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Pulsatory magma supply to a phonolite lava lake

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ABSTRACT

A few lava lakes, like that at Erebus volcano, Antarctica, have been continuously active for decades, reaching a steady-state. We report spectroscopic and thermal observations from Erebus that reveal remarkable, phase-locked cycles of lava lake convection and gas plume composition. We argue that the observed fluctuations in gas ratios, including the SO_2/CO_2 content in the plume, identify two end-member contributions to the Erebus emission: a sustained source of CO_2-rich gas percolating through permeable conduit magma, and a shallower source of H_2O-rich gas exsolved from magma pulses that periodically enter the lava lake. The unstable magma flow may reflect the viscosity stratification between rising and descending magma in the conduit, and the resulting oscillatory behaviour of the phonolite lake exemplifies the relative roles of closed- and open-system degassing in persistently active volcanoes.

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1. Introduction

Volatiles exert fundamental controls on the physical properties of magma and thus on the chemical evolution, storage and transport of magmas. Ultimately, the behaviour of volatiles influences the style, magnitude and duration of eruptions. The relationships between degassing and magma rheology can also initiate feedbacks between magma dynamics and eruptive style (e.g., Voight et al., 1999). Vesiculation has a profound effect on the permeability of magmas (e.g., Burton et al., 2007; Mueller et al., 2008; Polacci et al., 2008), and can permit gas to percolate through a conduit. In this way, even highly viscous silicic and intermediate magmas can degas non-explosively (e.g., Eichelberger et al., 1988). Variations in, and pressurization feedbacks between, magma ascent rate, crystallisation, and open- *vs* closed-system degassing can also account for rapid transitions between explosive and effusive eruption style (e.g., Barmin et al., 2002; Slezin, 2003; Namiki and Manga, 2008). Knowledge of the relationships between magma ascent and degassing is therefore crucial to understanding volcano behaviour.

Lava lakes represent the exposed tops of magma systems and thereby provide an opportunity to observe directly the dynamics of magma transport and to infer degassing processes (Tazieff, 1997; Oppenheimer et al., 2004). The decadal persistence of some lava lakes, with no net effusion of lava beyond the lake, is best explained by bidirectional flow of magma in the feeder conduit (Francis et al., 1992; Kazahaya et al., 1994; Stevenson and Blake, 1998; Huppert and Hallworth, 2007). Convection is driven by density contrasts that can arise from combinations of degassing, crystallisation and cooling (Harris, 2008). In such a way, lava lakes provide an efficient means for magma to degas while limiting the accompanying heat loss.

One of the best-known lava lakes is found at an elevation of ~3510 m in the summit crater of Erebus volcano, Ross Island, Antarctica (Fig. 1a). It is fuelled by anorthoclase-bearing phonolite magma (Giggenbach et al., 1973; Kyle et al., 1992), and was only discovered in the early 1970s, though it may well have existed for a century or more (Oppenheimer and Kyle, 2008). Since 2001, the lake has had a diameter of ~30–35 m and a surface area of ~770 m^2 (Csatho et al., 2008). The lake continuously emits a plume of gases and aerosols (Radke, 1982; Rose et al., 1985; Chuan et al., 1986; Zreda-Gostynska et al., 1997). Indeed, longevity and stability are terms that capture well the essence of the volcano's behaviour: spaceborne infrared observations made between 2001 and 2006 revealed an astonishingly stable radiant heat flux from the lake of 15 ± 8 MW (Wright and Pilger, 2008). Furthermore, the chemical and isotopic composition of the magma in the lake has remained unchanged since the 1970s (Kelly et al., 2008; Sims et al., 2008). The system is only perturbed transiently by sporadic Strombolian eruptions (Aster et al.,

