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Hydrogen emission from Erebus volcano, Antarctica

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Hydrogen emission from Erebus volcano, Antarctica

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Abstract

The continuous measurement of molecular hydrogen (H_2) emissions from passively degassing volcanoes has recently been made possible thanks to the development of electrochemical sensors. We have used this technology to measure H_2, along with SO_2, H_2O, and CO_2, in the gas and aerosol plume emitted from the phonolite lava lake at Erebus volcano, Antarctica. The measurements were made at the crater rim between December 2010 and January 2011. Combined with data for the long-term SO_2 emission rate for Erebus, they indicate a mean H_2 flux of 0.03 kg s^{-1} (2.8 Mg day^{-1}). The observed H_2 content in the plume is consistent with previous estimates of redox conditions in the lava lake (~0.9 log units below the quartz-

fayalaite-magnetite buffer). These measurements suggest that H_2 does not combust at the surface of the lake, and that H_2 is kinetically inert in the gas/aerosol plume, retaining the signature of the high-temperature chemical equilibrium reached in the lava lake. We also observe a cyclical variation in the H_2/SO_2 ratio with a period of ~10 min. These cycles correspond to oscillatory patterns of surface motion of the lava lake that have been interpreted as signs of a pulsatory magma supply at the top of the magmatic conduit.

Keywords: Mt Erebus, hydrogen, magma redox conditions, lava lake, magma degassing.

Introduction

Hydrogen is one of the most abundant trace species in volcanic emissions (Oppenheimer et al. in press) and is an essential participant in key redox reactions that take place in magmatic gases, e.g.:

$$H_2 + ½O_2 = H_2O \qquad (1)$$

and

$$H_2S + 2H_2O = SO_2 + 3H_2 \qquad (2)$$

At Erebus volcano, emissions to the atmosphere result from the sustained supply of gas via the persistently active lava lake and surrounding fumaroles. Gas composition measured in the plume provides important insights into the redox conditions of the lava lake (assuming thermodynamic equilibrium between the gas phase and the melt). Following recent chemical modeling (Burgisser and Scaillet 2007) arguing for an evolution of the oxidation state of an ascending magma, measurement of redox-sensitive volcanic gas species such as hydrogen assumes particular significance.

The recent development of highly portable and readily deployed multi-species gas sensing systems (Shinohara 2005; Aiuppa et al. 2005; Aiuppa et al. 2006; De Vito et al. 2007) has enabled measurements of volcanic gas ratios for extended periods, in some cases operationally (Aiuppa, Bertagnini, et al. 2010; Aiuppa, Burton, et al. 2010). Such "multi-gas" approaches complement ultraviolet and infrared spectroscopic applications (Oppenheimer 2010) to enable measurement of abundances and fluxes of a range of gas species. However, until very recently, there has not been a practical means for extended surveillance of H_2 abundance in dilute volcanic plumes. Here we use a "Multi-GAS" instrument incorporating a specific hydrogen sensor to measure H_2 in the plume emitted from the lava lake of Erebus volcano. Erebus is of particular interest because of the emerging evidence for redox change associated with magma ascent (e.g., Oppenheimer et al. 2011; Burgisser et al. in review). Despite challenging conditions at the rim of the summit crater, measurements were possible for several hours per day spanning a week. Our initial aims were to evaluate the performance of this instrument for continuous gas surveillance on Erebus, to assess implications of the measurements for lava lake redox conditions, and to identify any rapid variability in gas composition of the plume.

Methodology

The measurements were made between 6 December 2010 and 3 January 2011 using a purpose-built "Multi-GAS" instrument and a commercial CO_2 and H_2O infrared analyser (for intercomparison). The instruments were deployed intermittently at the crater rim of Erebus volcano at a site ~ 220 m vertically above and ~ 150 m horizontally from the active lava lake (Figure 1). The measurements were mostly made at the "Pump Site" situated on the northern

rim of the summit crater since this is where prevailing winds tend to carry the plume (Zreda-Gostynska et al. 1997; Ilyinskaya et al. 2010). Both instruments were powered by a 12 V DC battery, which sustained 6–10 h of unattended operation.

The commercial instrument was a LI-COR® LI-840 CO_2 and H_2O analyser. It is a non-dispersive infrared gas analyzer equipped with a dual wavelength, infrared detection system allowing measurements of CO_2 and H_2O gas species in the range of 0–3000 ppmv and 0–80 pptv (parts per thousand), respectively. The accuracy was better than 1.5% for both species and cross sensitivity is < 0.1 ppmv CO_2/pptv H_2O for H_2O and <0.0001 pptv H_2O/ppmv CO_2 for CO_2.

The "Multi-GAS" CO_2, H_2, SO_2 sensor consists of a series of electrochemical sensors and a nondispersive infrared (NDIR) sensor through which the sampled gas is circulated (via a miniature 12 V rotary pump) (Aiuppa et al. 2011). The H_2, H_2S and SO_2 sensors produce an electrical current as a response of the target gas entering the electrolyte and oxidizing or reducing the electrode. This current is proportional to the concentration of the target gas in the total gas volume. The electrochemical sensor for SO_2 (City Technology, sensor type 3ST/F) has a calibration range of 0–30 ppmv, an accuracy of ±2%, a repeatability of 1% and a resolution of 0.5 ppmv. The electrochemical sensor for H_2 (City Technology, sensor type 3HYT) has a calibration range of 0–500 ppmv, an accuracy of ±5% a repeatability of 2% and a resolution of 2 ppmv. The NDIR CO_2 sensor (model Gascard II) is calibrated for 0–3000 ppmv with an accuracy ±2% and a resolution of 0.8 ppmv. In addition to the gas sensors, temperature and relative humidity (RH) sensors (Galltec) are mounted in the instrument, providing a measuring range of 0–100 % RH and an accuracy of ±2%. All sensors were housed inside a weatherproof box, with the ambient air sampled via Teflon tubing connected

to a HEPA filter fed through an inlet in the box. The sampled gas was dispersed via an outlet similarly fed through a hole in the case. The sampled gas was heated to ~30°C on its way through the first hose to prevent freezing and other problems related to the low ambient temperatures (below –25°C).

An on-board data-logger card in the "Multi-GAS" instrument captured measurements at a rate of 0.5 Hz while the LI-840 output was logged at 1 Hz via a netbook PC. Both instruments were always started simultaneously. The Multi-GASinstrument was recalibrated using standard gas mixtures in the laboratory (accurately measured by gas chromatography) before and after the campaign and showed very little drift.

