Field Measurements of Active Volcanoes in the Southern Chilean Andes

February – March 2012

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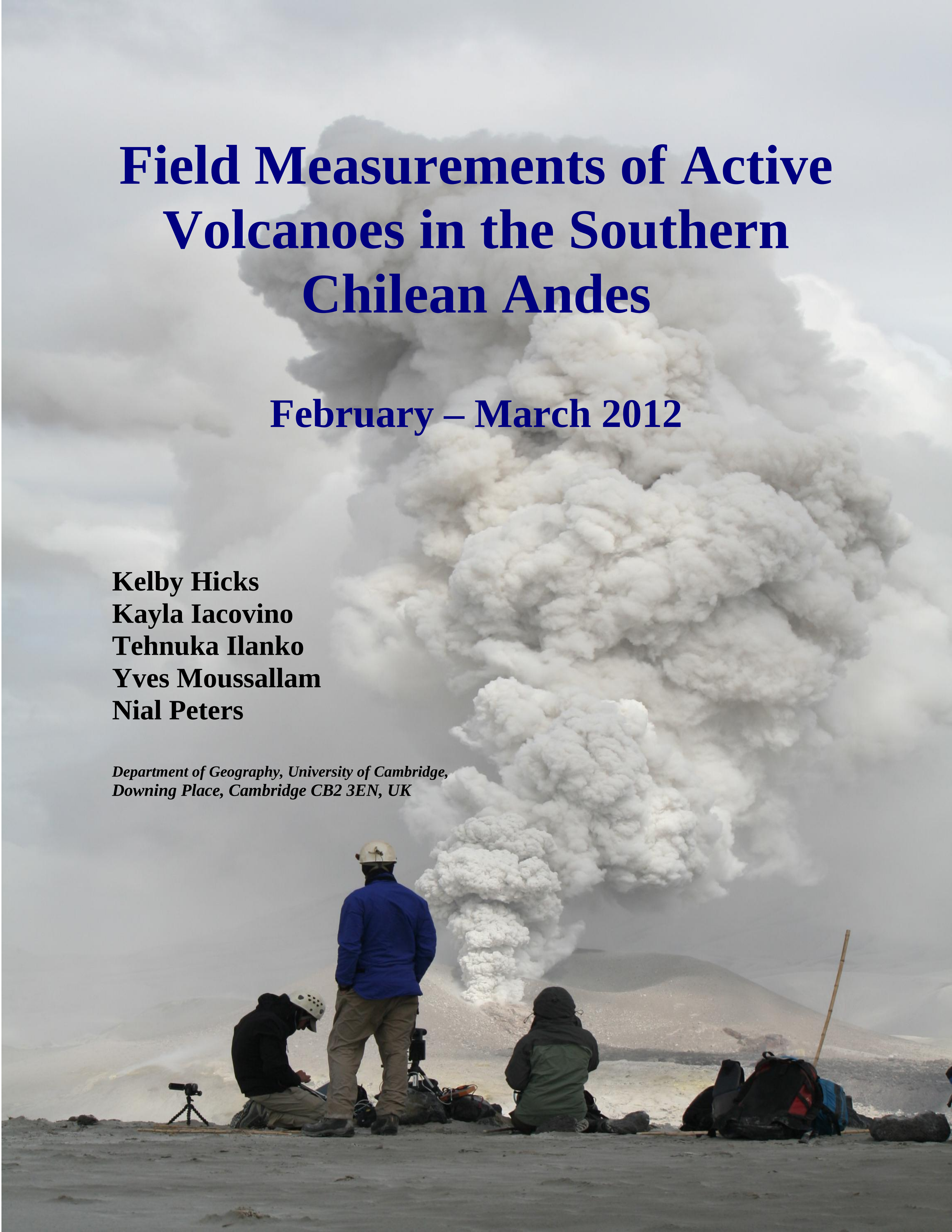

Funding provided by the Royal Geopgraphical Society with IBG facilitated a month-long volcano monitoring campaign on three active volcanoes in Chile: Villarrica, a steadily active and constantly degassing stratovolcano; Puyehue-Cordon Caulle, a recently active, explosive volcano; and Lascar, a periodically active volcano in the Atacama region, which showed signs of unrest prior to this field campaign. This funding combined with additional monies from Antofagasta, The Jeremy Willson Charitable Trust and the Cambridge University Department of Geography was used principally for equipment costs, transportation, and guide hire at the fieldwork sites.

From February 1st to March 6th 2012 our group of five PhD students, through collaboration with the local volcanic observatory OVDAS (Observatorio Volcanologico de los Andes del Sur), deployed a series of remote and direct sensing instruments previously unavailable to local observatory at Villarrica, Puyehue-Cordon Caulle, and Láscar, three active volcanoes that present a real and significant risk to surrounding populations. Here we present an overview of the work conducted and preliminary high-resolution data on the volcanic emissions at these three sites, an essential component of volcanic hazard assessment and eruption forecasting.

Cover Image: The team sets up equipment near the active vent of Puyehue-Cordon Caulle.

Fieldwork Overview

After a few days spent organising logistics in Santiago the team headed south to Temuco where we had scheduled a meeting with the head of OVDAS. Following a tour of their observatory we discussed the current state of activity of the three volcanoes that we planned to visit and explained in more detail the measurement strategy. The meeting was extremely productive and we gained invaluable information regarding access to the volcanoes as well as being given the use of their house at Villarrica. We spent the next week based at the house, conducting monitoring work on the gas output of Villarrica. The weather was extremely good, and conditions for our instruments were perfect!