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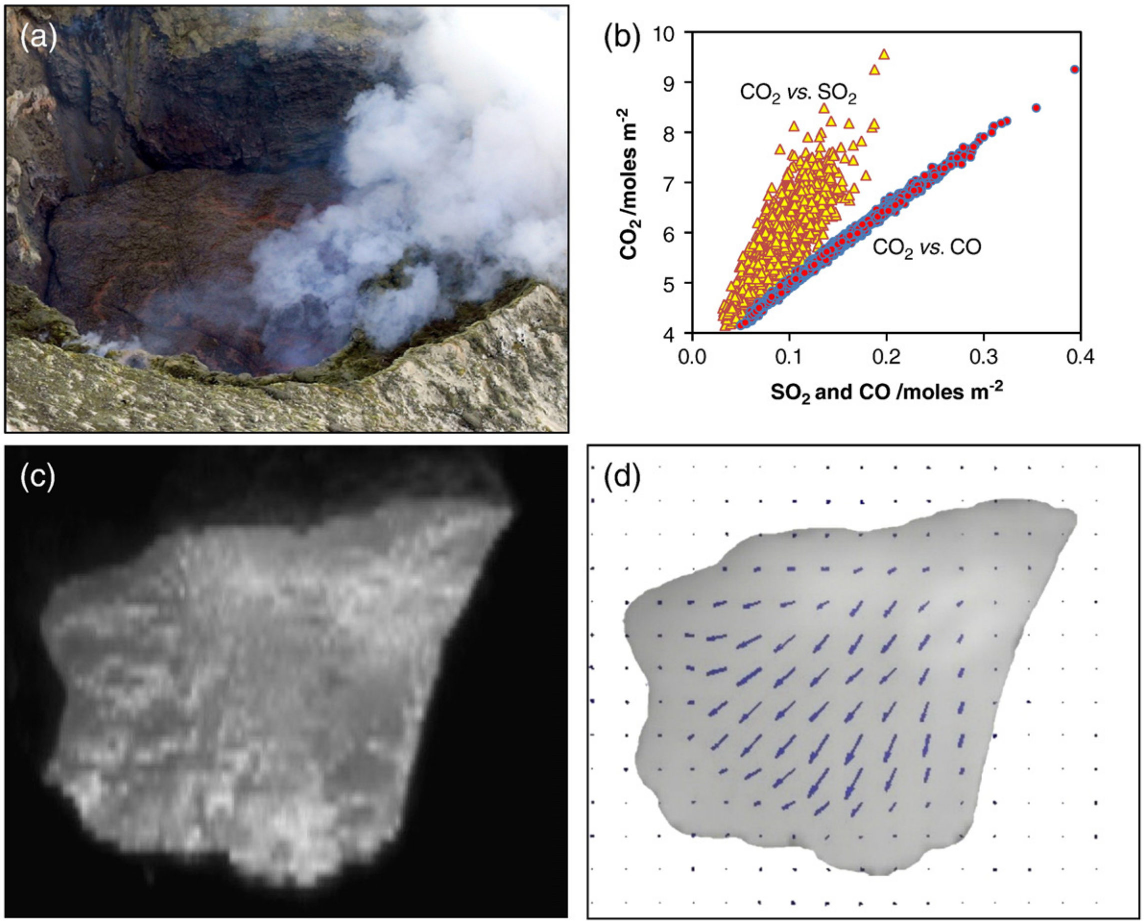

Fig. 1. (a) Photograph of the lava lake on 10 December 2004 taken from the observation point from which all thermal imagery and FTIR spectra were collected. (b) Representative retrievals of FTIR spectra recorded on 17 December 2004 showing correlation between CO_2 and CO (red circles), and CO_2 and SO_2 (yellow triangles). Note the high correlation of CO_2 and CO is controlled by oxygen fugacity and temperature of phonolite in the lake. The scatter for CO_2 *vs.* SO_2 is a function of mixing of deeper- and shallower-sourced gases. (c) Example of orthorectified thermal image of the lava lake. The image is masked at $T=600$ K to highlight the lake, and random noise substituted for the background to aid in image matching. (d) Typical output of lake surface velocities from which mean and peak speed, and mean direction have been derived. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2003, 2008; Gerst et al., 2008). These sometimes evacuate the lava lake revealing a funnel shaped crater ~20 m deep tapering to a single vent (uppermost conduit) of 5–10 m diameter (Dibble et al., 2008). (Importantly, this confirms that there is only one route for convecting magma to enter and leave the lake.) Assuming the shape of a right cone, the volume of lava in the lake is ~5000 m^3. Based on the melt composition, estimated dissolved H_2O and F contents of 0.39 and 0.31 wt.% (Eschenbacher, 1998), respectively, and the observed magmatic temperature (1273 K), we calculate that the melt viscosity is ~10^4 Pa s using the model of Giordano et al. (2008). This is substantially greater than the magma viscosities of the other renowned lava lakes at Nyiragongo (Democratic Republic of the Congo) and Erta 'Ale (Ethiopia), reflecting the petrogenesis of the Erebus phonolite.