Data Processing

Mixing ratios of SO_2, H_2O, CO_2 and H_2 in the gas phase are retrieved (in ppmv) directly from the laboratory-calibrated sensors using the "840-500" software for the LI-840 and in-house software (developed at INGV Palermo) for the multi-gas instrument. The raw data collected by both instruments show a good correlation between all measured species. The good agreement between the CO_2 measurements obtained by the multi-gas instrument and those obtained by the LI-840 furthers our confidence in the accuracy of the multi-gas instrument CO_2 sensor. Response times of the different sensors vary slightly but are all rapid (timescales of seconds to approach maximum reading). Figure 2 shows an example of a typical dataset, recorded on 27 December 2010.

In order to convert the raw mixing ratio data into reliable measurements, several processing steps were applied. Firstly, the difference in response time between sensors was corrected so

the time-series of volcanic gas ratios matched. Secondly, the sensor signal resulting from cross-sensitivity with other gases was subtracted.

The differences in response time for the different sensors were corrected by finding the lag times from correlation analysis of the various time series. Laboratory tests were performed using a set of CO gas standards (from 7 to 500 ppmv) circulated through the Multi-gas instrument in order to determine the cross-sensitivity of the hydrogen sensor to other species. CO was a particular concern because of its abundance in the Erebus gas/aerosol plume (Oppenheimer and Kyle 2008). Mixed CO and H_2 gas calibrations were also carried out. These tests revealed a constant but minor 4% cross sensitivity of the H_2 sensor due to the presence of CO. Although we did not have a CO sensor in the Multi-gas instrument, we can estimate CO abundances point-by-point from measured CO_2 abundance and using a CO_2/CO molar ratio of 13 well-constrained by FTIR spectroscopy (Oppenheimer et al. 2009; Ilanko personal communication). At each point 4% of the estimated CO value was subtracted from the H_2 signal to correct for the cross-sensitivity (Figure 3).

Results

Useful data were only acquired during favourable winds that resulted in grounding of the plume at the crater rim (figure 1b). We obtained 25 hours of good quality observations at a sample rate of 0.5 Hz over the 180 hours of data collection . The variable weather conditions and delays in stabilising the internal temperature of the “MultiGas” instrument were responsible for the limited collection time. It is worth noting that Strombolian eruptions of the nature occasionally observed at Erebus (Aster et al. 2003; Dibble et al. 2008) did not occur during the acquisition of this dataset – only the “passive” plume emitted from the lava lake

was sampled. Figure 4 shows scatter plots for measurements recorded during the last week of December 2010, which offered the best conditions for plume sampling.

Results from six days of data yield a mean H_2/SO_2 molar ratio between 1.38 and 1.52 (Figure 4a) with most days yielding a ratio close to 1.4, and the average ratio for the whole week being 1.44. Scatter plots for the CO_2 and SO_2 measurements yield CO_2/SO_2 molar ratios varying between 36 and 45 (Figure 4b), with the week's average being 40. We neglect the CO_2/SO_2 ratio obtained for 3 January which shows much higher variability which we ascribe to contamination from nearby fumaroles. The intercept of first order linear regression through the scatter plots of H_2 *vs.* SO_2 and CO_2 *vs.* SO_2 should correspond to the atmospheric background H_2 and CO_2 abundances, respectively (since ambient SO_2 is very low (less than 10 pptv). In fact, we find values for ambient H_2 between 1.06 and 0.42 ppmv and background CO_2 values between 433 and 385. These are both good approximations to expected atmospheric background mixing ratios for the two gases. For instance, measurements from December 2010 at the South Pole weather station (available at http://www.esrl.noaa.gov/) indicate atmospheric abundances of 387.5 ppmv for CO_2 and 0.54 ppmv for H_2. This station is the closest Antarctic research station routinely measuring atmospheric gas abundances at altitude (2900 m a.s.l , c.f. the altitude of the Pump Site of ~ 3700 m). A test run using the "Multi-GAS" instrument on 7 December carried out near Lower Erebus Hut (2 km from the crater) also yielded stable H_2 readings of ~0.5 ppmv though CO_2 readings fluctuated with temperature drift during acquisition (CO_2 values oscillated between 400 and 350 ppmv). These estimates of the ambient mixing ratios of the two gases give further confidence in performance of the "Multi-GAS" instrument sensors. While H_2O was being recorded simultaneously by the LICOR and Multi-GASs instruments, rapid changes of the background

atmospheric humidity and possible influence of nearby low-temperature fumaroles precluded reliable retrieval of the lava lake plume's water content.

Further inspection of our dataset reveals small but clear variations in the retrieved gas ratios which appear cyclical. Figure 5 shows the evolution of the H_2/SO_2 ratio for part of a 10 h run on 3 January 2011 together with the corresponding pseudo-periodogram obtained using a continuous Morlet wavelet transform analysis of the time series. The pseudo-periodogram shows a strong transform modulus with a cycle of 8 to 12 min. Similar pseudo-periodograms have been produced for all the time series for which data are presented in Figure 4, and all reveal cycles with periods of 7 to 14 min. In addition, some pseudo-periodograms show weaker signal strength at a shorter period of 3 to 5 min. Pseudo-periodograms were produced for the CO_2/SO_2 ratio time-series and reveal similar periodicities. This periodicity is the more remarkable since it suggests preservation of a source signature despite the passage of the plume within the crater (from the lava lake to the Pump Site). Time series of the SO_2/H_2 and SO_2/CO_2 ratios were constructed using background H_2 and CO_2 atmospheric values determined by the intersection of the linear regression with the H_2 or CO_2-axis for each day (Figure 4) except when that intercept was higher than the lowest measured H_2 or CO_2 value, in which case this lowest H_2 or CO_2 value was used as the background.

Discussion

Volcanic H_2 contribution to the Antarctic atmosphere

We have estimated the H_2 flux from Erebus volcano using the average SO_2 flux of 0.71 ± 0.3 kg s^{-1} (Sweeney et al. 2008) and the measured H2/SO2 ratio. Using dual-wide field of view UV spectroscopy, Boichu et al. (2010) reported an SO_2 flux varying cyclically from 0.17 to

194 0.89 ± 0.2 kg s^{-1}. Oppenheimer et al. (2005) measured an average SO_2 flux of 0.86 ± 0.2 kg s^{-1}
195 by traversing beneath the horizontal plume using a simple ultraviolet spectrometer system,
196 and Sweeney et al. (2008) estimate was a decadal mean SO_2 flux. Using our mean H_2/SO_2
197 ratio of 1.44 (equivalent to a H_2/SO_2 mass ratio of 0.045) we estimate the mean H_2 flux at
198 Erebus volcano as 0.03 kg s^{-1} (2.8 Mg day^{-1}).
199 This estimated H_2 flux from Erebus represents a significant contribution to the local
200 atmospheric chemistry and the single largest recorded point source of H_2 to the Antarctic
201 atmosphere. For context, the global anthropogenic emission of H_2 from the use of fossil fuels
202 is estimated at 5 to 25 Tg a^{-1} (Novelli et al. 1999). The Erebus source amounts to ~1 Gg a^{-1} of
203 H_2 corresponding to 0.004 to 0.02 % of the total global anthropogenic emission. For
204 comparison the hydrogen flux at Mt Etna has been estimated at ~0.00065 Tg a^{-1} (Aiuppa et al.
205 2011). Mont Erebus hydrogen flux is therefore 1.6 time greater than Etna's while its SO_2 flux
206 is 71 time smaller.

