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Correlation of cycles in Lava Lake motion and degassing at Erebus Volcano, Antarctica

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Key Points:
- Cycles in degassing, motion, and level of Erebus's lava lake are correlated
- Peak degassing and motion lags peak level by 1–3 min
- The cycles are unaffected by large explosive events

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Abstract Several studies at Erebus volcano have recorded pulsatory behavior in many of the observable properties of its active lava lake. A strong correlation between the variations in surface speed of the lake and the composition of gas emitted has previously been noted. While previous studies have shown that the SO_2 flux and the surface elevation exhibit pulsatory behavior with a similar period to that of the surface speed and gas composition, suggesting they are linked, a lack of overlap between the different measurements has prevented direct comparisons from being made. Using high time-resolution measurements of surface elevation, surface speed, gas composition, and SO_2 flux, we demonstrate for the first time an unambiguous link between the cyclic behavior in each of these properties. We also show that the variation in gas composition may be explained by a subtle change in oxygen fugacity. The cycles are found to be in-phase with each other, with a small but consistent lag of 1–3 min between the peaks in surface elevation and surface speed. Explosive events are found to have no observable effect on the pulsatory behavior beyond the ~5 min period required for lake refill. The close correspondences between the varying lake surface motion, gas flux and composition, and modeled oxygen fugacity suggest strong links between magma degassing, redox change, and the fluid dynamics of the shallow magmatic system.

1. Introduction

Cyclic behavior has been recognized at a number of open-vent volcanoes around the world. Pulsatory patterns in both degassing [e.g., *Pering et al.*, 2014; *Tamburello et al.*, 2013, 2012; *Edmonds et al.*, 2003] and in the behavior of active lava lakes [e.g., *Bouche et al.*, 2010; *Patrick et al.*, 2011] has been observed. However, the processes underlying such activity remain uncertain.

The persistent, low-level activity of Erebus volcano, Antarctica makes it an outstanding natural laboratory for investigating volcanic and magmatic processes. The rim of Erebus's main crater commands a direct view of its active lava lake, which has been a permanent feature of the volcano since at least 1972 [*Giggenbach et al.*, 1973]. It is one of only a handful of active lava lakes in the world [*Tazieff*, 1994], but is unique in its phonolitic composition [*Kelly et al.*, 2008].

A high degree of thermal structure in the crust which covers the lake has enabled feature tracking algorithms to be applied to time series of infrared images acquired from the crater rim so as to investigate the lake's motion [*Oppenheimer et al.*, 2009]. These thermal images have also been used to quantify the radiative heat losses from the lake [*Calkins et al.*, 2008]. Thermal radiation from the lava surface can be used as a source for open-path Fourier Transform Infra-Red (FTIR) spectroscopy, allowing detailed compositional analysis of emitted gases at high temporal resolution [*Oppenheimer and Kyle*, 2008]. The extremely dry atmosphere of Antarctica is highly advantageous for FTIR measurements and has also facilitated terrestrial laser scanning (TLS) observations of the lake's surface [*Jones*, 2013] during periods of particularly low humidity inside the crater.

In common, with other open-vent volcanoes Erebus's volcanic plume is a sustained feature. During favorable weather conditions it is often coherent and vertically rising over a sufficient distance to permit application of UV spectroscopy to ascertain SO_2 flux [*Kyle et al.*, 1990, 1994; *Sweeney et al.*, 2008]. The use of a Dual Wide Field of View (DW-FOV) instrument has enabled rapid variations in flux to be measured [*Boichu et al.*, 2010]. During less favorable weather conditions, the plume is often grounded across the northern side of the crater allowing direct measurements using "multigas" instruments [*Shinohara*, 2005; *Aiuppa et al.*, 2005] to be made. In addition to complementing the FTIR measurements, these have also enabled the measurement of hydrogen emissions [*Moussallam et al*., 2012].

A common finding of the aforementioned studies is that many of the lava lake's properties (SO_2 flux, gas composition, radiant heat, and surface velocity) demonstrate pseudoperiodic fluctuations with a period of 5–18 min. Henceforth we use the terms "pulsatory" and "cyclic" interchangeably to refer to these fluctuations. We note, however, that the periods, amplitudes, shapes, and baselines of individual cycles are variable (albeit within relatively narrow ranges); thus, we use this terminology in its more colloquial sense. The phenomenon was first reported by *Oppenheimer et al*. [2009], who showed correlated pulsatory behavior in surface speed and gas composition for a ~1 h period in December 2004, and also in surface speed and radiant heat for a different ~1 h period from the same month. Pulsatory SO_2 flux was recorded for a ~2 h period in December 2006 by *Boichu et al*. [2010], but measurements of other lake properties were not available for this time period. Observations of pulsatory behavior in the surface elevation of the lava lake during a ~2 h period in December 2009, and again during a ~6 h period in December 2010 were presented by *Jones* [2013]; however, no comparison was made with other lake parameters in this study. *Peters et al*. [2014a] analyzed a much larger data set (>1000 h) and showed that the pulsatory behavior of the surface speed was a persistent feature of the lake between 2004 and 2011, and this correlated strongly with the radiant heat. Again, however, no comparisons with gas composition, SO_2 flux, or surface elevation were made.

Drawing on findings from laboratory experiments with viscous exchange flows [*Huppert and Hallworth*, 2007], it was proposed by *Oppenheimer et al*. [2009] that the behavior of the Erebus lava lake may be due to instability in bi-directional flow in the lake's feeder conduit causing pulsatory injection of degassing magma from the conduit into the lake. The bi-directional flow is likely driven by the density contrast between the gas-rich magma in the conduit and the more degassed magma in the lake [e.g., *Shinohara*, 2008]. Recent findings suggesting that bubbles arriving at the surface of the lava lake are uncorrelated with the fluctuations in surface velocity [*Peters et al*., 2014a] lend weight to the bi-directional flow hypothesis and largely rule out other mechanisms for pulsatory behavior at Erebus such as gas pistoning [*Patrick et al*., 2011; *Orr and Rea*, 2012], bubble driven pressurization changes [*Witham et al*., 2006] or the periodic arrival of large gas slugs [*Bouche et al*., 2010]. The behavior of the Erebus lake may well differ from that of other basaltic composition lava lakes (e.g., Kīlauea) due to its viscosity, which, although never measured, is expected to be orders of magnitude higher given its silica content and temperature [e.g., *Moussallam et al*., 2013].

