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Remarkable geochemical changes and degassing at Voui crater lake, Ambae volcano, Vanuatu

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ABSTRACT

Ambae (also known as Aoba), is a 38×16 km^2 lozenge-shaped island volcano with a coastal population of around 10000. At the summit of the volcano is lake Voui — one of the largest active crater lakes worldwide, with 40×10^6 m^3 of acidic water perched 1400 m a.s.l. After more than 300 years of dormancy, Ambae volcano reawakened with phreatic eruptions through Voui in 1995, and culminating in a series of surtseyan eruptions in 2005, followed by a rapid and spectacular colour change of the lake from light blue to red in 2006. Integrating lake water chemistry with new measurements of SO_2 emissions from the volcano during the 2005–2006 eruptive period helps to explain the unusual and spectacular volcanic activity of Ambae — initially, a degassed magma approached the lake bed and triggered the surtseyan eruption. Depressurization of the conduit facilitated ascent of volatile-rich magma from the deeper plumbing system. The construction of a cone during eruption and the high degassing destabilised the equilibrium of lake stratification leading to a limnic event and subsequently the spectacular colour change.

1. Introduction

Ambae island volcano (167°50′E, 15°23′S) is one of the 83 islands and islets that constitute the Vanuatu archipelago (lying between 166–170°E and 13–21°S, Fig. 1). It is the largest volcano in Vanuatu, (2500 km^3), rising 3900 m height from seabed. It is associated with the active Melanesian arc, which lies along the margin of the Pacific and Australian plates. The recent tectonic evolution of the arc has been dominated by the collision of the D'Entrecasteaux Zone (DEZ, e.g., Greene and Collot, 1994) with the central zone, which coincides with Ambae (Fig. 2). The collision began 1.5–3 Ma ago near Epi and has been migrating northwards as a result of the obliquity of the DEZ relative to the trench (Greene et al., 1994). The DEZ collision triggered the detachment of the Australian plate lithosphere beneath the central part of Vanuatu. This detachment is less pronounced under Ambae due to a westward and upward invasion of Indian-type MORB mantle (Monzier et al., 1997).

Ambae is a shield volcano whose volcanic pile consists of primitive basalts (Eggins, 1993). It is surmounted by a broad pyroclastic cone whose youngest summit caldera hosts the acidic crater lake Voui. Ambae is one of the least accessible volcanoes in Vanuatu and few volcanological observations have been made there. What we do know of the recent volcanic activity is summarised in Table 1, while Fig. 3 highlights changes in the crater lake. Following an earthquake swarm beneath the edifice in late 1994 (Rouland et al., 2001), and a phreatic eruption in 1995, which was accompanied by increased gas emissions and seismicity (Robin et al., 1995), the volcanic hazards became more widely recognised, especially in view of the perched crater lake (Cronin et al., 2004). But then Ambae volcano remained calm for a decade, until on the night of 16 February 2005, a succession of earthquakes were felt by the islanders. A seismometer was installed several days later on the north coast of the island but did not record any further significant seismicity prior to the ensuing eruption.

On 21 November 2005, an increase of 5 °C was observed in lake Voui (http://www.ulb.ac.be/sciences/cvl/aoba/Ambae1.html), which was subsequently recognised in MODIS thermal infrared imagery (http://modis.higp.hawaii.edu/cgi-bin/modis/modisnew.cgi) suggesting a precursory increase in magmatic degassing into the lake (Nemeth et al., 2006). The first eruptive activity occurred on 27 November 2005 and the episode climaxed in mid-December. A new tuff cone about 50 m high and 500 m in diameter arose from the lake, acting in such a way as to isolate the vent from the lake water. Strong degassing persisted after the eruption through this newly formed islet. Then, in May–June 2006 lake Voui suddenly