207 ***Oxidation state of the Erebus lava lake***

208 Based on a mean bulk plume SO_2/H_2O ratio of 0.023 obtained by FTIR spectroscopy
209 (Oppenheimer et al. 2009), we can convert the mean "Multi-GAS"-measured H_2/SO_2 ratio to
210 an H_2/H_2O ratio of 0.033. From this ratio we can calculate the corresponding oxygen fugacity
211 based on the redox reaction in Equation [1] as follows.

212 The equilibrium constant, K, for this reaction is given by $\frac{f_{H2} \times (f_{O2})^{\frac{1}{2}}}{f_{H2O}}$

213 where $f_{H2} = \gamma_{H2} \times P_{H2}$; $f_{O2} = \gamma_{O2} \times P_{O2}$; $f_{H2O} = \gamma_{H2O} \times P_{H2O}$

214 with $P_i = x_i \times P$

215 and where f_i is the fugacity of the i^{th} species, γ_i the fugacity coefficient of the i^{th} species, P_i is
216 the partial pressure of the i^{th} species, x_i the mole fraction of the i^{th} species and P is the total
217 gas pressure.

Which yields: $(f_{O2})^{1/2} = \frac{K \times f_{H2O}}{f_{H2}} = K \frac{\gamma_{H2O} \times x_{H2O} \times P}{\gamma_{H2} \times x_{H2} \times P}$

and therefore $f_{O2} = \left(K \frac{\gamma_{H2O} \times x_{H2O}}{\gamma_{H2} \times x_{H2}}\right)^2$

At atmospheric pressure, the fugacity of a gas is equal to its partial pressure (assuming ideal behaviour) therefore $\gamma_{H2O}/\gamma_{H2} = 1$. The equilibrium constant can be calculated as follows:

$$K = exp(-\Delta G/RT)$$

$$\Delta G = \Delta H - T\Delta S$$

$$\Delta H = \int_{T_1}^{T_2} C_p \, dt$$

$$\Delta S = \int_{T_1}^{T_2} \frac{C_p}{T} \, dt$$

Where ΔG is the change in Gibbs' free energy, ΔH the change in enthalpy, and ΔS the change in entropy of the system. C_P is the heat capacity which can be fit by a function of the form: $C_P = a + bT + cT^{-2} + dT^{-0.5}$ with a, b, c and d representing Maier-Kelly coefficients specific for each substance and obtained here from the Supcrt92 software (Johnson et al. 1992). At T = 1273K (the most widely accepted temperature of the lava lake), K= $3.72.10^{-8}$, the logfO_2 is equivalent to QFM–0.92 (using a H_2/SO_2 ratio of 1.44, and where QFM refers to the quartz-fayalite-magnetite buffer). Using the obtained oxygen fugacity and prior measurements (Oppenheimer et al. 2009), we can recalculate the composition of the Erebus plume to include H_2 and the expected abundance of H_2S (Table 1, first column). Note that, in the Table, H_2S is estimated based on the gas redox properties (calculated using the "Dcompress" software from Burgisser et al. (in review)) though it has not been detected at Erebus despite multiple attempts (Oppenheimer and Kyle 2008).

The oxidation state of the phonolite magma in the persistent lava lake of Erebus volcano has been estimated by several techniques. Kelly et al. (Kelly et al. 2008) used mineral chemistry to estimate an oxidation state of ΔlogQFM = –0.9 (using the QUILF program and a temperature of 1000°C). Oppenheimer & Kyle (2008) and Oppenheimer et al. (2011) used the

CO_2/CO ratio obtained using FTIR spectroscopy (and the same temperature) to estimate the oxidation state at ΔlogQFM = –0.9 to –0.88. Both of these estimates are very similar to our mean ΔlogQFM = –0.92. It should be noted however that our new estimate of the oxidation state is not entirely independent as we used the SO_2/H_2O ratio previously measured by FTIR spectroscopy in our calculation.

The presence of H_2 in the volcanic plume suggests that H_2 is not burning at the interface between the lava lake and the atmosphere as has been observed, for instance, at Kīlauea's lava lake (Cruikshank et al. 1973). The correspondence of computed redox conditions for the lava lake also indicates that the H_2 abundance at the crater rim corresponds to the high-temperature equilibrium with the lava lake as hypothesized by Martin et al. (2009), and experimentally verified at Etna by Aiuppa et al. (2011). If any H_2 is oxidizing in the plume (e.g., to form HO_x radicals) it is only in very small amounts.

Periodicity and magma supply to the lake

From the time-series, the H_2/SO_2 molar ratio varies mostly between 1 and 2 for all six days while the CO_2/SO_2 molar ratio varies mostly between 25 and 50. These upper and lower values can be attributed to two end-member compositions associated with a periodic dynamic behavior of the lake (Table 1) recognised in the lava lake surface motion and other gas ratios (Oppenheimer et al. 2009). The terms "top" and "bottom" of the cycle are adopted here to echo previous literature; the "Top of cycle" refers to high SO_2/CO_2 ratio, faster lake motion and higher lake level, and, as shown in Figure 5, corresponds to high SO_2/ H_2. The "top of cycle" composition is calculated using an H_2/SO_2 ratio of 1 and SO_2/H_2O gas ratios of 0.0242 from the "mixed plume" composition of Oppenheimer et al. (2009) while the "Bottom of cycle" composition is calculated using an H_2/SO_2 ratio of 2 and SO_2/H_2O gas ratios of 0.0218 from the "conduit gas" composition of Oppenheimer et al. (2009). The difference between the

two end-member compositions is quite significant in term of redox state, representingQFM-0.65 at the "top of the cycle" and QFM-1.16 at the "bottom of the cycle" (assuming no change in temperature).