Observing how the cycles in the different parameters relate to each other is key in understanding the underlying mechanism responsible for them. Since the cycles are believed to derive from processes occurring within the conduit, a detailed knowledge of their behavior will undoubtedly lead to an improved understanding of how Erebus's magmatic system as a whole functions. Unfortunately, coordinating multi-instrument studies of volcanoes, such that the time series of different data overlap, is a nontrivial exercise. As a result, previous field campaigns at Erebus volcano have failed to record concurrently fluctuations in both SO_2 flux and in other parameters. Similarities between surface motion and gas composition were observed by *Oppenheimer et al*. [2009] in a short time series from 2004. However, due to the limited available data and a lack of high precision time-stamping, a detailed analysis of the correlation was not possible. Thus, although it has been widely assumed that the cyclic behavior of the different parameters must be linked, to date there has been no significant body of data to confirm this. However, as the infrastructure installed by the Mount Erebus Volcano Observatory (MEVO), such as power and data telemetry, continues to be improved, longer continuous time series are becoming possible [*Peters et al*., 2014b] and with them, a greater degree of overlap between different observations. Here we present data collected in December 2012 and December 2013 which show, for the first time, a definitive link between the pseudoperiodic behavior of the lava lake's surface speed, surface elevation, SO_2 flux, and plume composition.

Our specific aims are twofold: (i) to identify the relationship between the pulsatory behavior of SO_2 flux, plume composition, and the lava lake's surface motion and surface elevation at Erebus volcano; (ii) to improve the understanding of the underlying mechanisms responsible for the observed cyclicity. Our findings provide an important cornerstone for future studies and will be of particular relevance to future efforts to model pulsatory behavior either through experiments or computer simulations.

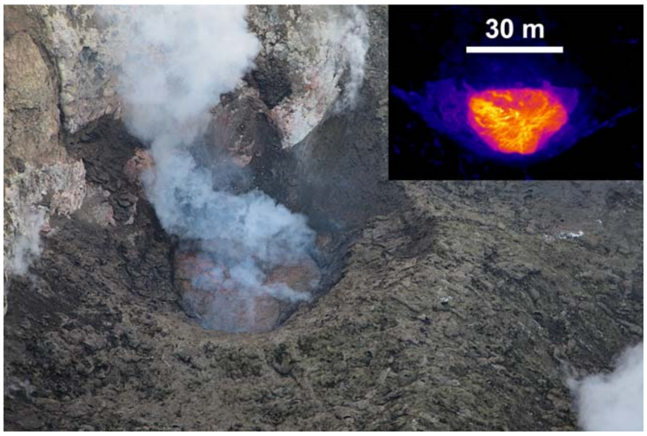

Figure 1. Visible and infrared images of the lava lake on 15 December 2013. Freshly ejected material surrounding the lake is apparent in both images.

2. Summary of Activity

Although in general terms the interannual variability of the Erebus lava lake is low, its apparent surface area can change significantly [*Peters et al.*, 2014a]. In December 2013, the lake was approximately 30 m across (Figure 1), with a surface area of ~580 m^2 (measured using TLS). This is slightly larger than its surface area in 2012 (~400 m^2), but is just a quarter of its 2004 size. Explosions associated with large (decametric) gas bubbles reaching the surface, ejecting bombs, and spatter from the lake typically occur a few times per week [e.g., *Dibble et al.*, 2008]. Ejecta are usually confined to the ~250 m deep "Main" crater and often land within the immediate vicinity of the lake. Fresh ejecta are apparent surrounding the lake in both the visible and IR images shown in Figure 1. During 2012, the activity was at a "normal" level. However, around August 2013, Erebus entered a more vigorously explosive phase, with two or three explosions each day that were large enough to propel ejecta out of the summit crater completely. Bombs several meters in length were observed to land up to ~400 m downslope from the crater rim. Such activity has not been observed at Erebus since 2005–2007 when a similar period of increased activity occurred [*Knox*, 2012]. At the time of writing in 2014, data from the seismic network deployed around Erebus [*Aster et al.*, 2004] show that large explosions continue to occur several times a day (although with a brief period in early March where activity subsided). Despite the increased activity during the 2013 field campaign (conducted in December), the lake's behavior in periods of quiescence between explosions was indistinguishable from other years. It seems reasonable to assume therefore that the data presented here are representative of Erebus's behavior in general rather than only during its periods of elevated activity.

3. Methodology

3.1. Lava Lake Surface Velocity

Using a thermal infrared (IR) camera situated on the northern rim of Erebus's main crater (~330 m from the lake), images of the lava lake were recorded at a rate of ~0.5 Hz. The thermal camera system used in this study is described in detail by *Peters et al*. [2014b]. Despite the small visible surface of the lake compared to many previous years, estimates of the surface velocity made using a wavelet-transform feature tracking algorithm [*Magarey and Kingsbury*, 1998; *Kingsbury*, 2001] were still possible. TLS surveys of the inner crater topography, collected during the 2013 field season, were used to correct the IR images for perspective effects and the mean lake surface speed was then calculated using the same methodology as described in *Peters et al*. [2014a]. Mean lake surface speed was chosen as a representative parameter of cyclic behavior as the cycles tend to be clearer than in other measurements such as peak speed, or the predominant direction of the surface motion.

Unlike the study conducted by *Peters et al*. [2014a], there was no need to search the images for periods of data with little camera shake. The rigid tripod system installed in 2012 [*Peters et al*., 2014b] has solved this issue. Instead, periods of data with good visibility of the lake (low humidity in the crater) which coincided with data from the FTIR and the DW-FOV DOAS were chosen. This selection process was achieved by manually inspecting the images.

3.2. SO_2 Flux

Ultraviolet Differential Optical Absorption Spectroscopy (UV DOAS) has been increasingly applied to measurement of volcanic sulfur dioxide emissions since small and relatively low-cost spectrometers became commercially available [*Galle et al*., 2003]. Typically, UV spectra are collected across a transect of the volcanic plume perpendicular to its transport direction, either through the use of a scanning unit or by carrying the spectrometer in a traverse [e.g., *Kyle et al*., 1994; *McGonigle*, 2002; *Salerno et al*., 2009]. SO_2 flux is calculated by integrating across the transect and multiplying by rise speed (for a vertically rising plume) or by wind speed (for a horizontally drifting plume). Although this technique is well established and widely used within the volcanological community, the necessity to record spectra at many positions across the plume greatly restricts the time resolution of the flux measurements made. It is therefore not possible to use the results in studies of dynamic phenomenon such as Erebus's pulsatory gas flux. Furthermore, the inclusion of plume transport speed, which is often poorly constrained, in the calculation introduces large errors which are difficult to quantify.