The team celebrates having arrived at Villarrica with a beer from the local brewery.

Having gathered sufficient data at Villarrica, we headed further south to Puyehue-Cordon Caulle (the eruptive column of which was just visible from the summit of Villarrica). With the help of a local guide (recommended by OVDAS), we were able to ascend to within a few kilometers of the erupting vent. The ash-rich nature of the eruption made it unsuitable for spectroscopy so we collected samples from the recent lava flows instead. Unfortunately we were only able to remain at the summit for a few hours before high winds caused an "ash whiteout" and we had to retreat.

Kelby takes in the stunning view of Puyehue-Cordon Caulle

At this point in the project, one of our team members had to return home. So after a quick stop in Temuco to return equipment borrowed from OVDAS, we returned to Santiago to drop him at the airport. Whilst in Santiago we managed to swap our hire cars for a four wheel drive, which we had been told we would need for getting around in the Atacama region. When we arrived at Lascar a few days later we found that this had been good advice as many of the roads had been washed away in recent rains. Despite the challenging conditions at Lascar (high altitude, difficult access) we were able to collect several days worth of good data before it was time for us to head home.

Jumping photos at 4500m using a self-timer are quite tricky!

The data collected during the fieldwork will form the basis for several scientific publications that the team are currently working on. We hope that at least one of these will be jointly authored by OVDAS members.

Fieldwork Budget

Income		Expenditure	
Antofagasta	£9,000	Flights	£5,200
Royal Geographical Society	£1,500	Car Hire	£1,300
Jeremy Willson Charitable Trust	£750	Food and Drink	£1,000
Phillip Lake Trust (Cambridge University)	£650	Fuel and Road Tolls	£1,500
		Accommodation	£500
Total:	£11,900	Carnet Document	£650
		Guide Fees	£300
		Equipment	£500
		Misc. Costs	£430
		Total:	£11,380

The remaining £520 credit in the budget will be used to pay for analysis of the filter pack data collected and for publication fees.

Instrumentation

Recent developments in ultraviolet (UV) remote sensing techniques for the monitoring of active volcanoes have lead to the invention of a novel high temporal resolution (1 – 3 Hz) UV camera technology quickly becoming the *Nec plus ultra* in flux analysis of volcanic gasses. This new technology, however, still awaits rigorous calibration and comparative studies with more established techniques (e.g. differential optical absorption spectroscopy (DOAS) to become of more routine use in the volcano monitoring community.

UV Camera

This camera uses a narrow bandpass filter to collect incident photons in scattered sunlight at the 310nm wavelength of the ultraviolet spectrum where the SO_2 absorption cross section is about $\sigma(310) = 20.5\ cm^2\ molec^{-1} \times 10^{20}$. At this wavelength, other species such as NO_2, HONO, BrO and OClO are also absorbing. The quantification of acquired images is achieved by frequent imaging of calibration cells of known SO_2 concentration and background is subtracted by imaging of the nearest plume-free portion of the sky.

Ultraviolet Spectroscopy

Three Ocean Optics USB 2000+ ultraviolet (UV) spectrometers (DOAS) were used to estimate SO_2 column amounts and flux. These spectrometers use scattered sunlight as a light source and are equipped with a wide-band spectra detector in the 283 to 427 nm range. Two scanning DOAS systems were assembled by connecting the spectrometers via fibre optic to a telescope mounted on a motorised rotating system termed 'AvoScan'. This system precisely records, at a 1Hz frequency, telescope angle from a given reference point. Data retrieval of SO_2 column amount was achieved by dividing all spectra by out-of-plume background spectrum (to reduce Fraunhofer line interferences), the log of the resulting spectrum is then obtained by the Beer-Lambert law and the SO_2 amount is obtained by scaling with reference spectra through known SO_2 amounts.

Sun Photometry

A handheld Microtops II Sun photometer instrument was used, which measures direct solar radiation in 5 channels with peak wavelengths of 380, 440, 675, 870 and 1020nm. This instrument allows the aerosol optical thickness of the plume to be measured by comparing in-plume values with out-of-plume background. Inversion of the measurements will yield estimates of the aerosol particle size distribution within the volcanic plume and can give insights into the effect of volcanic emissions upon regional and global atmosphere and climate.

Filter Pack

The filter packs used consist of a series of filters housed in a multistage cartridge linked to a 12v pump providing suction for the ambient air to circulate through the filters. The first filter is a polycarbonate (47 mm, 0.4um pore diameter) filter intended to collect particles. The second two filters (Whatman 41 Ashless) are intended to collect acidic gases (SO_2, HCl, HF, HBr, HI and HNO_3) and are impregnated with 5% K_2CO_3 and 1% glycocerol in 1:1 methanol/distilled deionized water (DDW). All filters were transferred to clean polyethylene bags following each sampling run. The particle filters are being analysed by ICPMS while the chemical filters will be analysed by ion chromatography.