Considering that the "tops" of the cycles are marked by an increase in lake level, surface motion and SO_2 flux, Oppenheimer et al. (2009) and Boichu et al. (2010) suggested that they are associated with the arrival of foaming magma batches in the lava lake (still exsolving water at near atmospheric pressure). We now observe that the "top" of the cycle is consistently associated with significantly more oxidized conditions (log fO_2=QFM–0.65) than the "bottom" of the cycles (log fO_2=QFM–1.16). If the "top" of the cycles is indeed associated with the influx of rising magma batches, then these batches appear to be releasing gas whose composition is a relic of chemical equilibrium acquired at some depth. This signature may be preserved as a result of rapid ascent of the magma batch (i.e., fast with respect to the kinetics of redox reactions such as [1] and [2]). The dichotomy we identify between the oxidized "top" and reduced "bottom" of the cycles therefore provides further empirical evidence for redox stratification in the Erebus plumbing system as discussed in Oppenheimer et al. (2011) and Burgisser et al. (in review), and as hypothesized from a more general standpoint by Burgisser and Scaillet (2007).

Conclusion

In-situ measurements of the gas plume emitted from the lava lake of Erebus volcano by means of a multi-gas sensing instrument indicate that the hydrogen abundance in the magmatic gas phase is around 1.6 mol%. These measurements constrain the oxidation state of the lava lake to ~QFM–0.9 log units, consistent with previous estimates; provide strong evidence that hydrogen burning is not prevalent at the surface of the lake; and that hydrogen is at least

largely kinetically inert in the gas/aerosol plume rising in the crater. The hydrogen flux to the atmosphere from the summit of Erebus is estimated at 2.8 Mg d^{-1}. A strong ~10 min periodicity in the proportions of H_2 and other species in the plume infers corresponding redox state variations, and points to a pulsatory supply of magma to the top of the lava lake. The more oxidized signature of the magma periodically entering the lake provides strong empirical evidence of a redox stratification in the shallow plumbing system, as has been hypothesized by previous numerical models.

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Tables

Table 1: Estimated composition of the Erebus plume in mol% and in molar ratio. The CO_2/CO and SO_2/H2O molar ratios are obtained from Oppenheimer et al. (2009). The H_2/SO_2 and CO_2/SO_2 molar ratios are obtained from the "MultiGas" instrument measurements and the SO_2/H_2S molar ratio is calculated using the "Dcompress" software from Burgisser et al (in review). The "Top of cycle" composition correspond to the "mixed plume" composition of Oppenheimer et al. (2009) while the "Bottom of cycle" composition correspond to the "conduit gas" composition of Oppenheimer et al. (2009).

Figures

Figure 1: **a)** Typical field operating conditions of the Licor 840 and multigas sensor at the crater rim. Gases are pumped through both instruments via a narrow hose connected to a particle filter to avoid contamination of the instrument. **b)** View of Erebus (looking north) under optimal plume sampling conditions on 26 December 2010. Turbulent airflow results in grounding of the plume allowing for easy sampling.

Figure 2: Example of time series for gas mixing ratios obtained from both instruments (the multi-gas sensor and LI-840). This 1-h-long time series is an extract from a 10-h-long run acquired at the crater rim on 27 December 2010. All gas species are reported in ppmv.

Figure 3: a) Hydrogen time series (red) and aligned time series (corrected for instrumental offset between sensors) of the estimated hydrogen counts from cross sensitivity with CO gas (in blue) estimated as 4% of the CO_2 signal from which a constant background atmospheric value of 387.5 ppmv is subtracted and whose residual is divided by 13 (from measured

CO_2/CO ratio in Oppenheimer et al. 2009). The dotted black line represents the residual of the H_2 time series after removal of the H_2 counts due to CO cross-sensitivity. b) H_2 and SO_2 time series after correction of H_2 from atmospheric background concentration and CO cross-sensitivity and after alignment of both times series from correction of an offset calculated using the maximum correlation factor between the time series.

Figure 4: **A:** H_2-SO_2 and **B**: CO_2-SO_2 Scatter plots from six days of sampling of the Erebus plume under favourable conditions a) 26 December 2010, data recorded from 11:20 to 16:33 h UTC. b) 28 December 2010, data recorded from 02h16 to 10h01 UT. c) December 29th 2010, data recorded from 11h07 to 13h58 UT. d) December 30th 2010, data recorded from 06h25 to 11h45 UT. e) December 31st 2010, data recorded from 04h10 to 06h12 UT. f) January 03rd 2011, data recorded from 22h42 to 01h32 UT. Regression lines are shown in red and corresponding parameters displayed on the lower right corner of each plot.

Figure 5: Morlet Wavelet transform pseudo-periodogram computed from a 3 h time series of the H_2/SO_2 ratio obtained from a 10 h long run of the MultiGas instrument on 3 January 2011. Note the strong transform modulus emerging steadily at a period of ~10 min. The central diagrams shows a 3 h time series of the evolution of the H_2/SO_2 ratio in which ~10 min cycles (600 sec) can be observed. The lower diagram shows the evolution of the SO_2/H_2 and SO_2/CO_2 ratios for the first 1400 sec (~23min) of a time series obtained from an 8 h long run of the MultiGas instrument on 26 December 2010. This lower diagram shows 3 cycles of ~8 min each.

Table 1

	Mean	Top of cycle	Bottom of cycle
		mol%	
CO2	44.00	34.86	47.25
H2O	47.84	57.62	43.37
SO2	1.10	1.39	0.94
CO	3.30	2.61	3.54
HCl	0.46	0.56	0.42
HF	1.16	1.39	1.05
H2	1.58	1.39	1.89
OCS	0.01	0.01	0.01
H2S	0.55	0.16	1.53
		mol/mol	
CO2/CO	13.33	13.33	13.33
SO2/H2O	0.02	0.02	0.02
H2/SO2	1.44	1.00	2.00
CO2/SO2	40.00	25.00	50.00
SO2/H2S	2.01	8.72	0.62
log(fO2) at 1000°C	-11.90	-11.63	-12.14
Delta QFM	-0.92	-0.65	-1.16