Increasingly, ultraviolet cameras [*Mori and Burton*, 2006; *Bluth et al*., 2007] are being used to quantify SO_2 emissions associated with short-lived events such as Strombolian eruptions [*Dalton et al*., 2009; *Mori and Burton*, 2009; *Tamburello et al*., 2012] and for comparison with other high time-resolution monitoring data, such as observations of seismic tremor [*Nadeau et al*., 2011] and very long period (VLP) seismic events [*Kazahaya et al*., 2011; *Waite et al*., 2013]. Plume transport speeds can be determined from the UV images either by a simple correlation of pixel values between successive frames or by more advanced optical flow methods [*Kern et al*., 2012; N. Peters et al., Use of motion estimation algorithms for improved flux measurements using SO_2 cameras, submitted to *Journal of Volcanology and Geothermal Research*, 2014]. However, despite their promise as a tool for high time-resolution SO_2 measurements, there remain many significant calibration issues which must be addressed before accurate fluxes can be obtained [*Kern et al*., 2010]. Although some of these issues have begun to be addressed by using a colocated UV spectrometer to calibrate the images [*Lübcke et al*., 2012], the technique is still very much in its infancy. This, combined with the rather low SO_2 flux of the Erebus plume ($\sim$0.5 kg s^{-1}), makes measuring the periodic fluctuations using a UV camera problematic. Instead, we took a similar approach to that of *Boichu et al*. [2010], the so-called Dual Wide Field of View DOAS (DW-FOV DOAS) technique.

DW-FOV DOAS uses a pair of UV spectrometers connected by optical fibers to two telescopes. Each telescope houses cylindrical lenses to give its spectrometer a field of view that is very wide in one-dimension (typically the horizontal) and very narrow in the other. The fields of view of the two spectrometers are aligned parallel along their long axes, with a small offset in the narrow field of view direction. The width of the fields of view is such that they encompass the entire plume (the width can be adjusted according to plume dimensions and viewing geometry) allowing the column amount of SO_2 to be measured instantaneously at two different heights in the plume. Column amount measurements are made repeatedly with both spectrometers, and, by cross correlation of the two time series, the plume transport speed, and therefore flux, can be measured.

SO_2 column amounts were estimated using the standard DOAS methodology [*Platt and Stutz*, 2008]. Plume rise speeds were determined using the same windowed cross-correlation approach as *Boichu et al*. [2010], whereby a fixed length window of column amount data from the lower spectrometer is extracted at regular time intervals, normalized with respect to its mean and standard deviation, and cross correlated with the normalized column amount data from the upper spectrometer (up to a certain maximum lag). In this study we used a window length of 600 s and a maximum lag of 120 s. The peak in the cross correlation of the two signals is taken to represent the time taken for the plume to rise the separation distance between the two fields of view, in our case a distance of 36.5 m (Figure 2). The rise speeds calculated were smoothed using a low-pass filter before being used in the flux calculation.

The column amounts recorded by each spectrometer in the DW-FOV DOAS system represent the mean column amount across its field of view at the distance of the plume [*Boichu et al*., 2010]. The SO_2 flux, ϕ, can therefore be expressed as:

$$\phi = \frac{10^4 M}{N_{Av}} A_{\mathrm{lower}} D v \theta_{\mathrm{WFOV}}, \tag{1}$$

where M is the molar mass of SO_2 in kg mol^{-1}, N_{Av} is Avogadro's number, A_{lower} is the column amount recorded by the lower spectrometer in molecules cm^{-2}, D is the horizontal distance to the plume in meters (see Figure 2), v is the rise speed in m s^{-1}, and θ_{WFOV} is the field of view of the spectrometer in the horizontal (wide) direction in radians.

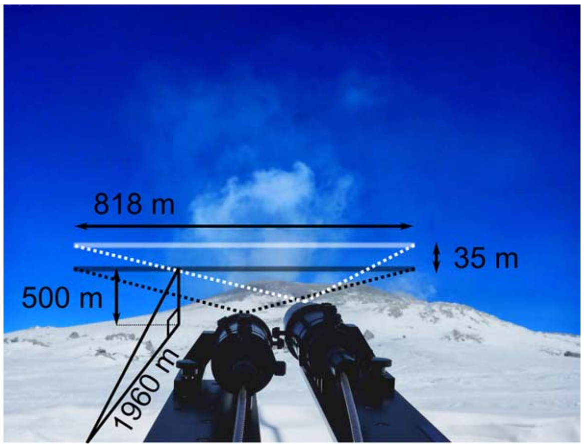

Figure 2. Photograph showing the plume conditions on 14 December 2013, with annotations describing the viewing geometry of the DW-FOV DOAS instrument. Although the plume is rising approximately vertically, there is a certain amount of grounded plume around the crater which will cause the instrument to overestimate the SO_2 flux.

Note that our equation for flux differs slightly from that of *Boichu et al*. [2010], since we have accounted for the increased path length through the plume due to the inclined viewing angle. This results in an additional $cos(\alpha)$ term, which cancels with that in the expression used by *Boichu et al*. [2010]. We use the column amounts recorded by the lower spectrometer in our flux calculation to minimize the distance above the lake that we are measuring.

The weather conditions at the summit of Erebus on 14 December 2013 were clear, with no clouds within the fields of view of the spectrometers and light winds of between 1 and 3 m s^{-1}. The plume was rising approximately vertically for a few hundred meters above the crater rim, before drifting sideways with the wind. However, as can be seen in Figure 2, the plume was somewhat "messy" with a certain amount of stagnated gas within the fields of view of the spectrometers. While this will not adversely affect the rapid variations in SO_2 flux that we are interested in, it is important to realize that the fluxes reported here may be overestimates. Light-dilution and multiple scattering [e.g., *Kern et al*., 2009] can also cause significant errors in SO_2 flux measurements made using UV spectroscopic techniques. The viewing conditions did not change significantly during the period of measurement, and therefore these errors are likely to be constant across the ~10 min cycles in flux.