Background, previous work, and scientific questions

Villarrica

Villarrica (39.42°S, 71.93°W) is a 2847m high stratovolcano located within the Central Southern Volcanic Zone of the southern Andes. Since its last large eruption in 1984-1985, the summit region of Villarrica volcano has been occupied by a vigorously convecting and persistently degassing basaltic to basaltic andesite lava lake, periodically perturbed by Strombolian eruptions and fountaining up to 30m high (Calder et al., 2004). The lava lake is located within a cylindrical cavity 24m underneath a 65m diameter spatter roof overhang (Goto and Johnson, 2011), which grew from the repeated accumulation and agglutination of ejected spatter with more explosive phases creating terraces (Palma et al., 2008). Witter et al., (2004) provided the first estimates of SO_2, HCl, and HF gas fluxes at Villarrica using data acquired during two field campaigns in 2000 and 2001. Shinohara and Witter, (2005) obtained gas measurements during Strombolian eruptions and found no difference in H_2O/CO_2 and CO_2/SO_2 gas ratios between passive and explosive degassing. Mather et al., (2004) and Mather, et al., (2004b) characterised the passive degassing in 2003 while Sawyer et al., (2011) characterised it in 2009. SO_2 flux measurements have also been taken intermittently during the period from 2004 to 2006 by Palma et al., (2008) and showed a positive correlation with measurements from a real-time seismic amplitude measurement system (RSAM). From 2000 to 2009, SO_2 flux appears to have stayed relatively constant excepted for a period in 2005 when values on the order of 1000 $tday^{-1}$ were measured (Palma et al., 2008). Fluxes of HCl and HF measured in 2009 by Sawyer et al., (2011) are half those measured in 2003 by Mather, et al., (2004).

Our aim at Villarrica was twofold: to build on past studies and investigate the evolution of the volcanic plume since it was last reported in 2009 and to compare three different methods of measuring volcanic SO_2 flux from volcanoes. From February 4 to 11 2012, we acquired high resolution UV camera images of the plume in chorus with two scanning and one static ultraviolet spectrometers (USB 2000+), located within 4km of the active vent. On February 8 and 10, ascensions of the volcano were performed. Pedestrian transects of the plume at the vent were completed together with sun photometry and filter pack measurements.

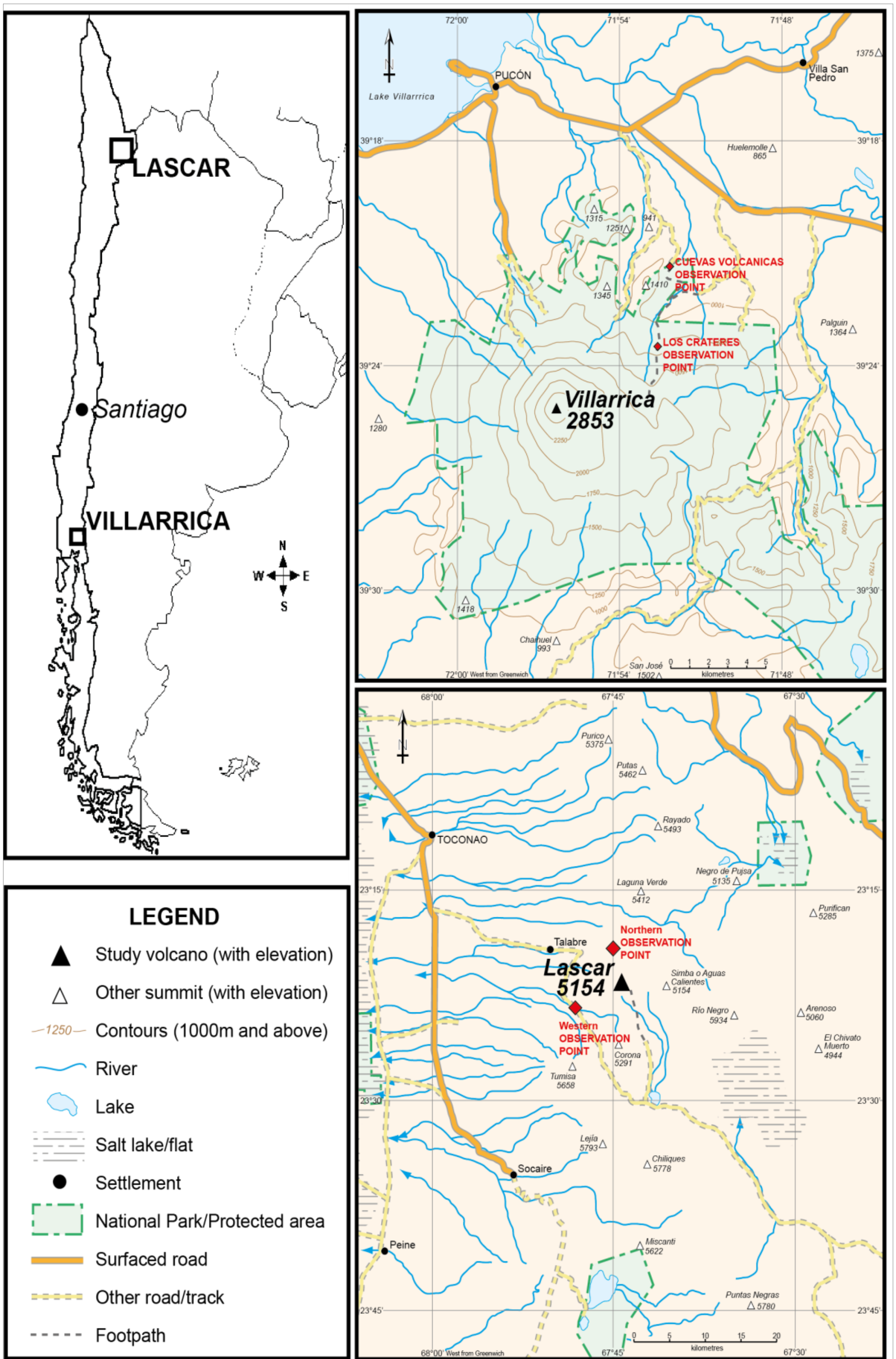

Figure 1: *Simplified maps showing the location of Villarrica and Lascar volcanoes together with the location of observation points used during the field campaign.*