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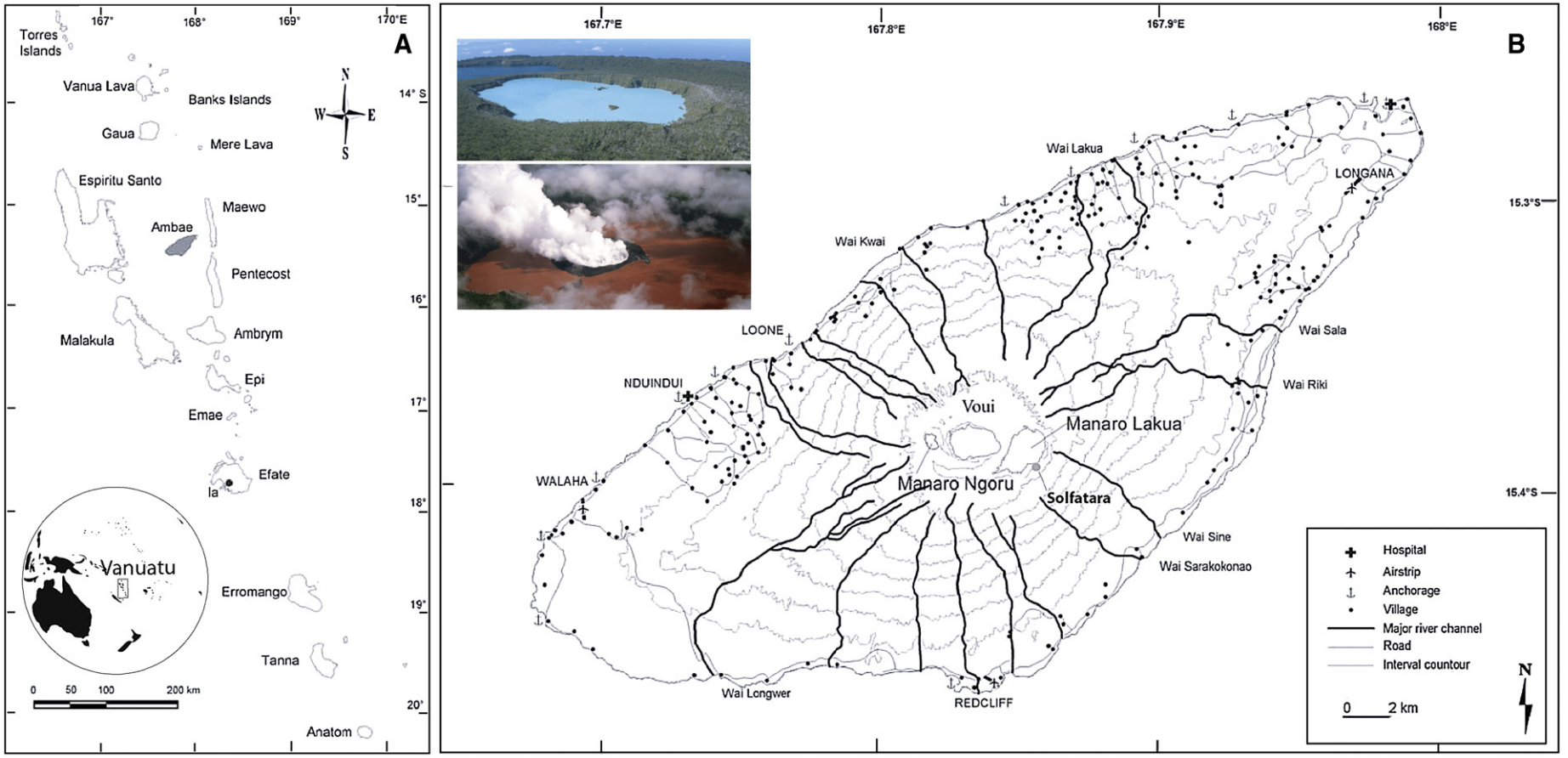


Fig. 1. Map showing Ambae, located roughly in the geographic centre of the Vanuatu archipelago (left), and of the island, including Voui crater lake (right). Insets show photographs of Voui, with its usual blue colour (July 2005; courtesy S. Cronin) and its recent red colour (June 2006; courtesy P. Métois).