3.3. Gas Composition

Open-path absorption spectra of the gas emissions were collected with a MIDAC Corporation M-4402-1 FTIR spectrometer sited on the crater rim, with the lava lake, ~330 m line-of-sight distant, acting as infrared source [*Oppenheimer and Kyle*, 2008; *Oppenheimer et al*., 2011]. All interferograms were recorded with a time step of 1.7 s and a nominal 0.5 cm^{-1} spectral resolution. The measurements presented here were made in December 2013. Retrievals of the species recognized in the absorption spectra were made from transformed interferograms using a code that simulates and fits atmospheric transmittance in discrete wavebands [*Burton et al*., 2000], specifically 2020–2100 cm^{-1} for H_2O, CO_2, CO, and OCS. Uncertainties on these measurements are typically about 5% [e.g., *Horrocks et al*., 2001]. Gas ratios are calculated from the raw column amounts after corrections are made for contributions of atmospheric water and CO_2 [*Oppenheimer and Kyle*, 2008]. This procedure works particularly well in this setting owing to the hyperarid background atmosphere.

We inspected the ratios of all possible pairs of the seven magmatic gas species detected and found that the CO_2/OCS ratio most clearly revealed the cyclic variation sought. We have therefore focused on this quantity for the purposes of the multiparameter intercomparison sought here.

3.4. Lava Lake Surface Elevation

An Optec ILRIS 3D terrestrial laser scanner was used to survey the lava lake surface from the same location on the crater rim as the thermal camera and FTIR spectrometer. The scanner uses a near-infrared laser (1535 nm wavelength), with a scanning frequency of 2.5 kHz. At a distance of 300 m (the approximate distance to the lake's surface), the spot diameter of the laser beam is ~7 cm. The scanner was connected to a Trimble GPS pulse-per-second signal to provide accurate time stamps for each data point.

The data used in this study consist of a series of repeated 30 s duration scans, focused on the lava lake surface. Scan data from within a circular region of 4 m diameter, approximately centered in the middle of the lake, are averaged and used as a measure of lake surface elevation. The density of points within the averaged region is variable due to changing plume conditions; however, it typically contains around 90 measurements. The time taken to record these measurements ($<$2 s) is small compared to the time scale of change in lake surface elevation.

4. Results

Although cyclic behavior is observed in many of the gas ratios measured with the FTIR (T. Ilanko et al., Cyclic degassing of Erebus volcano, Antarctica, submitted to *Bulletin of Volcanology*, 2014), in the 2013 data set they are most apparent in the CO_2/OCS ratio time series and we therefore use this ratio to characterize the changing gas chemistry. Figure 3 shows four 3 h time series of mean lake surface speed and CO_2/OCS ratio from 6, 12, and 13 December 2013. Each 3 h sequence contains a large (lake-emptying) explosion. These are highlighted, and inset sequences of thermal images show the progression of each event with a $\sim$2 s time step. The correlation between the gas ratio and speed data is striking and clearly demonstrates that the cyclic behavior of the two properties must be inherently linked. Periods where there is no obvious correlation (e.g., around 16:00 on 12 December) correspond to times where there are no appreciable cycles in the time series.

The large explosions shown in Figure 3 do not appear to have any significant impact on the cyclic behavior of the lake. Following a short period ($\sim$5 min, corresponding to the time scale of lake refill) of elevated speed and CO_2/OCS ratio, both time series are seen to return to similar values as prior to the explosion and resume their pulsatory behavior. No obvious changes in the period or amplitude of the cycles following an explosion are apparent.

Figure 4 shows a little over 2 h of SO_2 flux, CO_2/OCS ratio, and mean lake surface speed data collected on 14 December 2013. The SO_2 flux data have been offset by -3 min to account for the time taken for gas emitted at the lake's surface to rise to within the DW-FOV DOAS instrument's field of view, a distance of $\sim$500 m (the mean rise speed measured with the DW-FOV DOAS was 2.7 m s^{-1}, giving a rise time of $\sim$3 min from the lake's surface to the field of view of the DW-FOV DOAS instrument). However, it is important to realize that this is an approximation, and the true delay time will be a (possibly nonlinear) function of time. The correlation of the SO_2 flux with the other signals is contingent on inhomogeneities in gas flux at the lake's surface rising coherently until they can be measured with the DW-FOV DOAS. Turbulence and mixing in the lower portions of the plume are likely to disrupt any structure in the emissions from the lake, and we believe that this may account for the rather poor correlation of the data series at some times. Despite this, the general agreement between the three time series is compelling and provides very strong evidence for the fluctuations in SO_2 flux being driven by the same underlying mechanism as those in the gas composition and lake surface motion. Peaks in SO_2 flux are observed to coincide with peaks in lake surface speed (e.g., at 03:38 UTC). However, given the uncertainty in the time delay between gas being emitted from the lake to when it is measured, particularly since this will vary with time, it is not possible to investigate the alignment of peaks in any greater detail, and there may well be short lags between the signals which are not resolvable. There were no explosions during the acquisition period of the SO_2 flux data, so we cannot comment in detail on how they might influence the flux. However, data collected in 2005 using a scanning UV spectrometer system indicate that explosions are associated with an ephemeral increase in SO_2 flux (MEVO 2005 field report, unpublished).

A $\sim$7 h time series of mean lake surface speed and lake surface elevation recorded on 17 December 2012 is shown in Figure 5. Again, the correlation between the cyclicity in both properties is readily perceived. The sequence of IR images in the figure shows the progression of the large bubble burst that occurred at 17:24 UTC. Immediately following the explosion, there is a $\sim$2 min gap in the TLS acquisition due to the lake being obscured by the fumes from the explosion. The lake is then seen to refill rapidly over the next $\sim$3 min and subsequently resume a pulsatory behavior indistinguishable from that exhibited prior to the explosion. This recovery time is consistent with that of the large bubble events highlighted in Figure 3 as is the fact that the pulsatory behavior does not appear to be influenced by the explosions beyond the time scale of lake refill. It is worth noting, however, that a longer recovery time was observed for a large explosion by *Jones* [2013].