Puyehue-Cordon Caulle

On February 15 an attempt was made to obtain SO_2 flux measurements from the ongoing sub-plinian eruption of the Puyehue-Cordón Caulle volcanic complex. Our team hiked to a proximal (<1 km from vent) ridge and observed the eruption column. The vent was located at the center of a breached pyroclastic cone, just above a small dome that marked the starting point of a 50m high 2km long obsidian coulee. A scanning DOAS and the HD camera were deployed about 1.5km away from the vent. The very ash-rich nature of the column prevented successful DOAS spectra acquisition and a dust storm destroyed the HD camera. Fresh samples of the glassy coulee and of an obsidian bomb were collected for future chemical analysis.

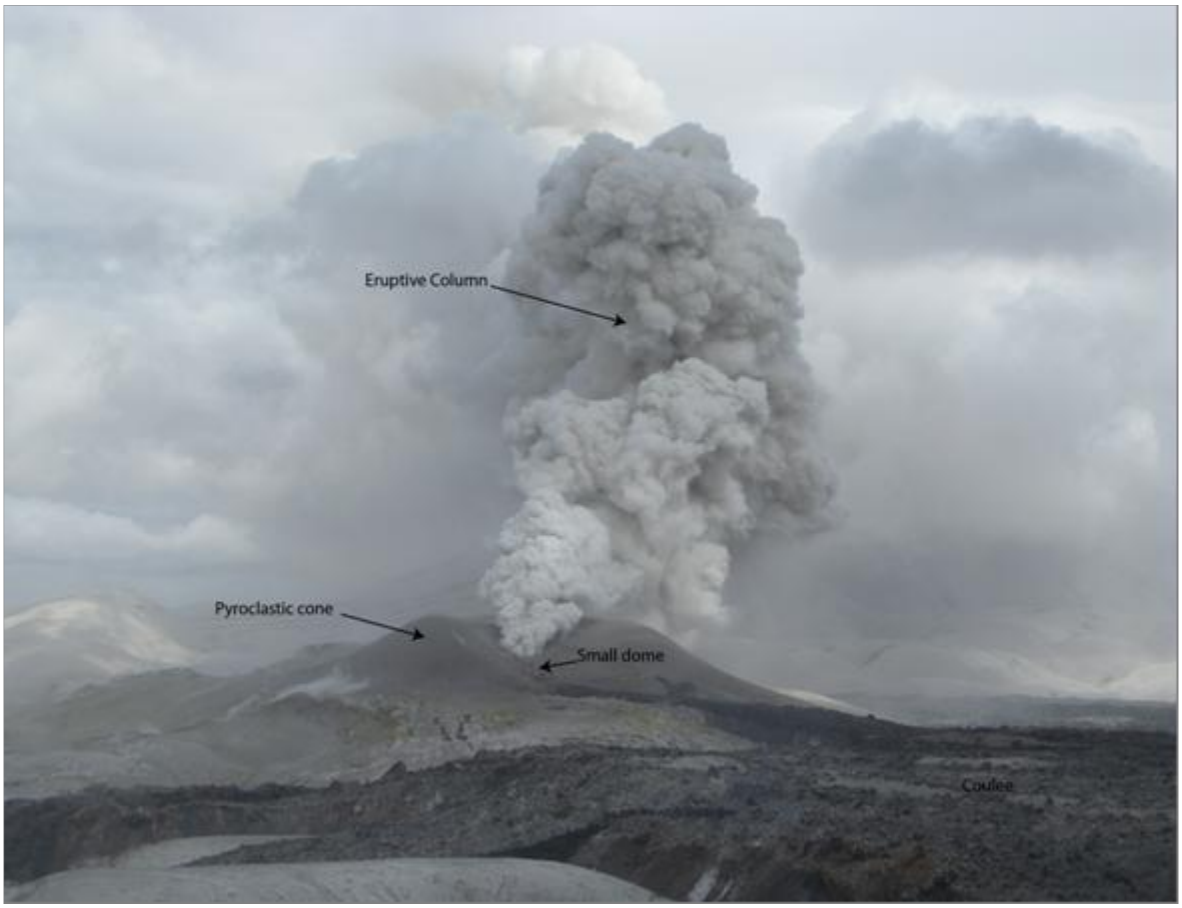

Figure 4: *General view of the activity at the Puyehue-Cordón Caulle volcanic complex volcano as observed on February 15.*

Lascar

Lascar volcano (23°22'S, 67°.44'W) is a 5592m high composite stratovolcano located in the Central Volcanic Zone of the Andes. Since 1984 the volcano has entered a period of vigorous activity culminating in April 1993 by the most substantial eruption since 9.2ka (Gardeweg and Medina, 1994). Small vulcanian eruptions occurred in 1994, 1995, 2000 and 2002. A large phreato-vulcanian eruption occured in 2005 and a 5-day eruption sequence with a plume rising 10km above the vent occurred in 2006 followed by minor eruptions in 2006 and 2007. On January 5, 2012 OVDAS-SERNAGEOMIN reported increased seismicity at Láscar with over 300 small earthquakes in 26 hours, changing the alert status to yellow. By March 5^{th} the seismicity had dropped to 2 events per day and the alert status was returned to green.