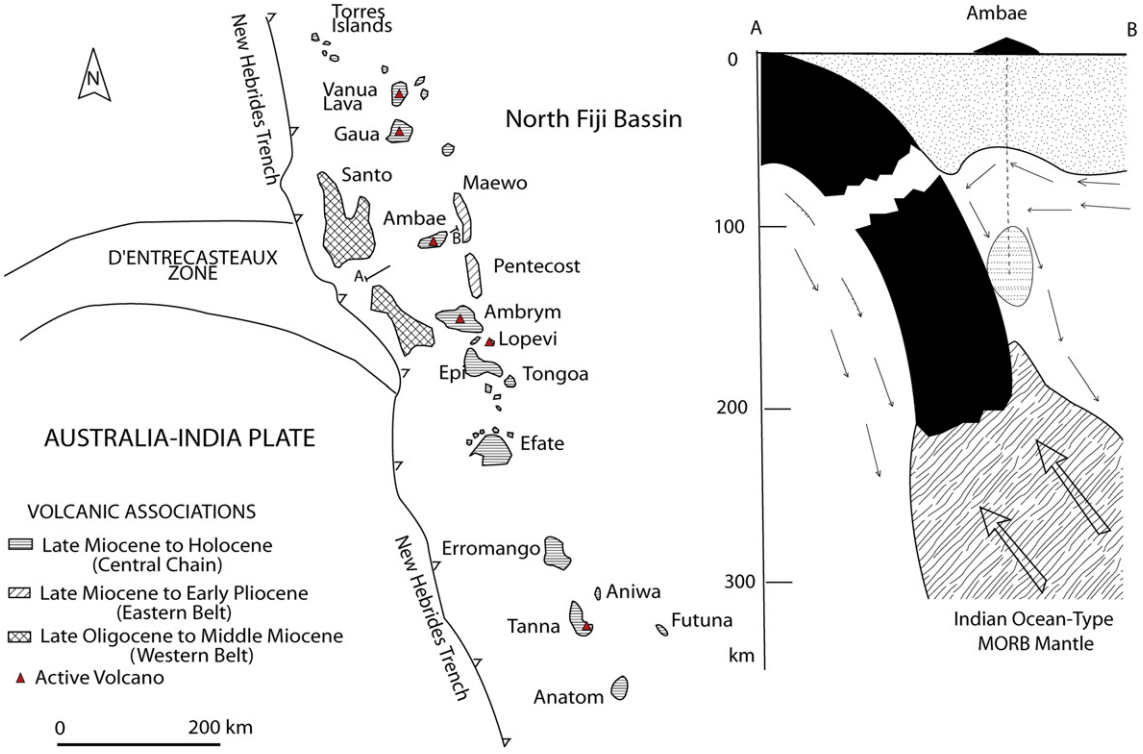


Fig. 2. Tectonic setting of Vanuatu archipelago — three volcanic associations including Eastern Belt, Western Belt and Central Chain; six subaerial active volcanoes along the New Hebrides Trench. The collision of D'Entrecasteaux Zone with the Vanuatu arc have caused the detachment of the subducted slab which appears to be slowly sinking beneath Ambae due to the presence of the Indian Ocean-type MORB mantle (right).

changed colour from blue to red (Figs. 1 and 3). Our aims here are to understand aspects of the magmatic–hydrothermal system, the related gas fluxes to the atmosphere through the recent eruption, and the geochemistry associated with the dramatic colour transformation. Ambae is remote and receives limited scientific attention, thus the data available are sparse. Nevertheless, they shed light on a fascinating and rare variety of eruptive sequence.

2. Methods

Water samples were collected at the lakeshore in July 2005 (four months before the 2005 eruption); December 2005 and January 2006 during the eruption; in February 2006 after the eruption; and in May 2006 and June 2006 after the lake had changed colour to red. Samples were collected immediately below the water surface near the northern lakeshore. Water temperatures were measured in situ using a thermocouple. Cations were analysed by inductively coupled plasma-optical emission spectroscopy (ICP-OES); anions (SO_4^{2-} and Cl^-) were analysed using a Technicon Auto-Analyzer II; and pH was measured with a Schott laboratory pH meter.

The colour change in the lake was associated with the formation of a thin layer of red–brown deposits on the lake bed. Samples of these deposits were analysed using INEL X-ray powder diffraction (XRD) techniques.