Also evident in Figure 5 is that the peak in surface speed occurs after the peak in surface elevation. Figure 6a shows the results of a windowed cross correlation of the two series (as described in section 3.2) using a

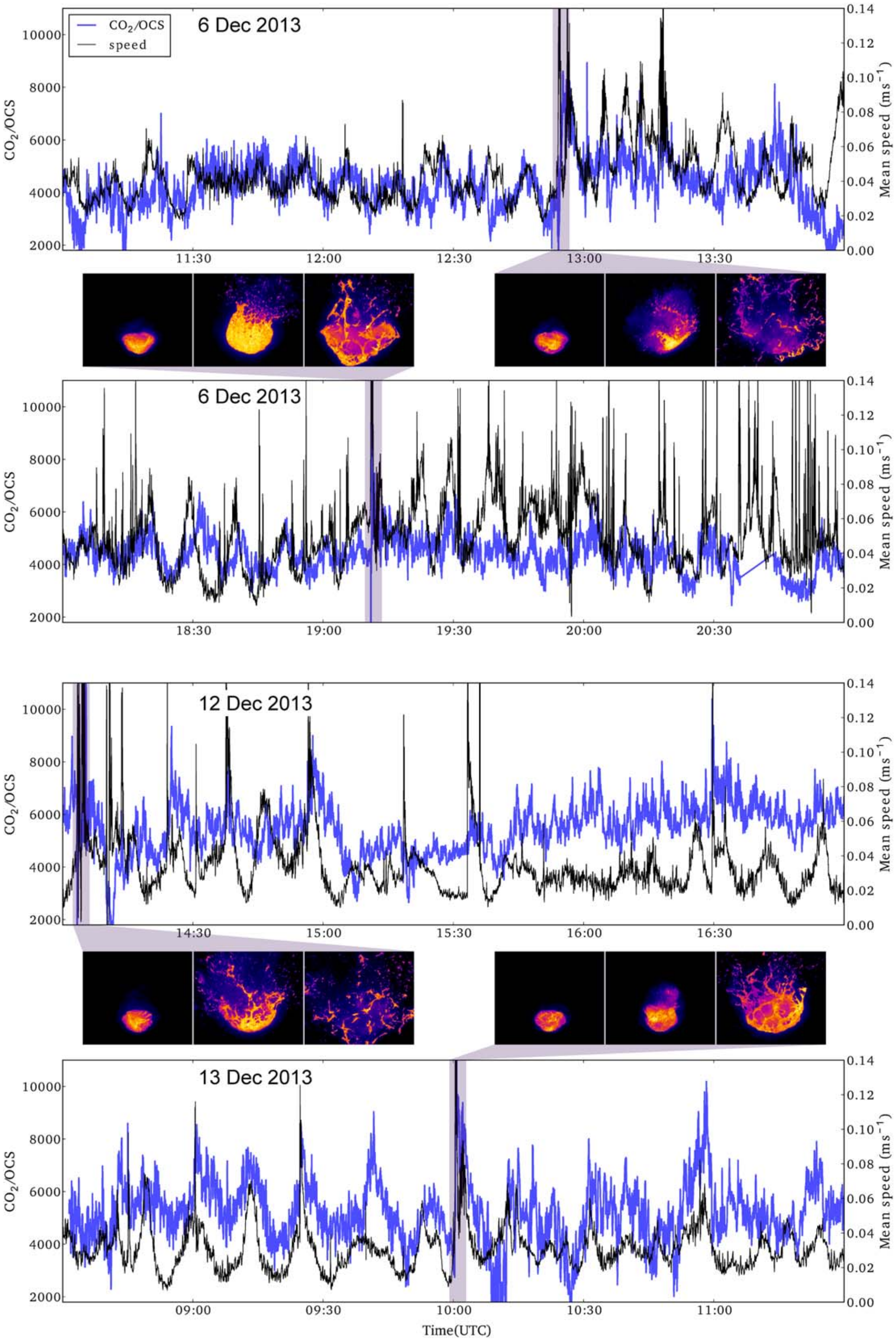

Figure 3. Comparison between the CO_2/OCS molar ratio measured with the FTIR and the mean speed of the lake surface. IR images show the progression of explosive events at a ~2 s time step.

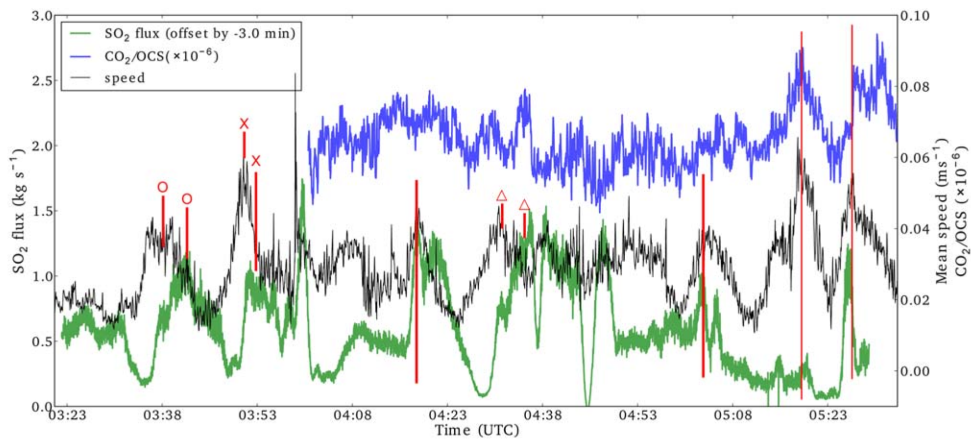

Figure 4. Data collected on 14 December 2013 showing the correlation between SO_2 flux, CO_2/OCS molar ratio, and the mean speed of the lava lake surface. Cycles with particularly good correlation are highlighted with vertical red lines, where there is a lag between the correlated peaks, and corresponding red lines are labeled with matching symbols.

window length of 1200 s and shows that the surface speed typically lags the surface elevation by 1–3 min. This contrasts with the relationship between the surface speed and CO_2/OCS ratio (Figure 6b), which are generally in-phase with each other. Periods when the time series were very dissimilar and could therefore not be cross correlated successfully (e.g., due to the explosion at 17:24 on 17 December 2012) have been omitted from the figure for clarity.