Here we analyse time-series of thermal imagery of the Erebus lake along with measurements of the gas composition of the emitted plume. The data were collected in December 2004. While our initial motivation was to investigate the correspondence between heat and gas output, we discovered that the thermal imagery also enabled measurements of the surface motion of the lava lake. These revealed striking oscillations that we also recognized in gas ratios. The observations, in some respects, were counter-intuitive. We report the data set here, and use them to build a conceptual model for the magma and gas flow in the upper conduit and lake, based on the theoretical framework provided by studies such as that of Huppert and Hallworth (2007). The findings provide a rich illustration of shallow magmatic processes occurring at Erebus, and highlight the ability of high-time resolution geochemical and thermal observations to "image" magmatic plumbing systems.

2. Methods

All the observations reported here were made from the crater rim of Erebus, ~300 m distant from the lava lake (measured with laser-ranging binoculars). Open-path absorption spectra of the gas emissions were collected using a MIDAC Corporation Fourier transform infrared (FTIR) spectrometer using the lava lake itself as the infrared source, as described by Oppenheimer and Kyle (2008: Fig. 1b). Column amounts of H_2O, CO_2, CO, SO_2, HCl, HF and OCS were retrieved from FTIR spectra (collected every 8 s by co-adding eight consecutive interferograms) using a code (Burton et al., 2000, 2007) that simulates and fits atmospheric transmittance in discrete wavebands. Gas composition in mol% was then calculated by normalising each suite of retrieved gases to 100%. (This represents a very good approximation since H_2 is the only unrecorded species likely to be present at around the 1 mol% level).

Thermal imagery of the lake (Fig. 1c) was acquired with an Agema "Thermovision" 3–5 μm, 320×280 pixel camera as described by Oppenheimer et al. (2004) and Calkins et al. (2008). The infrared images, which were recorded with a 10 s time-step, were orthorectified, and masked using a threshold temperature of 600 K to isolate the lava lake. We derived radiative heat losses (uncorrected for atmospheric

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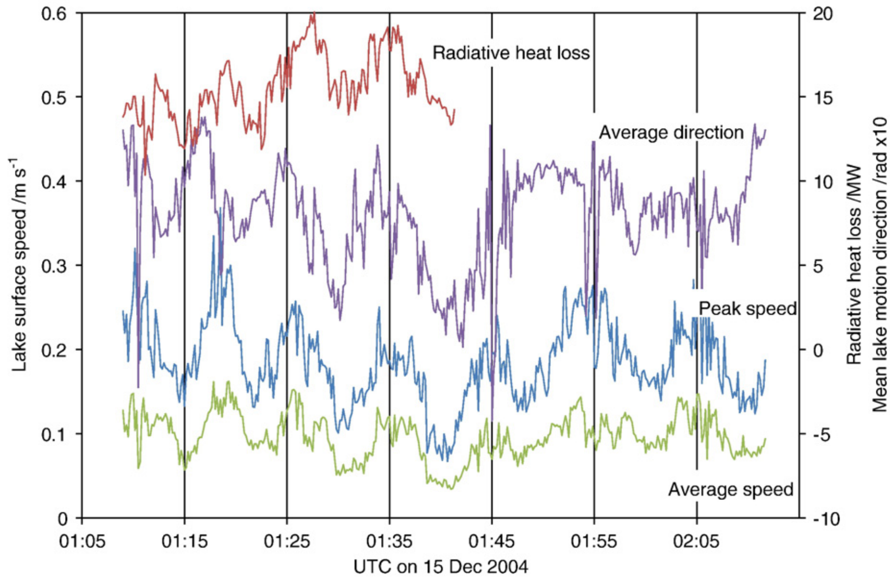

Fig. 2. Representative sequence showing radiative heat loss, peak and mean lake surface speeds and mean direction of flow, calculated from thermal imagery. The cycles in lake surface velocity are apparent in almost all the data collected but the thermal patterns are generally weaker due to the intermittent passage of fumes within the field of view of the thermal camera (which attenuate the signal and depress apparent temperatures). Only a portion of heat loss data is shown to highlight the clear signal recorded during good viewing conditions. The lake surface direction cycle has a more variable phase compared with the surface speed.

transmission) from the lava surface using the Stefan–Boltzmann law. We also produced maps of the velocity of the lake surface (Fig. 1d) from successive frames using an image matching algorithm based on the complex wavelet transform (Kingsbury, 2001), and used in medical imaging (Hemmendorff et al., 2002). This procedure worked well for the Erebus thermal imagery thanks to the continuous migration of incandescent cracks across the lake surface, combined with the strong thermal contrast between the cracks and the adjacent, much cooler crust. To minimize the boundary effect of the steep temperature gradient at the lake periphery, the threshold mask was substituted with a mid grey level with random noise added to introduce texture. To further reduce any risk of edge effects, the velocity time-series presented below were derived from a central rectangular region covering ~50% of the lake surface and well clear of the margins.