Andres et al., (1991) provided the first estimation of SO_2 fluxes from Lascar using a correlation spectrometer in 1989 and found an average of 2300 $tday^{-1}$. In January 2003, Mather, et al., (2004), reported similar SO_2 fluxes on the order of 2400 $tday^{-1}$. In sharp contrast, Henney et al., (2012) reported SO_2 flux between 200 and 500 $tday^{-1}$ for December 2004, five month prior to the large 2005 eruption.

Our main objective in Lascar was to obtain high resolution measurements of the newly re-established volcanic plume at a time coeval with increased seismic activity and interpreted magma movement. We also used the volcanic plume of Lascar to investigate the kinetics of oxidation of a volcanic plume in the atmosphere.

Fieldwork methodology

Villarrica

From the observation site of Los Crateres, located 3.6km away from the vent (Figure1) the UV camera was deployed and ran simultaneously with a scanning DOAS, a static DOAS and a high-definition camera from February 6 to 11 2012 (Figure 2A). While the UV Camera field of view covers the summit area and a large part of the plume, the static DOAS provides independent measurements from a smaller area located directly above the summit. The scanning DOAS used in horizontal mode provides a transect of the volcanic plume directly above the vent. The rise speed of the plume is measured by tracking individual portions of the plume between images acquired by the UV and HD cameras. In addition and concurrently with this initial setup, ascension of the crater was performed on February 8 and 10 and an additional DOAS system was deployed for pedestrian traverses underneath the plume together with filter pack and sun-photometer measurements (Figure 2B). On February 9 and 10 intermittent spattering from the lava lake was observed from the rim for the first time in several years suggesting a high-stand of the lava lake.

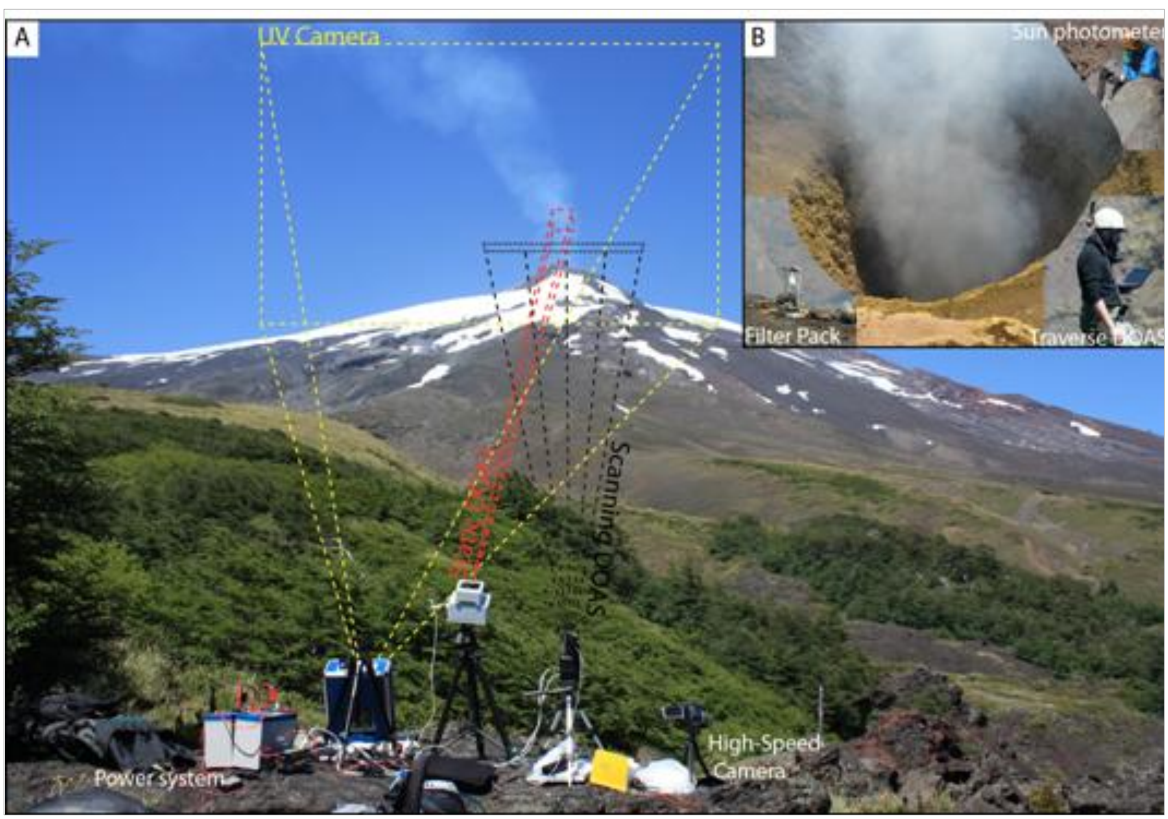

Figure 2: **A**. *Typical multi-instrumental setup to monitor Villarrica degassing from Los Crateres observation site.* **B**. *Additional instrumental deployment made simultaneously at the crater rim of February 8 and 10.*

On February 11 two scanning DOAS were deployed at the observation sites of Los Craters and Cuevas Volcanicas (1.12km away, see Figure 1) and were directed to scan the drifting plume in a co-planar fashion (Figure 3). Using this method, the plume height and location can be estimated from the recorded angles of the in-house produced AvoScan scanning device. Some wind speed measurements were collected at the summit with a handheld anemometer, however wind speed can also be estimated from either meteorological data or using images acquired by the UV camera.