5. Discussion

Given the apparent complexity of Erebus's shallow magmatic system [e.g., *Zandomeneghi et al*., 2013] and the sensitivity of multiphase flows to small changes in system parameters [e.g., *Molina et al*., 2012], the regularity and longevity of the cyclic behavior of the lava lake is somewhat surprising. That such disparate methodologies as FTIR spectroscopy, motion estimation, and DW-FOV DOAS are not only all capable of independently detecting this behavior but also demonstrate such a striking correlation with each other is

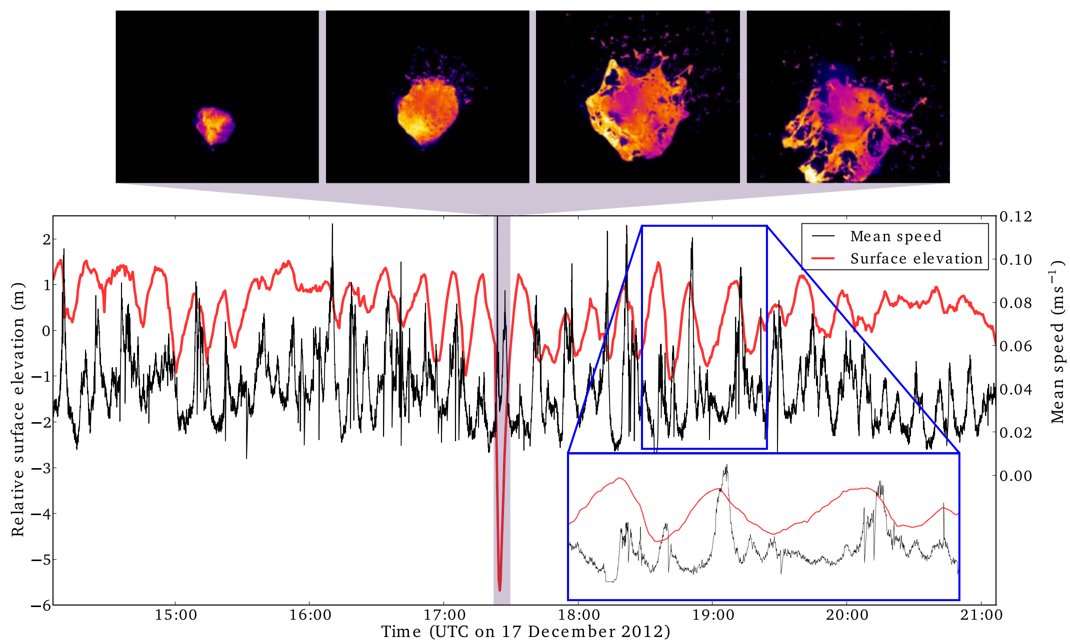

Figure 5. Data from 17 December 2012, showing the surface elevation of the lake (measured using TLS) and the mean surface speed (estimated from IR images). The expanded section highlights the time lag between the two time series. IR images show the progression of a large explosion that occurs at 17:24 with a time step of ∼2 s.

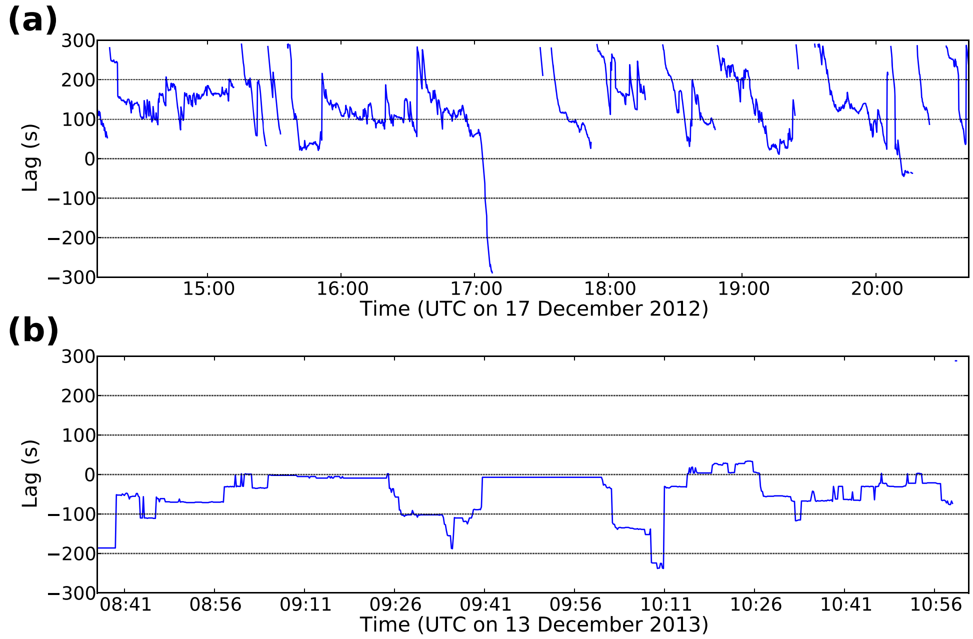

Figure 6. Results of a windowed cross correlation using a window length of 1200 s of (a) the lake surface speed and the surface elevation on 17 December 2012; (b) lake surface speed and CO_2/OCS molar ratio on 13 December 2013. The plotted data are the lags corresponding to the maximum in the cross correlation at each time step and therefore represent the lag between the two data series.

remarkable, particularly given the challenging conditions under which the data were collected. The correlation between the different data provides persuasive evidence that the cycles are not an artifact of the measurement techniques.

Figure 6 shows that the cycles in CO_2/OCS ratio are in-phase with those in the lake's surface speed. In other words, the CO_2/OCS ratio reaches its peak when the lake motion is most vigorous, and its trough when the lake is most sluggish. This raises the important question as to why the CO_2/OCS ratio is varying. A comprehensive analysis of the gas composition cycles is forthcoming in T. Ilanko et al. (submitted manuscript, 2014), but we note here that the two species are related through the following redox equilibrium:

$$3CO+SO_2 \rightleftharpoons 2CO_2+OCS, \tag{2}$$

whose equilibrium constant, K_1, is given by:

$$K_1=\frac{x_{OCS}{x_{CO_2}}^2}{{x_{CO}}^3 x_{SO_2}}\cdot P^{-1}, \tag{3}$$

where x_a is the mole fraction of species a and P is the pressure.