Moussallam et al., Table 1

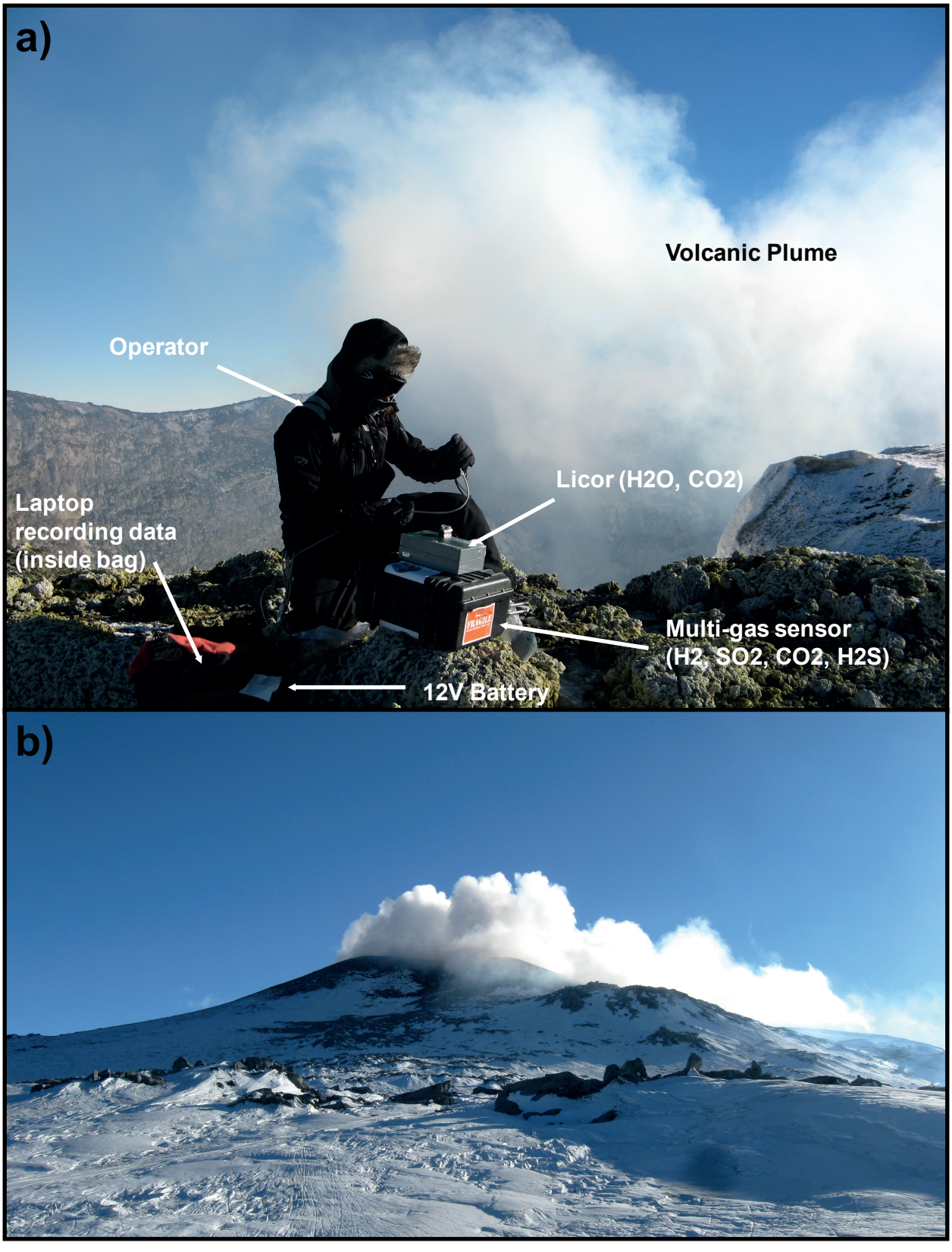

Figure 1 Moussallam et al.,

Figure 2

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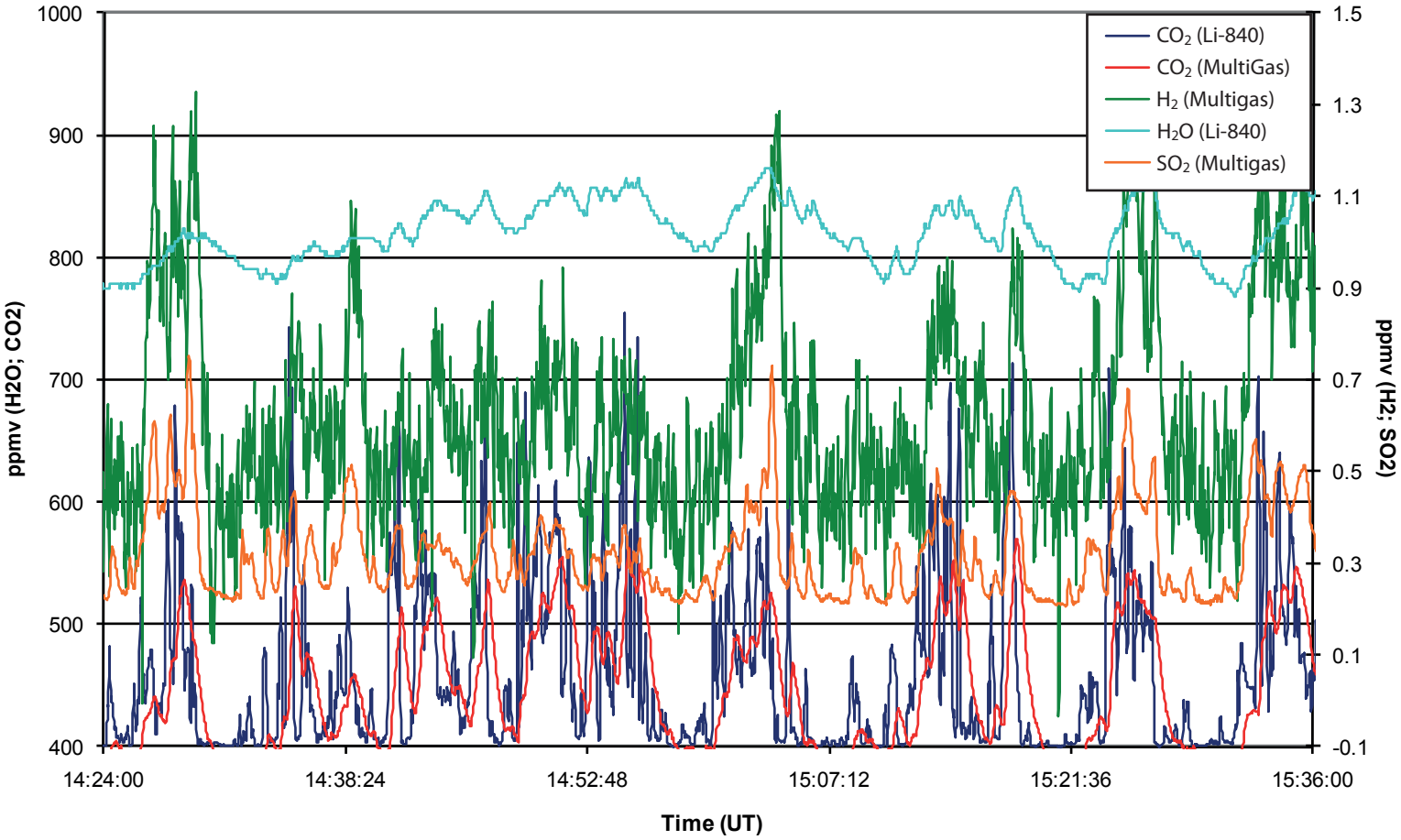