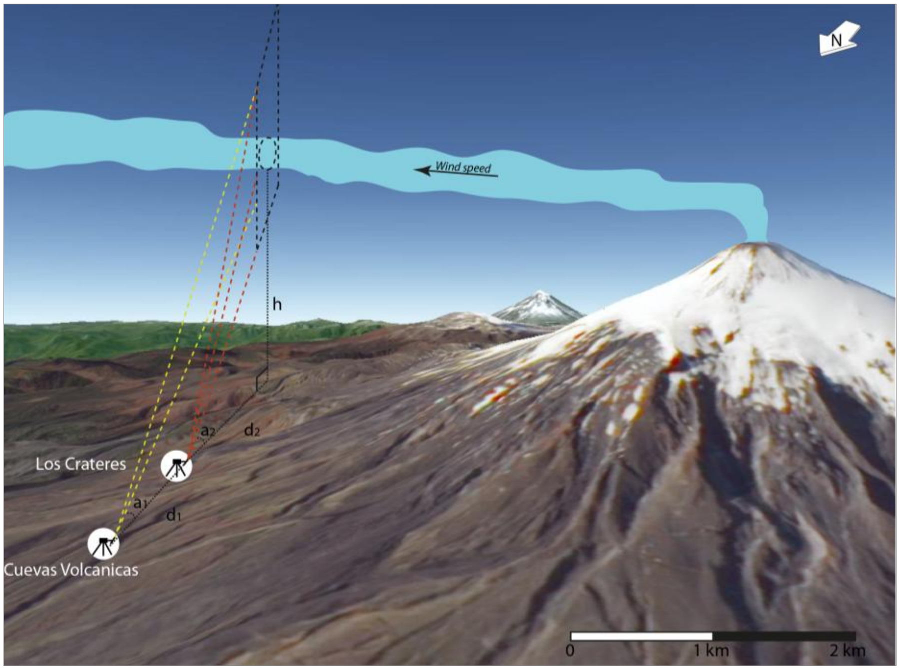

Figure 3: *Schematic representation of the parallel scanning DOAS method used on Feb 11 where h is the plume height, d_1 and d_2 the distances from los craters to cuevas volcanicas and to the plume respectively and a_1 and a_2 are the angle recorded by both scanning DOAS.*

This methodology allows us to compare the measurement of SO_2 flux from the UV camera to three different frequently used methods with DOAS instruments: Horizontal transects of the initial rising plume, vertical transect at the crater rim and vertical transect of the down-wind plume.

Puyehue-Cordon Caulle

On 29 February, we attempted measurements of the recently developed ash-rich plume at Puyehue-Cordon Caulle volcano. Because of the high ash content of the plume, however, most of our instruments were unable to gather any accurate data. HD video of the plume was recorded for approximately one hour, until the camera was destroyed by high velocity wind-blown ash particles entering the instrument. Lava samples were also collected from the recent and still growing lava flows for chemical analysis.

Lascar

Challenging field conditions at Lascar precipitated the unfortunate death of our UV camera and filter pack instruments. This limited our monitoring capacities during the field period spanning from the 24 to the 29 of February.

Horizontal DOAS scans immediately above the summit were collected during periods of low wind (i.e. when plume was rising vertically), while vertical scans were collected during periods of wind-blown, drifting plume. Sun photometer data were acquired in tandem with DOAS scans and additionally on one occasion where the plume was cascading down the side of the volcano. A series of static DOAS scans of the drifting plume were acquired at a range of distance from the vent in order to estimate the timing of appearance of oxidized species within aging plume (Figure5).

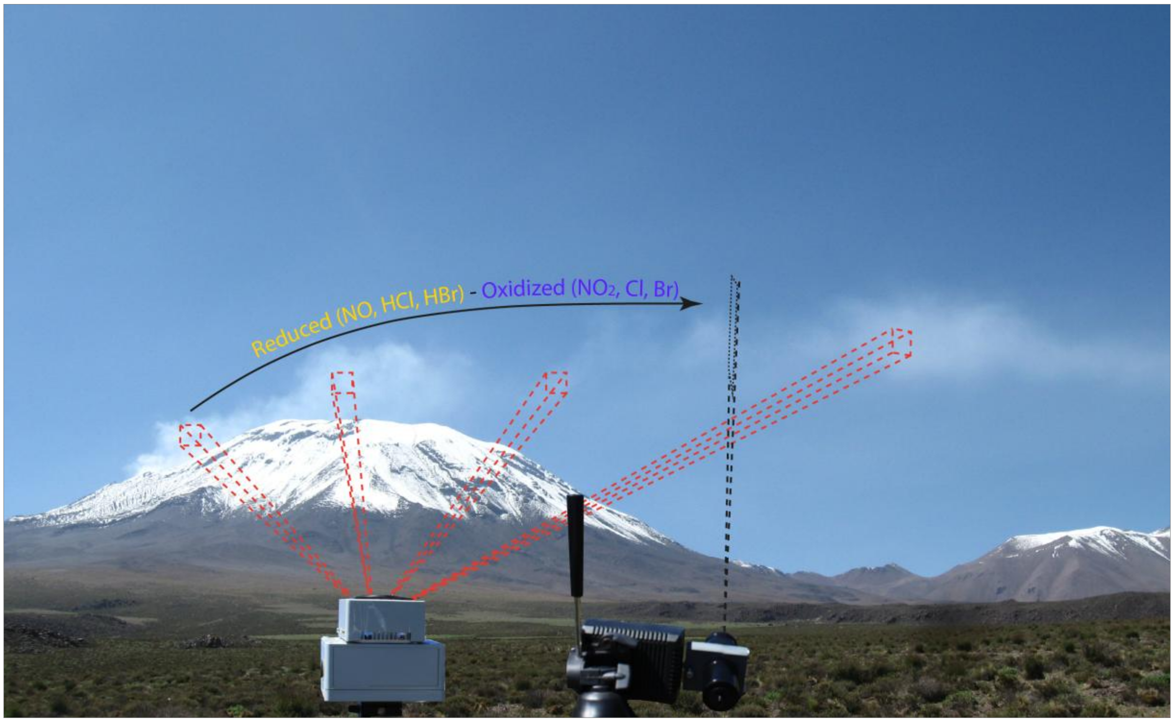

Figure 5: *Schematic representation of the multiple static DOAS technique to study the chemical evolution of the aging plume at Lascar volcano.*