We can also consider the equilibrium between CO_2 and CO as follows:

$$CO+\frac{1}{2}O_2 \rightleftharpoons CO_2, \tag{4}$$

for which the equilibrium constant is given by:

$$K_2=\frac{x_{CO_2}}{x_{CO}\sqrt{f_{O_2}}}. \tag{5}$$

Rearranging, we can write the CO_2/OCS molar ratio as:

$$\frac{x_{CO_2}}{x_{OCS}}=\frac{{K_2}^3}{K_1}\cdot\frac{{f_{O_2}}^{\frac{3}{2}}}{x_{SO_2}}\cdot P^{-1}. \tag{6}$$

There are thus several factors that can influence the CO_2/OCS ratio, including temperature (the equilibrium constants are temperature-dependent), oxygen fugacity, and pressure, in addition to the mole fraction of

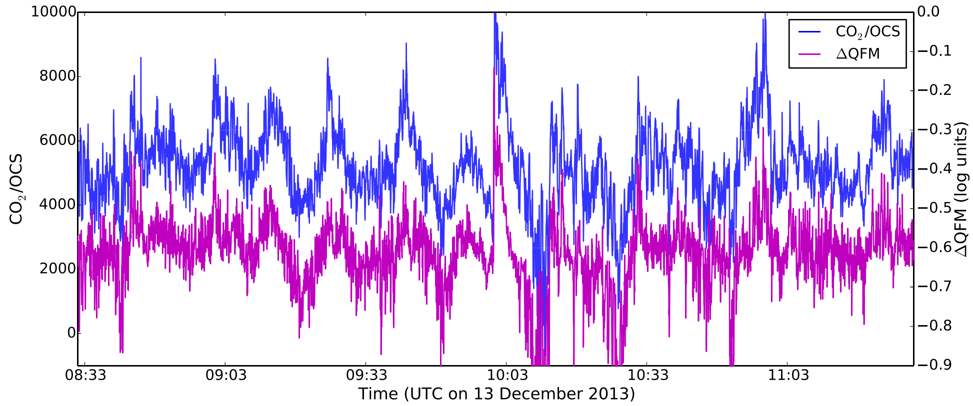

Figure 7. Comparison of the CO_2/OCS molar ratio on 13 December 2013 and the computed oxygen fugacity at which the gas equilibrated (relative to the QFM buffer).

SO_2 in the gas phase (itself dependent on redox conditions, temperature, and pressure). The system is underdetermined but can be solved if we assume (i) the measured gases represent an equilibrium composition, and (ii) one of the unknown parameters. In this case, we make the assumption that the gases are equilibrated at atmospheric pressure. This enables us to compute, spectrum by spectrum, the equilibrium temperature and oxygen fugacity. Under these assumptions, we may conclude that the cycles represent variation of approximately 0.1 log units relative to the rock buffer Quartz-Fayalite-Magnetite (QFM; Figure 7). This does not explain the origin of this variation but provides compelling evidence for a close association between magma degassing, redox conditions, and the fluid dynamics of the lava lake.

Measurements made by *Ripepe et al*. [2002] on Stromboli revealed a correlation between increased explosive activity and intensified gas puffing. Periods where degassing consisted of vigorous puffing were found to coincide with a high number of Strombolian explosions, whereas periods with a low number of Strombolian events were characterized by fewer, lower-velocity gas puffs. Stromboli alternates between these two different degassing regimes on time scales of 5–40 min, not dissimilar to the $\sim$5–18 min cycles in SO_2 flux observed on Erebus. *Ripepe et al*. [2002] proposed that the observed behavior at Stromboli was due to changes in the gas supply rate into a shallow foam layer. On Erebus, however, no correlation between explosive activity and passive degassing behavior is observed. Large (decametric) bubbles are too infrequent to correlate with the cyclicity in the gas flux. For example, cyclic variations in SO_2 flux were observed in the data presented in Figure 4, during a period when no large bubbles were recorded. Although smaller (meter-scale) bubbles occur on a similar time scale to that of the cycles in SO_2 flux, these have been found to be uncorrelated with the fluctuations in surface speed [*Peters et al*., 2014a] and by inference therefore, also with variations in the gas flux. Explosive activity on Erebus appears to be entirely decoupled from its passive degassing behavior. This is consistent with the findings of *Burgisser et al*. [2012], who propose that while explosive degassing at Erebus is due to rupture of gas bubbles that rise from depth independently of the melt, its passive degassing is dominated by exsolved and exsolving volatiles from magma in the lake itself. This would suggest that the fluctuations in SO_2 flux observed at Erebus (Figure 4) are due to changes in supply of gas-rich magma into the shallow system. However, in contrast to the mechanism proposed by *Ripepe et al*. [2002] for Stromboli, we argue that significant gas accumulation at a shallow level does not occur at Erebus. This prevents large bubbles from forming in the shallow system due to coalescence, allowing significant changes in SO_2 flux without any changes in explosive activity.

A high degree of gas permeability of the Erebus lava lake was also proposed by *Peters et al*. [2014a]. This argument can be strengthened by considering the emissions that occur during a single cycle. From the TLS data (e.g., Figure 5) we can see that a change in surface elevation of $\sim$2 m is typical during a single cycle. Treating the upper part of the lake basin as cylindrical, with a surface area of $\sim$400 m^2 (its 2012 size), this represents a volume change of 800 m^3. The additional amount of SO_2 released during a single cycle (above the background SO_2 emission rate) is $\sim$5300 mol (found by integrating the flux data in Figure 4). FTIR measurements indicate a typical SO_2/total gas molar ratio of $\sim$113, giving a total gas output of 1.4×10^4 m^3 in a single cycle (assuming standard temperature and pressure). These results are summarized in Figure 8, which

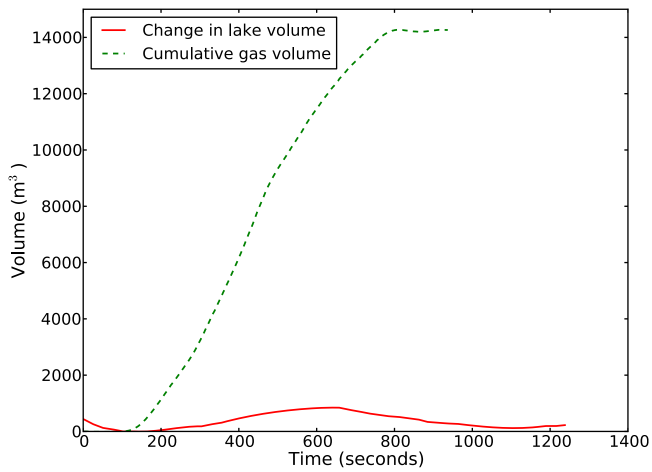

Figure 8. Comparison of the volume change of the lava lake and the additional volume (at atmospheric pressure) of gas released (above the background level) during a single cycle.

shows a comparison between the volume of gas released and the volume change of the lake during a single cycle. It should be noted that overlapping SO_2 flux data and TLS data are not yet available, and so while the lake volume data are from 17 December 2012, the gas volume data are calculated from SO_2 flux data recorded on 14 December 2013. However, since interannual variability in surface elevation variations and SO_2 flux is small at Erebus [*Sweeney et al.*, 2008; *Jones*, 2013], it is reasonable to compare these data. The data show that the total volume of gas released during a single cycle is an order of magnitude greater than the volume change of the lake, supporting the argument that the lake must be highly permeable to gas.

