Gas compositions and fluxes at Lascar and Lastarria volcanoes, Northern Chile: Preliminary results from the field measurements in November – December 2012

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Lastarria fumarolic fields

The Quaternary Lastarria volcano is located on the Chile-Argentina border at 25.17°S - 68.50°W and rises to 5706 m, above a regional base level of about 4200 m. The NNW-trending edifice contains five nested summit craters. The youngest volcanic feature is a lava dome that overlaps with the northern crater rim (Naranjo, 1986). The large andesitic-dacitic lava field on the western flank, Negriales del Lastarria or 'Big Joe', was erupted from a single SW-flank vent. A large debris-avalanche deposit is found on the SE flank (Naranjo & Francis, 1987; Francis & Wells, 1988). Recent pyroclastic-flow deposits form an extensive apron in the northern flank of the volcano. Although no historical eruption has been recorded, the youthful morphology of deposits suggests that Lastarria has been active during historical time.

![Map of northern Chile](image1a.png)

![Lastarria volcano and its fumarolic fields](image1b.png)

![Multigas path across the bottom field and the hottest fumarole](image1c.png)

**Figure 1**: (a) Map of northern Chile; (b) Lastarria volcano and its fumarolic fields; (c) Multigas path (red) across the bottom field and the hottest fumarole (black diamond).

Persistent fumarolic activity occurs at the summit (upper fields) and NW flank (bottom field) since the earliest records were made. Casertano (1963) reported solfataric and vapour activity at the end of the 19th century and in December 1960. The bottom field is located at ~5000 m a.s.l. and is the largest (~0.023 km²) emission area of the volcano (Fig. 1b). The present campaign was focused on this area.
On 27 November 2012 a portable MultiGAS device (see appendix for details) was used for measuring at 0.5 Hz rate and for more than 1 hour, Fig. 3a) the concentrations of major volcanogenic gas species in the gas issuing from the bottom field of Lastarria volcano (Fig. 1c), allowing the characterization of its chemical structure and heterogeneity. The fumarolic field was easily accessible allowing an accurate determination of each emission point. Due to the very high sulphur concentrations (up to 160 ppmV), the volcanic gas plume was sampled 1 to 5 meters away from the fumaroles. Our high-resolution analysis reveals that the bottom field of Lastarria has a surprisingly homogeneous chemical composition, as displayed in Fig. 3b. The CO₂/SO₂ molar ratio ranged within the field from 1.1 to 2.3 (averaging 1.6). From measurements of H₂O and H₂ concentrations, we also obtained the characteristic H₂O/CO₂ and H₂/H₂O ratios of 27.8 ± 2.8 and 6·10⁻⁵± 2·10⁻⁴, respectively.

Figure 3: (a) A 4400 s MultiGAS acquisition at Lastarria's bottom field on 27 November 2012 (acquisition frequency, 2 s); (b) Scatter diagram of CO₂ vs. SO₂ concentrations from the previous time series. The CO₂/SO₂ plume ratios are calculated from the gradient of the best-fit regression line.
On 28 November 2012 a fixed MultiGAS station (see appendix) was deployed downwind the hottest gas emission (~400 °C, Fig. 1c) of the bottom field in order to explore potential daily variations in composition. The 24 hours long dataset revealed some systematic temporal oscillations of CO₂/SO₂ and H₂O/CO₂ molar ratios (Fig. 4), which varied by factors of up to 2 and 4, respectively. The high thermal excursion between day and night (from 15°C to -2°C) may play an important role here, leading to extensive overnight water condensation, and sulphur dioxide scavenging in liquid/solid phase.

Fluxes of SO₂ from the volcano were determined using two transportable scanning mini-DOAS UV spectrometer stations of the NOVAC type (Galle et al., 2002) (see appendix). On each of the days 27, 28 and 29 November, 2012, the Lastarria plume was measured downwind for several hours (Fig. 5). The instruments were located about 8 km from the source, and used in the continuous scan mode, which implies scanning from horizon to horizon perpendicular to the plume direction, thus producing a complete plume profile every few minutes. Evaluation of the SO₂ columns were done with the NOVAC software (Johansson, 2009), and wind speed at plume height was obtained using the GDAS (Global Data Assimilation System) model provided by NOAA, which seemed to fit well with anemometer data. As expected, the calculated SO₂ fluxes varied during each day and also between the days, mainly due to turbulence in the plume, but also due to periodic variations in degassing strength. The instantaneous fluxes for single scans ranged between 107 and 3123 metric tons per day (t/d) (Fig.5). Average daily fluxes for the three days were 1787, 566, and 551 t/d, respectively, which gives a mean for the three days of 968 t/d, taken to be the typical value for Lastarria during the campaign interval.
**Lascar volcano**