Preliminary results

UV Camera:

Preliminary UV camera results show the majority of acquired data to be of excellent quality and within the desired temporal resolution (1 – 3 Hz). Due to an intermittent shutter malfunction, the images have been individually examined for focus and undesirable shutter effects. Upper right inset in Figure 6 shows a single calibrated SO_2 absorbance image from 10 February. Figure 6 is representative of the dataset as a whole and shows the calculated SO_2 flux in kg/s for a 28 minute timeframe on the same day. The entire dataset is currently being processed and will eventually be combined with the UV spectroscopic data being processed using the DOAS methodology.

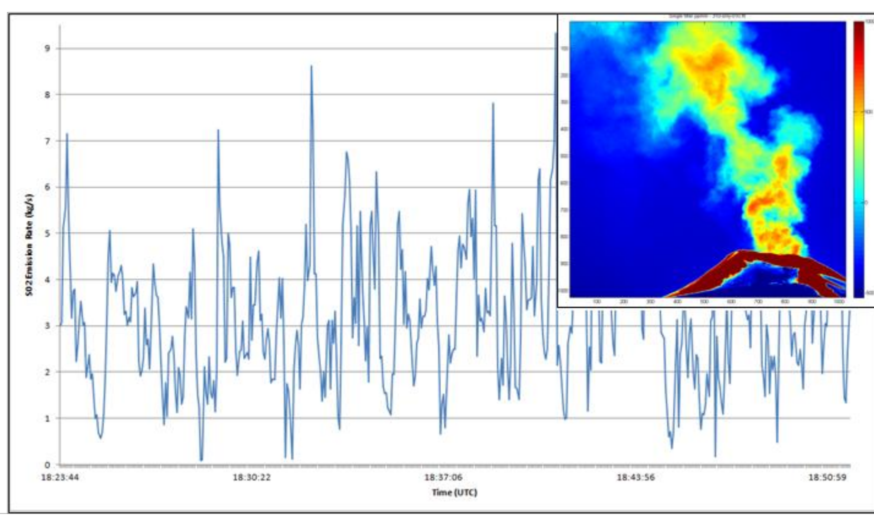

Figure 6: *SO_2 flux in kg/s vs Time. Upper right inset shows a Calibrated SO_2 absorbance map showing the SO2 concentration in the volcanic plume rising from the crater.*

Ultraviolet Spectroscopy:

Calculation of plume composition from UV spectroscopic data is a complex and time consuming process which we are still undertaking. We cannot therefore publish final results here. However, Figure 7 shows a small sample (three scans) of the data collected at Lascar using a spectrometer scanning horizontally across the volcanic plume. The column amounts shown are not background subtracted, so the exact values are meaningless, however, the volcanic plume can easily be seen as the spectrometer scans across it. We are currently working on more accurately retrieving the SO_2 amounts and integrating them to calculate the gas fluxes from both Lascar and Villarrica. Final results are expected within the next month.

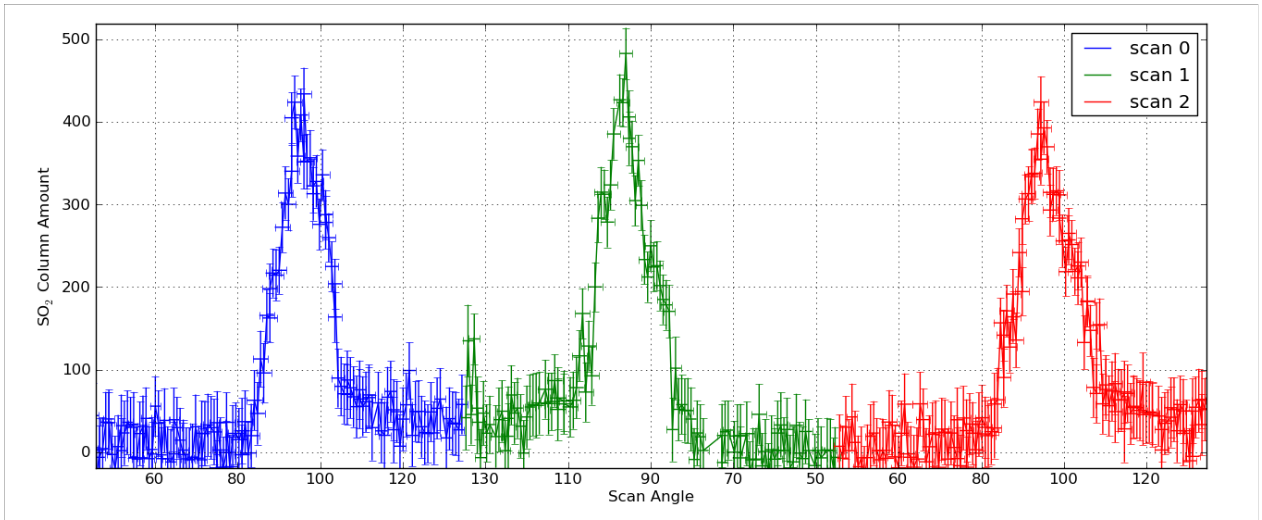

Figure 7: *Plot of SO_2 column amount against scan angle from three horizontal scans of the Lascar plume.*

Sun Photometry:

Preliminary handling of the Microtops Sun Photometer data indicates a bimodal size distribution of aerosol particles in the volcanic plumes of both Villarrica and Lascar volcanoes, with a high abundance of both ~1- and10-µm sized particles.