Figure 2 Moussallam et al.,

Figure 3

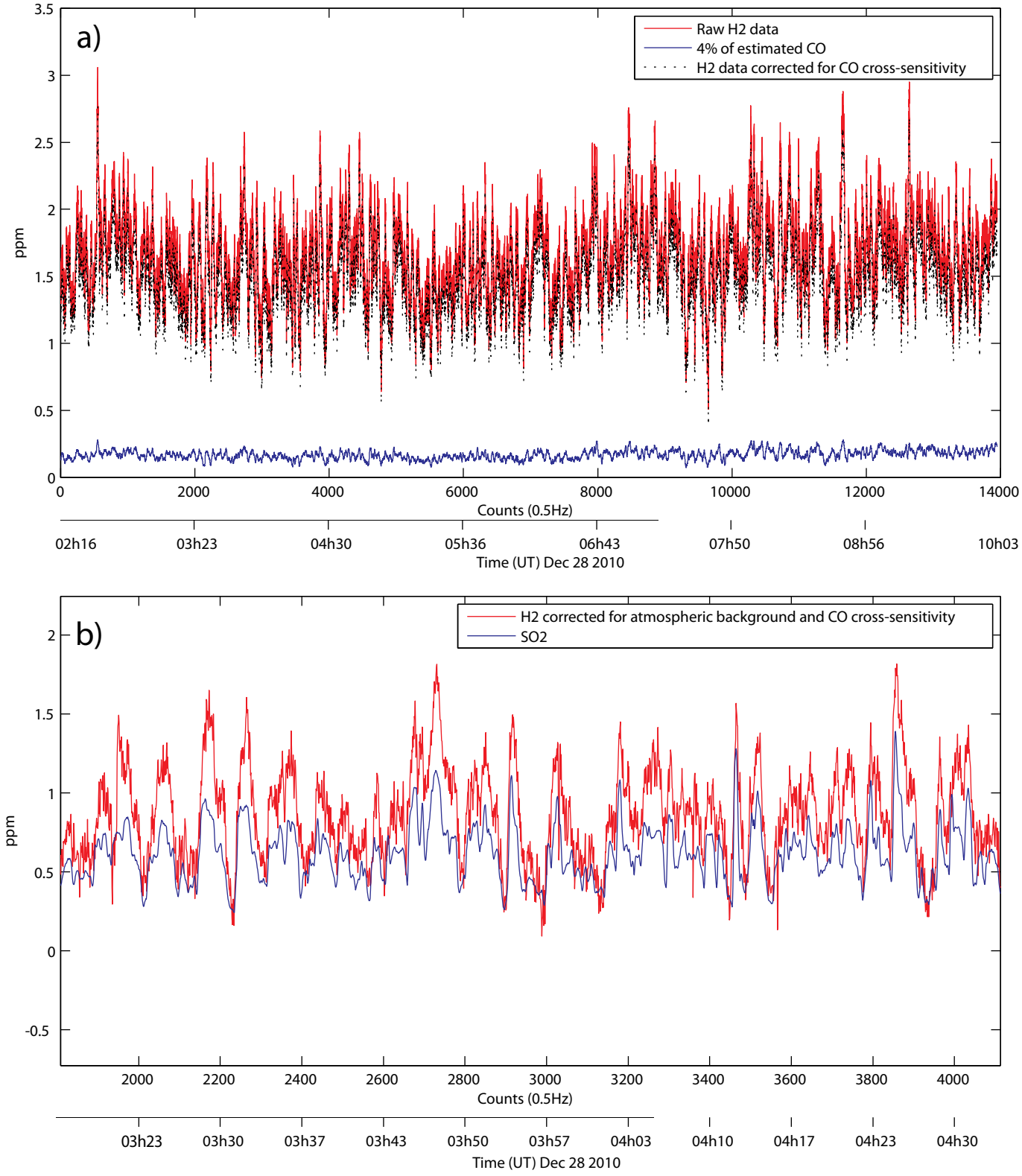


Figure 3 Moussallam et al.,

Figure 4a

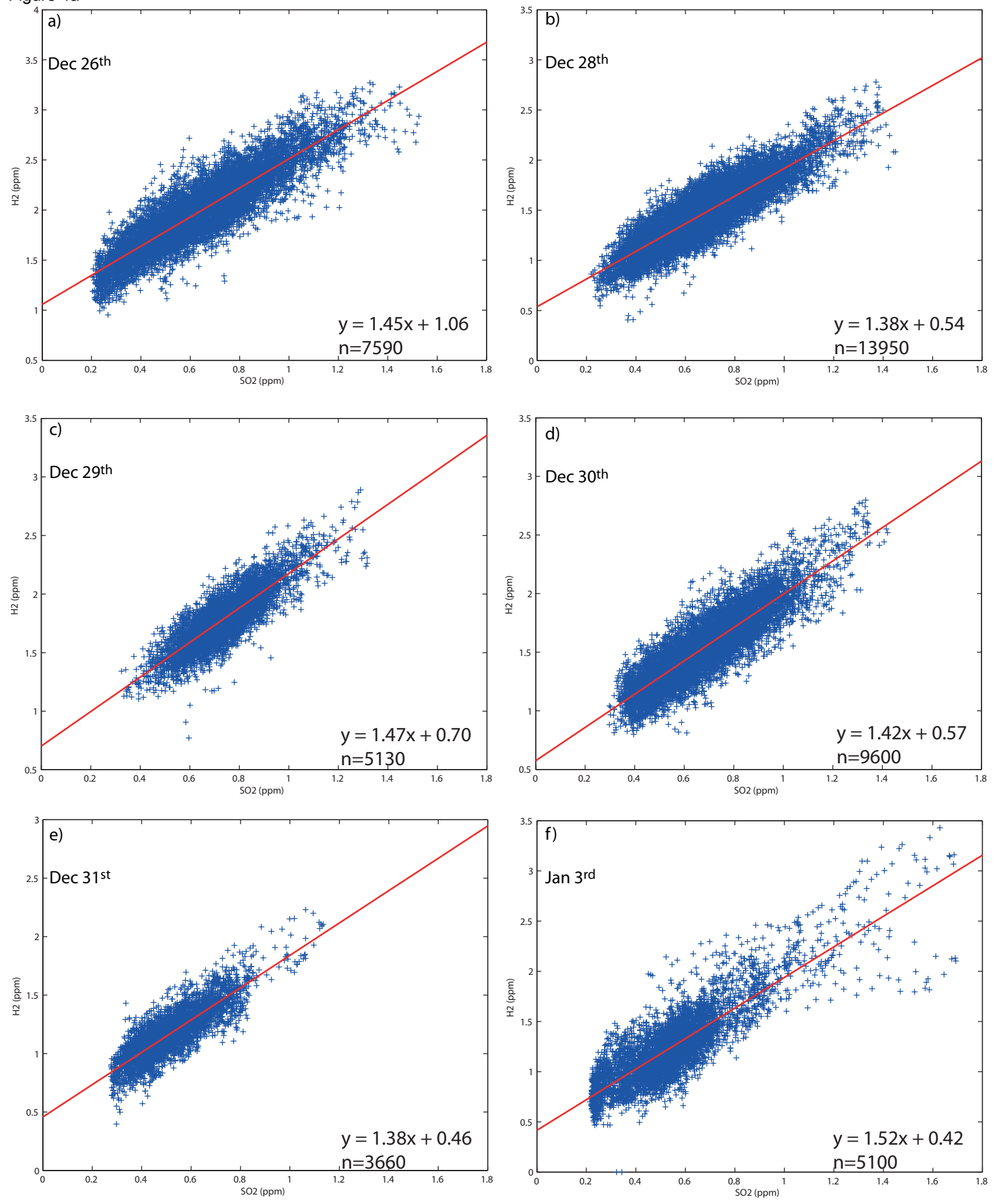