Lascar is a calc-alkaline strato-volcano located in the Central Andes of northern Chile, east of the Salar de Atacama, at 23.37°S - 67.73°W, 34 km from the village of Toconao, 5 km from the older and higher strato-volcano of Volcán Aguas Calientes. Lascar is the most active volcano of the Chilean segment of the central Andes (Oppenheimer et al. 1993); it counts six overlapping summit craters, and an active central crater at 5450 m altitude hosting a persistent fumarolic field ~200 m deep inside the crater. This generates a sustained steam plume above the volcano, and occasional minor explosions. Frequent small-to-moderate vulcanian explosive eruptions have been recorded from Láscar in historical time since the mid-19th century (some registered eruptions: 2006-07, 2005, 2002, 2000, 1994-95, 1994, 1993-94, 1993, 1991-92).

*Figure 6: The 2006 eruption of Lascar Volcano.*

The majority of these eruptions are small and create ash columns extending up to a few kilometres above the summit. The largest historical eruption of Láscar took place in 1993, producing pyroclastic flows that travelled 7.5 km NW of the summit and ash-fall in Buenos Aires, 1500 km downwind. Since 1984 the activity of Lascar has been characterised by cyclic behaviour; in each cycle, a lava dome is extruded in the active crater, accompanied by vigorous degassing through high-temperature fumaroles distributed on and around the dome. Fumaroles are source of a sustained steam plume above the volcano. Matthews et al. (1997) proposed a model in which gas loss from the dome is progressively inhibited during a cycle and gas pressure increases within and below the lava dome, triggering a large explosive eruption.

*Figure 7: Panoramic view from the rim of Lastarria Eastern crater*
Lascar central crater is accessible from the south, a footpath starts at 4700 m a.s.l. going up along the flank (Fig. 8a). The hike takes about 2.5 hours and ends at the southern rims of the central crater (5400 m a.s.l.) from which the inner fumarolic field is visible. The gas plume, while rising up in the atmosphere, occasionally fumigates the crater's rim, depending on wind direction and intensity. The dominant winds blow from west, but turbulence and topographic effects resulted in highly variable plume directions.

Figure 8: (a) View of Lascar and Aguas Calientes volcanoes from the south, the dotted line is the footpath. (b) Map of the region of Antofagasta. (c) Satellite photo of the three summit craters (western, central and eastern), the star is the fumarolic field, grey diamonds are the MultiGAS measurement sites.

From 4th to 7th December 2013, a MultiGAS analyzer was deployed at three different sites (Fig. 8c) in order to derive the bulk plume composition. The MultiGAS typically detected a dilute plume with clearly volcanic H₂O (1,600–2,000 ppm), CO₂ (~140 ppm; not-corrected for pressure), and SO₂ (1–6 ppm) (see example in Fig. 9a). Volcanic H₂O detection was facilitated by the dry and cloud-free conditions on Lascar's summit, that prevented condensation effects. The high dilution of the volcanic gas hampered detection of volcanogenic H₂. The CO₂/SO₂ and H₂O/CO₂ molar ratios ranged from ~1 to ~1.7, and from ~12 to ~34, respectively, during our acquisition interval.

Figure 9: (a) Temporal variation of gas concentrations (b) CO₂ vs SO₂ scatter plot (sensors' readout not corrected for pressure).
On each of the days 03, 05, 06 and 07 December, 2012, the Lascar plume was measured downwind for several hours, using one or two scanning mini-DOAS stations (Figs. 10, 11). Due to the fluctuating wind conditions in the Lascar area during the campaign period, the instruments were placed at various locations downwind from the volcano, at distances from the summit ranging between 2.5 and 11 km.

Due to the changing wind conditions, the plume height above the instruments, which is an important parameter for the data quantification, varied during the day. In two specific cases, the plume height could be derived directly by triangulation, which helped us to secure a high data quality. In both cases the mass centre of the plume was situated about 500 m below summit height (Fig. 12). The plume speed was measured directly for 90 minutes on December 6 using an SO$_2$...
camera pointing at right angle to the plume movement, thus enabling speed calculations. Wind speeds determined with the GDAS model did not work well for the Lascar area, probably related to the sub-optimal fit between the model and the local topography. Thus the average wind speeds of 11 m/s determined for 06 December were also used for the days 03, 05 and 07 December. Including also the variable plume heights in the flux evaluations, calculated instantaneous SO₂ fluxes for single scans ranged between 34 and 1551 t/d (Fig. 11). Average daily fluxes for the four days were 233, 821, 277 and 707 t/d, respectively, giving a mean for the four day period of 509 t/d, which is considered typical for Lascar during this campaign.