3. Results

The several time-series of lake motion calculations reveal an unmistakeable pulsatory behaviour, shown in Fig. 2 in the mean and peak surface speeds, the mean direction, and the radiative heat loss to the atmosphere. The pulses or cycles in surface velocity are observed in most of the (discontinuous) 7 h of recordings of the lava lake that we

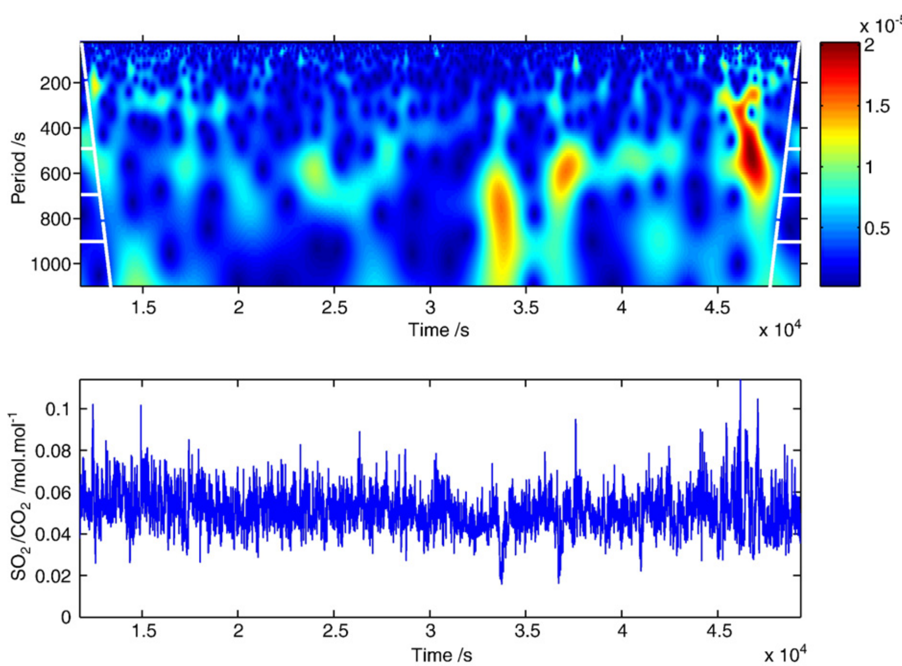

Fig. 3. Over 10 h of continuous FTIR spectra of the lava lake were recorded on 18 December 2008. The SO_2/CO_2 molar ratios retrieved from these data are shown in the lower panel, while the upper panel displays the Morlet Wavelet transform computed from the geochemical time-series. Note the strong transform modulus that emerges intermittently, particularly at a timescale of ~600 s. The white dashed regions of the plot are prone to artifacts arising from boundary effects.

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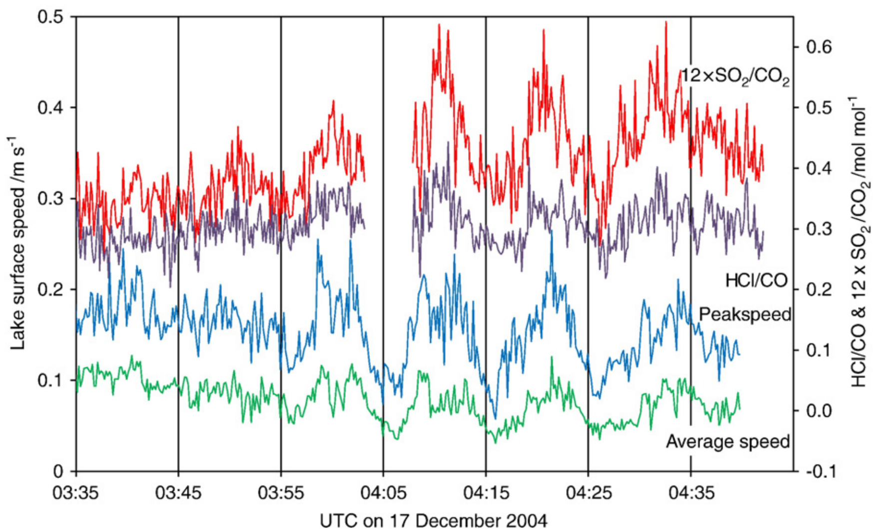