Measurements of SO_2 flux were made (for the first time at Ambae volcano) in December 2005, using an ultraviolet spectrometer and differential optical absorption spectroscopy (DOAS) retrieval methods. The spectrometer was carried on board a CESSNA 206G and a Britten-Norman Islander flying at ~900 m a.s.l., beneath the plume. Ultraviolet spectra were also collected in February 2006, in June 2006 and in August 2007. The spectrometer spanned the spectral interval 280–400 nm with a spectral resolution of ~0.5 nm (FWHM), and was coupled by fibre optic bundle to a simple telescope pointed to zenith. Exposure time for individual spectra was 150 ms, and successive batches of 8 spectra were co-added to enhance the signal. The spatial position of each UV spectrum was determined from a continuously recording GPS unit. Sulphur dioxide column abundances were retrieved following standard DOAS procedures (Platt, 1994; Galle et al., 2002). The optimal window used to fit the SO_2 (310.7–321.4 nm) was found by obtaining near random fit residual structure with minimal standard deviation. Wind speeds were obtained from the aircraft navigation systems.

Table 1
Chronology of Ambae volcanic activity.

~1575 +/ − 54	Explosion at the summit and formation of the Voui cone and the Manaro Ngoru crater (C^{14} — Warden, 1970).
~1670	Fissural eruption from the western flank, along the N50 fractures, damaging the Ndui Ndui region (Joly, 1906). Formation of a palagonitic tuf cone in the lac Voui (Williams and Warden, 1964).
1870 +/− 1	Explosive eruption leading to lahars causing victims (Simkin et al., 1981)
~1916	Eruption? (and/or earthquake) leading to mass movement killing around 100 people (De la Rüe, 1945). Volcanic activities along flank fissures (Warden, 1970).
1966	Vapour emission, strong fumarole activity (Blot, 1976).
1971	Strong vapour emission (N.H.G.S. Ann Rep. for 1971).
1976	Strong activity on Solfatara (N.H.G.S., Ann. Rep. For 1976).
1991	On the 13 of July — 3 boiled zones identified in lake Voui and acid impact on vegetation on Voui crater rim (Wiart, 1995).
1993	Increase of vegetation damage around Voui (Wiart, 1995).
1994	On the 4th and 5th Dec. significant quakes were felt on the island (Wiart, 1995).
1995	On the 3rd of March ash plume was seen. High tremor recorded, high degassing from lake Voui (Wiart, 1995).
2005–2006	Surtseyan eruption and spectacular colour change in lake Voui

3. Results

3.1. Lake water chemistry and variations with time

The variations of key chemical constituents between July 2005 and June 2006 are summarised in Table 2 and Fig. 4 demonstrate that