The 1–3 min lag between the peak in surface motion (and therefore also in gas composition) and the peak in surface elevation may be indicative of the dwell-time of gas in the lake. The lag may be explained by the time taken for fresh pulses of magma injected into the lake to rise to the surface, but this would suggest that gas escaping at the surface has traveled with the melt rather than rising independently through the lake. It is important to remember however, that even at the low-point of the cycles there is a net gas flux. If bubbles are not rising independently of the melt, then there must be a sustained transfer of magma to the surface of the lake. Since the surface motion is not seen to stagnate, this seems feasible. However, the definition of "surface" in this argument is rather unclear, and it is not yet possible to constrain either the depth at which magma motion might influence the surface motion measured with the thermal camera, or the depth at which the gas might separate from the magma.

Witham and Llewellin [2006] showed that stable lava lake systems would rapidly return to equilibrium following a perturbation. This is indeed what is observed in the Erebus lake, with a rapid return to "normal" behavior following explosive events. It is interesting to note that the refill following an explosion does not appear to "overshoot" the maximum lake level reached during periods of quiescence. Recovery from an explosion is rapid and shows that the response of the lake system to a perturbation is much faster than the time scale of the pulsatory behavior. This would suggest that the recorded waveform of the cycles in surface elevation (which must be a convolution of the lake's response function and the driving mechanism's waveform) are representative of the underlying process responsible for the cycles and has not been overly smoothed due to a sluggish response of the lake system. Although the waveforms of the surface motion and gas composition indicate that the observed cyclicity is caused by periodic perturbations to a system that is otherwise at equilibrium [*Peters et al*., 2014a], the surface elevation appears to be approximately symmetric about its mean, indicating a system that is oscillating about its equilibrium state. It seems likely that the surface elevation of the lake is a more "direct" measure of the underlying process responsible for the pulsatory behavior, and we therefore believe it to be an oscillatory mechanism rather than an impulsive one. One possible explanation is that the base of the lake is maintained at magmastatic equilibrium. Fluctuations in surface elevation balance changes in the bulk density of the lake caused by injection of bubbly (lower density) magma from the conduit, and gas loss at the surface.

Peters et al. [2014a] noted that while the cycles in surface speed were not always clear, there did always appear to be some periodicity present, concluding that the pulsatory behavior was a sustained feature of the lake. These findings are supported by the data presented here. In particular, Figure 5 (e.g., between 20:10 and 21:00) demonstrates that even when pulsatory behavior in the lake surface level is not evident, there are still clear cycles in the surface speed. A similar phenomenon is shown in Figure 4 (e.g., between

04:08 and 05:08) where cycles are apparent in the surface speed, but not in the CO_2/OCS ratio. It is curious that at different times, cyclic behavior may be present in some properties but not others. We attribute this behavior to the fact that each property being measured is a different surface manifestation of a common underlying periodic (or pseudoperiodic) process. The coupling between the underlying process and the measured quantity could be extremely complex, and also susceptible to other forcing mechanisms. The clearest example of this is the SO_2 flux measurements. Even if the flux of SO_2 is perfectly periodic at the lake's surface, changing atmospheric conditions within the crater will alter how visible this periodicity is at the point of measurement and under certain circumstances plume transport dynamics may dominate the flux, masking the periodic signal entirely. A similar argument may be made for the FTIR measurements, where the measured composition may be influenced by an accumulation of gases within the crater over the time scale of one lake cycle. In the case of the surface elevation and surface speed measurements, it is possible that other processes within the lake (e.g., thermal convection or foam formation) can overshadow the mechanism responsible for the pulsatory behavior, concealing its influence.

The discovery of periodic degassing at Mt. Etna in Sicily [*Tamburello et al*., 2013; *Pering et al*., 2014], raises the possibility that, despite the differences in magma viscosities, the models of magma flow being developed to explain the pulsatory behavior of the Erebus lava lake may be more widely applicable to open-vent volcanoes around the world. However, some care is needed when assessing periodic degassing since it is possible that the development of turbulence within the plume between the vent and the point of measurement (often a few hundred meters) could cause a periodicity in the measured flux, even if the source is constant. In the data presented here, we believe that this is not the case, as it would seem an unlikely coincidence for turbulence effects to be so well correlated with the cycles occurring in plume chemistry and lake surface motion.

6. Conclusions

We have presented measurements made during December 2012 and December 2013 of the SO_2 flux, CO_2/OCS ratio, surface elevation, and mean surface speed of the Erebus lava lake. Well-established methodologies (UV and FTIR spectroscopy, TLS and motion estimation from thermal imagery), which have been used during numerous previous field campaigns on Erebus, were employed. However, the unprecedented overlap in the time series presented has enabled us to show for the first time a definitive link between the pseudoperiodic fluctuations observed in each of these properties. Cycles (with an approximate period of 10 min) in SO_2 flux, CO_2/OCS ratio, oxygen fugacity, and mean surface speed were shown to be correlated, and in-phase with each other, providing strong evidence for a common underlying mechanism. The cycles in surface speed were found to lag cycles in surface elevation by 1–3 min. The volume of gas released during a single cycle (above the background gas flux) is an order of magnitude greater than the associated change in lake volume. This suggests that gas is effectively lost from the lake as soon as it has entered. Large explosions appeared to have no appreciable effect on the pulsatory behavior observed, at least beyond the time taken for the lake to refill to its normal level ($\sim$5 min). However, insufficient events were analyzed to rule out the possibility of subtle changes to the behavior caused by large gas bubbles, leaving this as an interesting avenue for future investigation.

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