Fig. 4. Time series of simultaneous measurements of SO_2/CO_2 and HCl/CO ratios (mol mol^{-1}) retrieved from FTIR spectra, and peak and mean lake surface speeds derived from thermal imagery. This pattern is also discernible in other gas species ratios. Note in the first 20 min of the record that the lake surface motion is stable, suggesting a hiatus or reduction in magma influx. Cycles resume in the SO_2/CO_2 content ahead of change in the lake motion suggesting the first pulse in the resumed magma input is insufficient to perturb the convective stability of the lake.

obtained. They are roughly symmetric with periods ranging from ~4 to 15 min. We are unable to discern any unambiguous evolutionary pattern in this period but in some intervals it is fairly constant (as seen in Fig. 2). The modal period is ~10 min and the arithmetic mean period of all measured oscillations is 8.8 ± 3.0 (1σ) min. Mean surface speeds range from 5 to 15 cm s^{-1}, with an overall average of ~10 cm s^{-1}. The peak speeds reach 35–40 cm s^{-1}. The amplitudes of the peak and mean speed waveforms are ~10–20 and ~5–10 cm s^{-1}, respectively (Fig. 2). The mean direction of surface motion also varies roughly in phase with the speed fluctuations, with amplitude of 40–50°. The heat flux varies in tandem with the lake speed fluctuations, with amplitude of ~5 MW.

Retrievals of a longer time-series of FTIR spectra reveal subtle cycles in gas composition, with a comparable period of ~10 min. The longest set of continuous FTIR spectra collected spans a 10 h interval on 18 December 2004. The SO_2/CO_2 ratios retrieved for this dataset are shown in Fig. 3 along with the corresponding periodogram obtained using a Morlet continuous wavelet transform. Once again, the pulsatory behaviour, with a characteristic period around 10 min, prevails through much of the record but it is also evident that it is an intermittent state.

Due to challenging field conditions there were unfortunately only a few intervals when the FTIR spectrometer and thermal imager were recording simultaneously (Fig. 4) but these clearly reveal another compelling and intriguing result: that the changes in gas composition were phase-locked with the cycles in lake velocity (and radiative heat loss). Closer inspection of the FTIR spectral retrievals yields representative compositions of the gas emitted at the peaks and troughs of

Table 1
Representative compositions and component fluxes of deeper-sourced “conduit gas” during sluggish movement of the lava lake and the mixed plume emitted from the lake during vigorous convection, and the derived composition of the shallow-sourced “lake gas”.

	Composition of “conduit” gas	Composition of mixed plume	“Conduit” gas flux	Mixed plume flux	Composition of “lake” gas
	(mol%)	(mol%)	(kg s^{-1})	(kg s^{-1})	(mol%)
CO_2	39.72	32.00	11.46	11.73	3.52
H_2O	54.61	61.99	6.45	9.30	89.23
SO_2	1.19	1.50	0.50	0.80	2.64
CO	2.98	2.40	0.55	0.56	0.26
HCl	0.50	0.60	0.12	0.18	0.98
HF	0.99	1.50	0.13	0.25	3.37
OCS	0.01	0.01	0.01	0.01	0.00

the cycles (Table 1). During low surface motion of the lake the gas was CO_2-rich, whereas during more vigorous convection gas emissions were more H_2O-, SO_2- and HF-rich (Table 1).