Figure 4 A Moussallam et al.,

Figure 4b

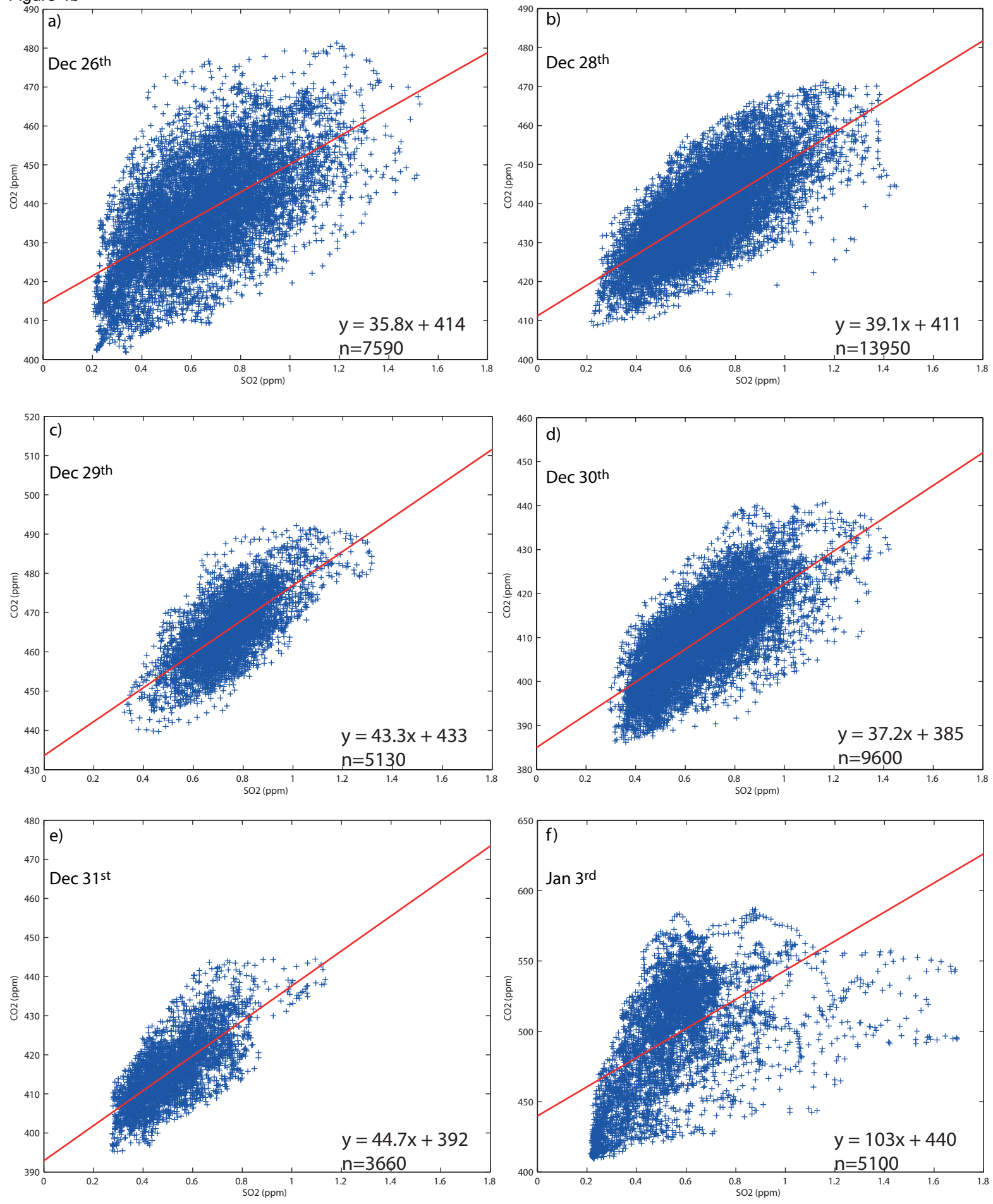
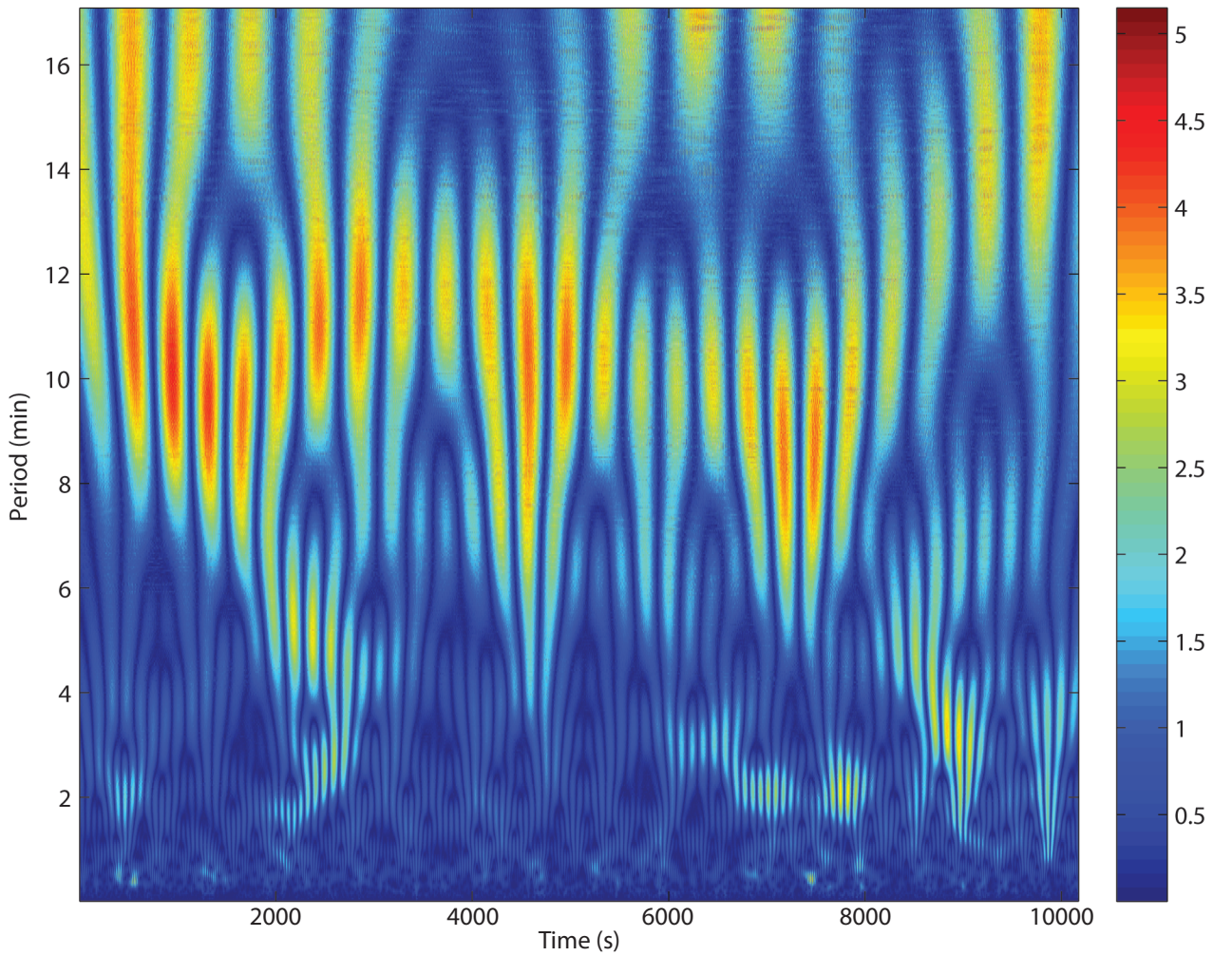
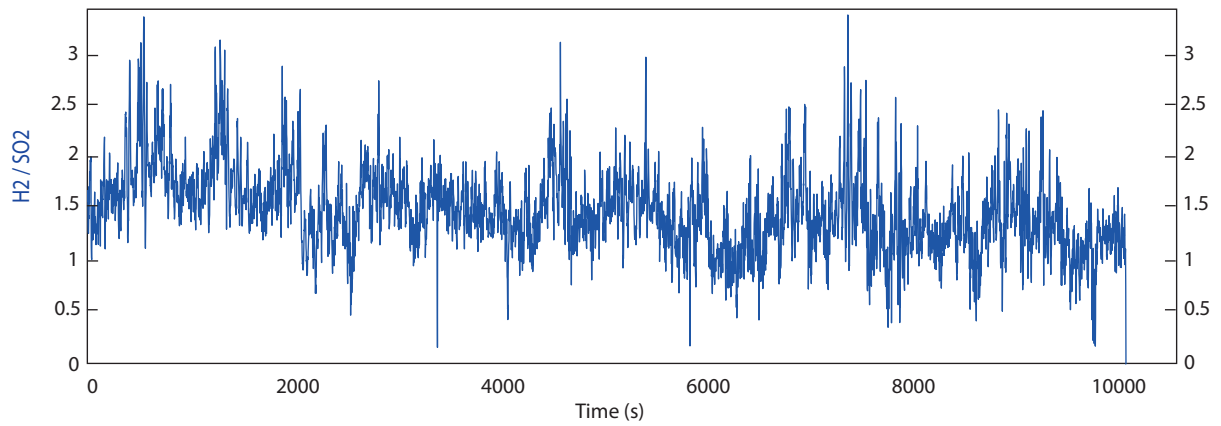