Figure 7 shows preliminary inversions of data from Villarrica volcano on 10 February 2012. For this inversion, an aerosol refractive index of 1.44 – 0.0*i* was assumed across the wavelength range, following Mather et al (2004). Further analysis of filter pack data will allow for the determination of aerosol chemical composition and, therefore, the computation of a refractive index specific to the aerosols of Villarrica during the period that these data were collected. The data are split into five groups, each group representing a period of peak plume flux across the line of sight of the instrument. All data groups are corrected for background atmosphere aerosols, and therefore show only the aerosol particles within the volcanic plume. Preliminary results agree well with previous studies such as Mather et al (2004) and Sawyer et al (2011), which both obtained similar results for the aerosol particle size distributions in the plume of Villarrica.

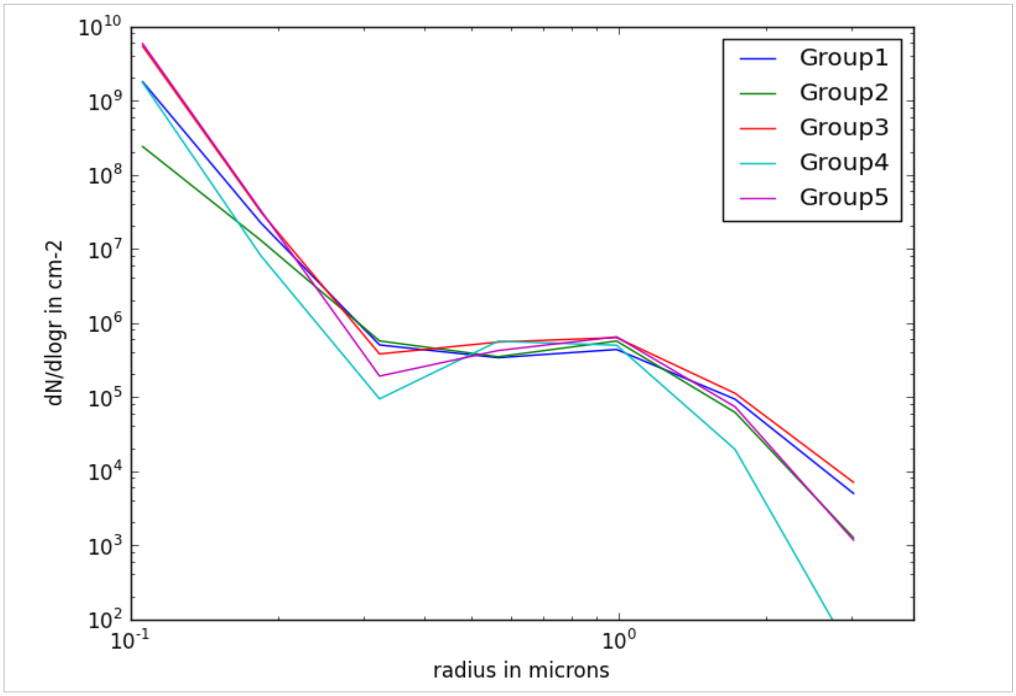

Figure 8 *Aerosol particle radius versus abundance in the volcanic plume of Villarrica volcano as obtained from preliminary inversions of Microtops data.*

Conclusions, dissemination of results, and future collaboration

Our field campaign in Chile has been a success not only in terms of the amount and quality of the scientifically valuable data acquired but also in terms of the establishment of collaboration with the Observatorio Volcanológico de los Andes del Sur (OVDAS). In the next few months we hope to continue this collaboration by sharing our results and possibly collaborating in the writing of scientific papers that would link our gas chemistry observations to their seismic record.

Public Outreach

The progress and results of this project have been actively shared through ongoing public outreach efforts including a large social media campaign carried out under the screen name, The Volcanofiles. In addition to our blog at volcanofiles.com, we have shared pictures, stories, relevant news items, scientific results, and more through Twitter (@TheVolcanofiles), Facebook (facebook.com/thevolcanofiles), and Google+. Thanks to regular internet access at some sites and the use of the satellite communication device SPOT Connect during times in the deep field, we were able to consistently post throughout the field portion of the campaign.

Feedback from members of the public following our activities on these social networking sites has been substantial and very positive. At the time of writing, The Volcanofiles have 212 followers on Twitter, 50 Likes on Facebook, and a regular readership of our blog and subscription to our YouTube channel.

Additional public outreach activities, such as participation in RGS sponsored outreach events such as Explore 2012, are planned to take place over the next few months.

Publications

The data collected on this campaign are currently being processed, with the ultimate goal of publication in recognized international scientific journals. Due acknowledgement will be given to our sponsors and supporters including RGS upon publication.

We would like to express our sincere gratitude to the RGS-IBG for their generous support.

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