4. Discussion

We interpret the observed fluctuations in lake velocity and gas output to result from episodic input of partially degassed magma into the lava lake. The pulsatory behaviour reflects a flow instability that develops due to viscosity stratification (Scoffoni et al., 2001) at the interface between upwelling and downwelling magma in the conduit (Fig. 5). This kind of instability in core-annular flows has been recognised in many studies (Joseph et al., 1997) and is illustrated in laboratory experiments for appropriate low Reynolds number flows (e.g., Movie 5 in the supplementary materials of Huppert and Hallworth, 2007). The rapid expansion of bubbly magma entering the lake facilitiates fast buoyant rise of each batch towards the lake surface, driving lake convection, and exposing more incandescent magma to the surface, hence increasing radiative heat output from the lake. This is consistent with the observation from our thermal imagery that peaks in surface motion correspond to increased numbers of pixels with high temperatures (>850 K). The gas exsolved at the top of the conduit and in the lake rapidly separates from the melt and discharges into the atmosphere. We do not resolve any phase offset between the lake convection and gas chemistry cycles, substantiating this interpretation. A comparable case of cyclicity in thermal radiation can be seen in the analysis of infrared image time-series recorded for the lava lake at Erta 'Ale volcano (Spampinato et al., 2008). We note also that oscillations in lava lake level have been conjectured based on the results of laboratory simulations (Witham et al., 2006) and on theoretical arguments (Witham and Llewellin, 2007). In the set of Erebus observations analysed here, the cyclic mode is the prevalent one but it is interupted by intervals when influx of magma into the lava lake is stalled, lower or steadier (Fig. 3).

A likely explanation for the observed variations in gas geochemistry is that they result from mixing of gases derived from distinct sources or from magma following contrasting degassing paths related to the pulsatory magma flow. For instance, one source could be the degassing of magma as it episodically enters the lake, the other from subsequent very low pressure degassing of the lava residing in the lake. In this scenario, given that the pressure and temperature conditions would be very similar for these two sources, for them to

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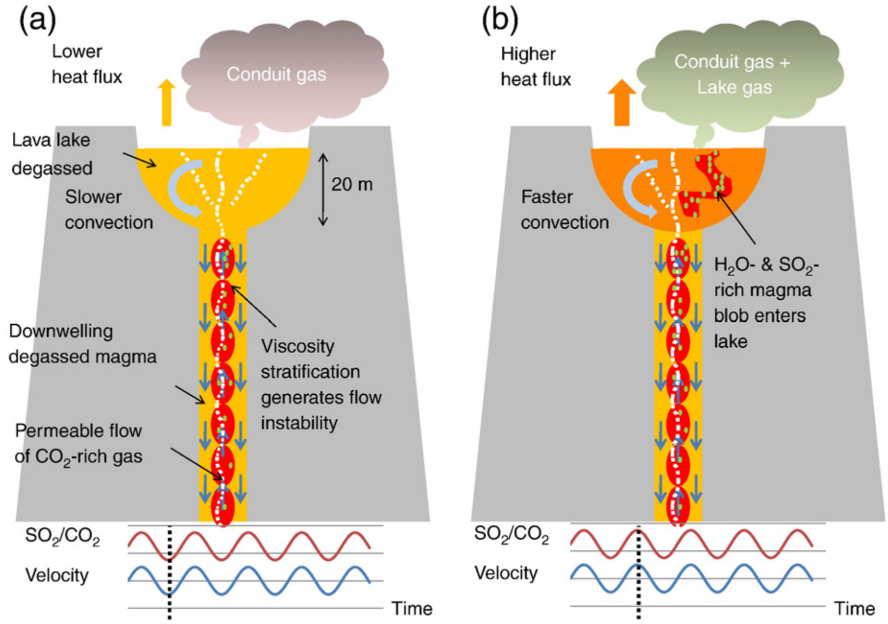

Fig. 5. Cartoons showing a conduit with bi-directional core-annular magma flow. The ascending magma exsolves a water-dominated gas at low pressure and develops a sinusoidal instability due to viscosity stratification at the interface between upwelling buoyant magma and descending higher viscosity, denser, degassed magma. (a) In a quiet phase the lake continues overturning but the gas plume from the surface is mainly sourced by "conduit gas" that percolates to the surface as a result of significant permeability developed by vesiculation. The surface velocity and heat flux are comparatively low. (b) Once a pulse of volatile-rich magma enters the lake it is quickly entrained and degasses a water-rich "lake gas", increasing the bulk plume flux and shifting its chemistry towards a more H_2O-, SO_2- and HF-rich composition consistent with low pressure degassing. The lake convects more vigorously as bubbles rise to the surface and expand, increasing surface speeds and exposing more incandescent magma, which, in turn, increases radiative heat losses from the lake surface. The dashed vertical lines in the two schematic graphs indicate the time in the velocity and degassing cycles that each cartoon (above) refers to. Not to scale.

yield distinct gas signatures would require contrasting degrees of equilibrium achieved by each. However, the observations completely rule out this explanation. Water is relatively soluble in silicate melts and will degas mainly in the shallowest regions of a magma system. On the other hand, CO_2 is much less soluble and exsolves significantly at Erebus at depths of at least ~10 km (Eschenbacher, 1998). If the Erebus gas cycles arose only from degassing of magma entering and residing in the lake, we would expect the peak of the surface velocity cycle to correspond to the maximum proportion of CO_2 in the gas phase. We observe the opposite signal, and can only reconcile this if the plume emitted from the lake is a mixture of a CO_2-rich "conduit gas" and a shallower-sourced, water-rich "lake gas" that is associated with pulses of magma supply to the lake.