Figure 4 B Moussallam et al.,

Figure 5





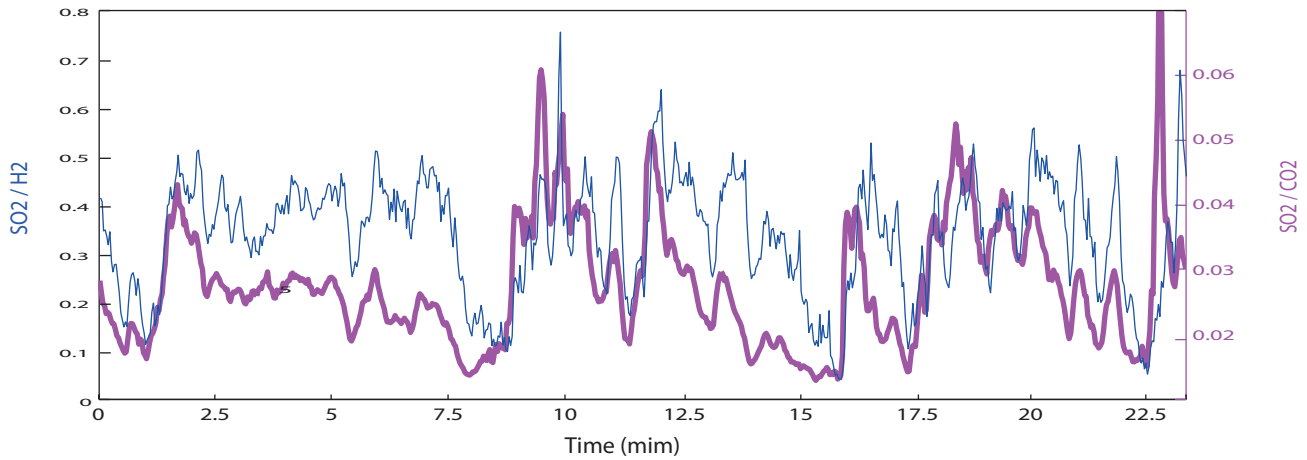


Figure 5 Moussallam et al.,