of the crater are continued toward the bottom of the crater and below the snow patch.

Relict ice of remarkable thickness is found in some sectors between craters 4 and 5 and in the northern part (far from the craters), with a thickness of 20 m but with poor expansion.

This ice will melt soon though as volcanic activity continues, and its disappearance is an indicator of increasing subaquatic volcanic explosions because the sector with covered and uncovered ice is frequently affected by the thermal wave from the interior of the volcano, which is thermally reflected on the surface and by strong emanations of gas and steam registered in 2011.

Although with the help of thermocameras *hot* spots (correlated with the present volcanism) and *cold* zones (associated with the presence of glacier ice and shadowy parts that represent sites with possible

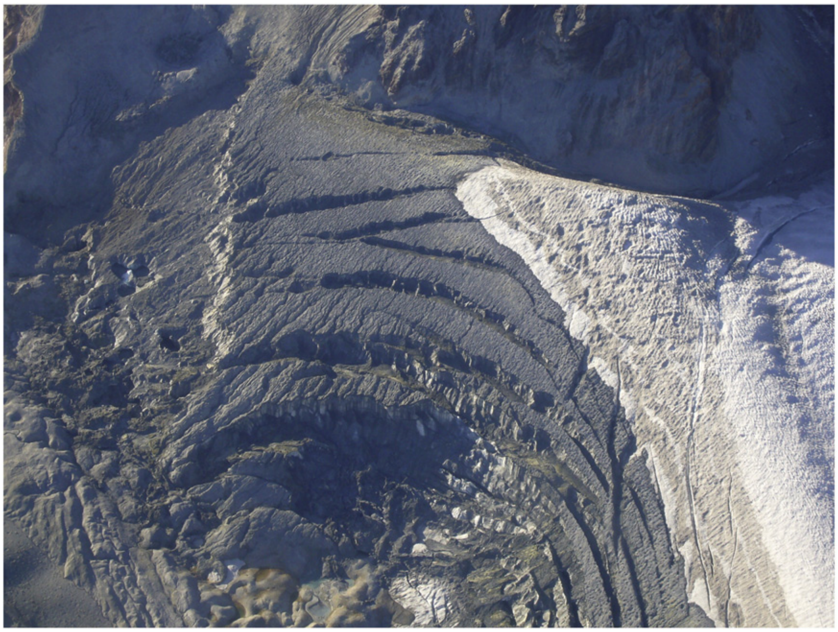

Fig. 14. Superior glacier (2009) on the top of the Volcanic Complex Peteroa affected by internal heat flow.

permafrost) could be identified, the most important result is the remarkable change of the craters comparing 2009 and 2010. The craters showed an increased volcanic activity with a chance of intensification. A possibility that soon came true with a peak of volcanic activity in 2010. Shortly after this monitoring report, the event was confirmed by informants and by Chilean as well as Argentine journalists who visited the area at that time.

In March 2010 new and stronger fumaroles appeared in the areas identified as *hot* spots in 2009, following a trend of heat displacements toward the west. New subaquatic fumaroles appeared in crater 3 on 3 March 2010. Together with tumbling walls in crater 1, variations of ice-covered areas, cold water supply, or the creation of a new lake in crater 2 are some of the outcomes observed that predicted an increase of volcanic activity.

Soil temperatures registered with data loggers at the monitoring site at the east of the volcanic avalanche caldera showed that at a depth of 45–80 cm the temperature gradient rose by 10 cm between 2008/2009 and 2009/2010 before the event. Air temperatures clearly show this influence up to 80 cm measured with data loggers. Mean monthly temperatures, however, generally decreased. The positive tendency of air temperatures may be explained by the increased volcanic activity in 2010.

From the observations and analyses of infrared images taken by the thermocamera, a general noticeable warming of the western sector of the volcanic avalanche caldera may be stated before the mentioned eruption in March. The most intense surface heat fumaroles predominantly occupied the Chilean side and were considered as indicators of an activity peak that indeed intensified, culminating in a maximum activity in March 2010 with the level 1 event of the phreatomagmatic type and a great expulsion of ashes, steam fumaroles, and sulphur components that shook up the community.

This event went on intermittently with another important peak in October 2010. The events might be relatively weak but not in relation with a big expansion of ash, which affects the total middle of the Argentine region. At present, volcanic activity has decreased (monitoring 2013).

Coseismic slips in depth and post-earthquake relaxation are also processes that ought to be considered when studying thermal and volcanic changes of the VCP (see Pollitz et al., 2011). A possible post-seismic displacement of the volcanic activity may give geodynamical proof of changes registered in other areas caused by the earthquake of 27 February 2010.

6. Conclusions

The activity of the Peteroa Volcano Complex affects its cryospheric system in different ways—system that is composed by uncovered and covered glaciers as well as permafrost (permafrost in situ and creeping permafrost). Recent volcanic activity and a high geothermal gradient favour the deglaciation of the peak of the volcanic complex. These phenomena help to reconstruct similar episodes of the past. The current work presents the first regional thermal and meteorological data applied to observe the activity of the volcano in the years 2007 to 2013.

Possible permafrost was calculated to cover 74 km^2 (approximately) and was corroborated by the detection of different cryoforms (rock glaciers, protalus lobes, protalus ramparts) and periglacial processes. On the summit, permafrost is superficial and isolated. It is associated with the cold dark spots detected by the thermocamera in the proximity of the glaciers.

Massive ice bodies covered by pyroclasts (glacier ice, *dead ice*), separated and disconnected from the retreating glaciers, have a cooling effect on their surroundings and enhance permafrost originated by different processes. This ice has to be included in permafrost.

Given the possible changes caused by the present volcanism, the glaciated surface calculated to be 20.76 km^2 (approximately) is no reliable value for the deduction of exact palaeoclimatic limits.

A consecutive multitemporal analysis of thermographs with relative temperatures of those areas detected as *hot*, close to the craters and the corroborations during fieldwork with quantity and intensity of superficial volcanic manifestations (fumaroles, solfataras), plus the changes of the glacier cover (decreases), allowed us to identify sites with major emissions and to predict locations of potential future explosions, such as the one in March 2010 and also made it possible to reveal the development of tiny zones that became more important, such as the case of SW sector close to crater 3 (double crater).

This work proves that after field work and registers of thermal changes between 2009 and 2010 and after the earthquake of Maule in Chile on 27 February 2010, a first important eruptive event actually occurred at the Volcanic Complex Peteroa in March 2010. This event was predictable with the applied thermal and geocryological method. The method proved to be helpful for volcanic monitoring.

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