Such arrival of CO_2-rich gas at the surface independently from magma batches entering the lava lake requires significant conduit permeability but is entirely consistent with the overall budget of CO_2 and H_2O in the plume: the bulk CO_2/H_2O ratio in the plume is ~2 mol mol^{-1} which is significantly less than the corresponding ratio of ~6 mol mol^{-1} for basanite melt inclusions considered to be the parental melts at Erebus (Oppenheimer and Kyle, 2008). If all the magma yielding the observed plume CO_2 flux reached the lava lake then the water flux should be substantially higher than the 10 kg s^{-1} observed (Oppenheimer and Kyle, 2008).

This explanation is reinforced by the following simple considerations: the residence time of magma in the lake (the ratio of lake volume to magma influx) of ~4 h greatly exceeds the convective timescale for the lake of ~5 min (the ratio of lake size to surface speed). Given the ease with which gas will separate from the vesiculated melt we can therefore expect the lava lake to be essentially degassed; except for magma just supplied from the conduit, the lake contributes very little to the atmospheric plume. This is consistent with frequent visual observations of a distinct, confined source for the plume spanning a small region of the lake surface.

This kind of differential degassing behaviour is recognised elsewhere, famously at Kīlauea volcano (Hawai`i; Gerlach and Graber, 1985; Greenland et al., 1985; Edmonds and Gerlach, 2007). There, the geometry of the plumbing system has resulted in emission of contrasting gases from the summit caldera, which is located a few km above the main shallow magma reservoir, and the sites of flank eruptions fed by intrusions from the main reservoir (such as the East Rift where lava has been erupted continuously since 1983). Volatile-rich, mantle-derived magma arrives in the shallow summit chamber, and is saturated in CO_2. The exsolved CO_2-rich, H_2O-poor fluid degasses through summit lava lakes (when present) or through fumaroles (so-called "type I gas"). The magma, now equilibrated in the summit chamber, passes laterally via dikes that may feed subaerial or submarine eruption sites along the rift systems. These emit a distinct "type II gas", with reversed H_2O and CO_2 contents compared with "type I gas", reflecting the second degassing stage of the now CO_2-depleted magma. Indeed, the water- and SO_2-rich gas emitted by the East Rift eruption sites is predominantly sourced by exsolution at pressures of only 2–3 MPa (Gerlach, 1986). Erebus manages to simulate this kind of fractional degassing through a single vent thanks to subtleties of magma transport and degassing in its shallow conduit.

The FTIR measurements further suggest that the rate at which gas is emitted from the lake changes in phase with lake convection rates: gas column amounts are low when the lake is sluggish and high during vigorous convection. Although gas column amounts are not an ideal proxy for gas flux, this observation is very likely to correspond to a ~10–20 min cycle in SO_2 flux from the Erebus crater identified by UV spectroscopy (Sweeney et al., 2008; Boichu et al., 2009). Taking representative SO_2 fluxes at the peaks and troughs of the cycle to be ~0.8 and ~0.5 kg s^{-1}, respectively (Boichu et al., 2009), and using our retrieved gas compositions (Table 1), we calculate mass balances for each of the gas species measured. We further assume that, in the trough of the lake motion cycle, the plume is sustained primarily by "conduit gas". Evidence for this is seen in the baseline signal for SO_2/CO_2 in the first 10 min or so of the record in Fig. 4, and prior to establishment of the cyclic behaviour; when magma pulses into the lake pause, the plume composition varies little. By differencing the

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component fluxes of the emitted mixed plume and "conduit gas" we estimate the composition of the "lake gas" supplied by magma entering the lava lake (Table 1). This "lake gas" is very water-rich (~89 mol% H_2O) as anticipated, reflecting near surface degassing. The high fluorine sourced in the "lake gas" is also consistent with the relatively high solubility of F in alkaline magmas and consequent shallow exsolution (Oppenheimer and Kyle, 2008).