![Figure 12: Plume creeping down Lascar’s southern flank](image)

**Conclusions**

Our measurement support large variations of water content at both volcanoes (Fig. 13), probably due to condensation effects in the plume. The gas composition of Villarrica (from Shinohara and Witter, 2005), a potentially good compositional proxy for the volcanic gas signature of Chilean volcanoes, is also shown in Figure 13. The combined Lastarria, Lascar and Villarrica data-set suggests a convergent trend towards a similar gas composition, characterised by CO₂/SO₂ and H₂O/CO₂ molar ratios of 1-2 and 30-40, respectively.

![Figure 13: Triangular plot CO₂–H₂O/10-SO₂ ternary diagram for Lastarria, Lascar and Villarrica volcanoes.](image)
SO₂ fluxes measured during the campaign averaged 968 and 509 tons per day for Lastarria and Lascar volcanoes, respectively. Using the molar CO₂/SO₂ ratios measured in-situ we obtain average CO₂ fluxes of 1065 t/d for Lastarria and 455 t/d for Lascar during the campaign. Such fluxes are comparable to those of other permanently active subduction zone volcanoes (e.g. Fischer, 2008).

References


Appendix

MultiGAS technique

The concentrations of major volcanogenic constituents in the volcanic plume were monitored by using a portable version on the INGV-type Multi-component Gas Analyzer System (MultiGAS, Fig. 14) (Aiuppa et al., 2007). This uses a LI-840 NDIR closed path spectrometer for CO₂ (measurement range, 0–3000 ppm; accuracy, ±1.5%) and H₂O (measurement range, 0–80 ppt; accuracy, ±1.5%), electrochemical sensors for SO₂ (City Technology, sensor type 3ST/F, calibration range, 0–200 ppmv, accuracy, ±2%, resolution, 0.5 ppmv), H₂S (SensoriC, sensor type 2E, calibration range, 0–50 ppmv, accuracy, ±5%, resolution, 0.7 ppmv), and H₂ (0-200 ppm; EZT3HYT electrochemical sensor “Easy Cal” City Technology Ltd.), temperature (measuring range, from −30 to 70 °C, resolution, 0.01 °C) and relative humidity sensors (Galltec, measuring range, 0–100% Rh, accuracy, ±2%). The sensors are housed in a water-proof box mounted on a backpack frame, and were calibrated, before and after fieldwork, with standard calibration gases. Signals from all sensors are simultaneously captured every 2s with a data-logger board, which also enabled data logging and storage. During each field survey, in-plume measurements are run for several hours, yielding acquisition of a large number of determinations; the raw data are processed according to Shinohara et al. (2008) and Aiuppa et al. (2009) to derive the characteristic volcanic gas molar ratios.

*Figure 14: MultiGAS inner structure.*
Mini-DOAS technique

SO₂ contents of the volcanic plumes were measured using two transportable mini-DOAS (Differential Optical Absorption Spectroscopy) systems. Such a system contains a scanning DOAS instrument similar to the Mark I system of the Network for Observation of Volcanic and Atmospheric Change (NOVAC) project (Galle et al., 2010) but is integrated into a single unit easy to transport and install in the field. It includes a back-pack/box containing the basic components: embedded computer, electronic controller, spectrometer, timer, power regulator, and 12V battery, and the corresponding connectors for: tube-protected optical fiber, tripod-supported scanner, GPS receiver, foldable solar panel, and communication cables. The only major modification of the systems used in Chile was the utilization of a new single board embedded computer (MOXA UC-7112) for measurement control and data storage. Data acquisition and analysis was done according to the procedures adopted in NOVAC.

In the ideal case, the instrument is located roughly beneath the plume, and scans are performed perpendicular to the plume direction. In practical terms, the wind direction and thus plume location normally changes during the day, meaning that some measurements are obtained close to the horizon within the selected field of view. In spite of such complications, however, the data quality was good to excellent throughout this campaign.

In order to obtain fluxes from the measured SO₂ contents, wind speed (plume speed) and plume height are needed as input parameters. Plume height was in two cases obtained using triangulation between two instruments running simultaneously at two locations underneath the plume. Plume speed was partly measured using an SO₂ camera, and partly calculated using the GDAS model of NOAA.

*Figure 15: Sketch showing the main components of the scanning mini-DOAS (Courtesy of Bo Galle)*