This degassing model is corroborated by the CO_2/CO ratio for the "conduit" and "lake" gases, which is ~13 mol mol^{-1} for both. This indicates that, despite their disparate origins, both deeper- and shallower-sourced gases attain thermodynamic equilibrium in the lava lake whose temperature and redox state vary little. The calculated CO_2/CO ratio corresponds closely to the log oxygen fugacity of ~ −11.9 calculated from mineral equilibria and the estimated temperature (1273 K) for Erebus phonolite (Kelly et al., 2008; Oppenheimer and Kyle, 2008).

The ~10 min surging of magma flow should correspond to the time scale of flow instability of magma in the uppermost conduit. To leading order this can be estimated simply from the ratio of magma ascent rate and a length scale given by the conduit diameter (taken as ~7 m). First, we estimate the magma flux in the shallow conduit from the measured HCl flux in the plume (0.24 kg s^{-1}; Oppenheimer and Kyle, 2008), the difference in Cl content of anorthoclase-hosted melt inclusions in the phonolite (0.18 wt.%; Eschenbacher, 1998) and corresponding matrix glass (0.14 wt.%; Kelly et al., 2008), and the observed crystallinity of the phonolite (~35 wt.%; Kyle et al., 1992). We use chlorine for this estimate since melt inclusion volatile contents for a range of species suggest it has the strongest affinity for the melt during fractionation of Erebus magmas (Eschenbacher, 1998). This gives a magma flux of ~10^3 kg s^{-1}, or volume flux, Q, of ~0.36 m^3 s^{-1} (using an Erebus phonolite density of 2400 kg m^{-3}; Eschenbacher, 1998), and hence a magma ascent rate of ~0.02 m s^{-1} (from the estimated conduit radius). In turn, this yields a timescale for magma batches of ~6 min, reasonably congruent with the observed mean cycle period of ~8.8 min (considering the uncertainties in magma flux, ascent rate and conduit dimensions).

We may also estimate the density contrast, $\Delta\rho$, that drives conduit convection using the following relationship from Huppert and Hallworth (2007):

$$Te = \mu Q / g \Delta\rho R^4 \quad (1)$$

where Te is a transport number given by 0.01γ, in which γ is the viscosity ratio of upwelling and downwelling magma, g is the gravitational acceleration, and R is the conduit radius (~3.5 m). For Q~0.36 m^3 s^{-1} and $\gamma = 2.6$, $\Delta\rho$ is ~100 kg m^{-3}. This value is several times higher than the density contrast that could be accounted for by the partial molar volume of dissolved volatiles in Erebus melt and suggests strongly that magma vesiculation plays a significant role in conduit convection.

5. Concluding remarks

Using thermal imaging and spectroscopic techniques, we have identified a striking, cyclic correspondence between the surface motion of Erebus lava lake, and its heat and gas output. We interpret this pulsatory behaviour as a reflection of unsteady, bi-directional magma flow in the conduit feeding the lake. We suggest that the flow instability develops from viscosity stratification between ascending and sinking magma. Furthermore, we find evidence that the convection in the conduit is driven partly by magma vesiculation. The remarkable phenomenology of phase-locked cycles in convection and heat and gas emissions highlights the relationships between magma transport and surface activity, and leads to a synthesis of a previously disparate set of conceptual and laboratory models for magma convection, degassing and volcanic gas geochemistry.

In particular, the observed cycles shed light on the geophysical and geochemical processes occurring in the uppermost part of the Erebus magmatic system. But more generally, they yield insights into the behaviour of 'open vent' volcanoes that deliver heat and volatiles to the surface via an active lava body. The arrival of CO_2-rich gas at the surface independently from magma batches entering the lava lake provides clear evidence for significant conduit permeability as argued for much less evolved magmas (Burton et al., 2007), and hence a high gas volume fraction in the conduit magma. The cyclic gas emission also explains the wide dispersion seen in scatter plots of different gas species (such as CO_2 *vs*. SO_2) emitted from Erebus (Oppenheimer and Kyle, 2008) and at other volcanoes, which has remained a puzzle until now. At any given instant of sampling, the ratio of two species reflects the extent of dilution of "conduit gas" by very shallow-sourced "lake gas". In contrast, the very tight correlation between CO_2 and CO reflects the redox equilibrium established in the lava lake.

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