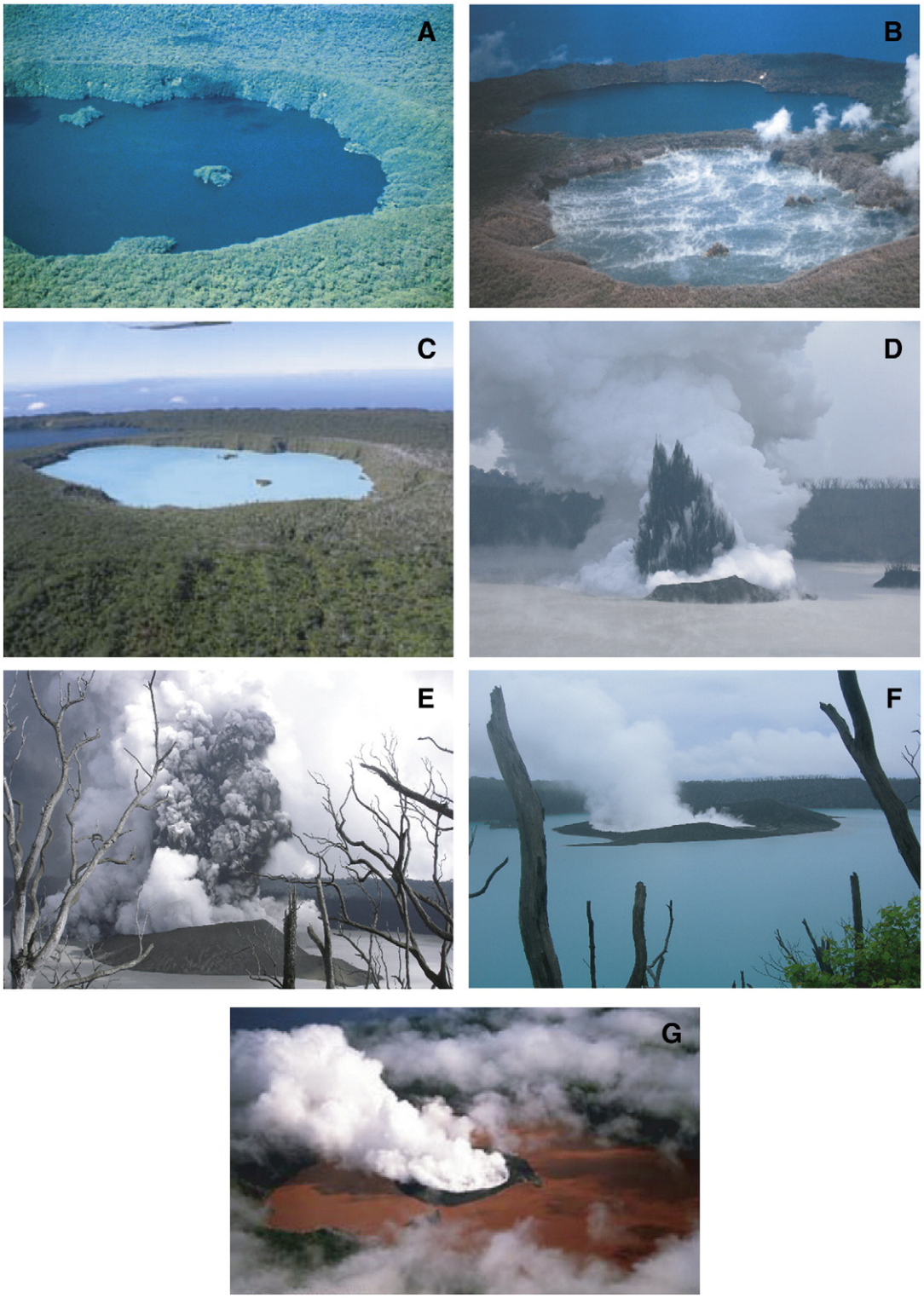


Fig. 3. Changes in Voui crater lake observed between 1986 and 2006: (A) Voui crater lake in 1986, before resumption of activity (courtesy P. Gardissat). Note the well established vegetation around the lake; (B) 1995 with evident hydrothermal activity in the lake and vegetation damage (courtesy Royal Air New Zealand); (C) July 2005 (courtesy S. Cronin); Voui water remained acid since 1995. Note the difference in colour between Voui and Manaro Lakua (background); (D) Surtseyan eruption on 4 December 2005; (E) more intense eruption on 12 December 2005 (courtesy M. Harrison); (F) Voui water back to its usual blue colour in February 2006; (G) Voui turned red (June 2006; courtesy P. Metois).

during this period Voui was a typical "rock-dominated" lake similar to the crater lake of Mt Ruapehu (Varekamp et al., 2000) due to the contribution of reactive, hot and freshly erupted material. However, mixing plots of Cl *vs*. SO_4, Na, K, Ca, Mg, Fe and Al (Fig. 5) do not fall along linear trends as expected, in respect of meteoric water interaction, suggesting changes that reflect eruption dynamics.

The Mg/Cl ratio increased between July and early-December 2005, and between January 2006 and May 2006 (Fig. 5). A rapid decrease occurred in December 2005 during the Surtseyan eruptions, and a slight decrease also occurred between May and June 2006. The SO_4/Cl was relatively constant between July and early-December 2005 but dropped sharply in December 2005 during the eruption. The ratio

Table 2
Water composition, temperature and pH of Voui crater lake between July 2005 and June 2006.

	06/07/2005	12/12/2005	20/12/2005	17/01/2006	27/02/2006	26/05/2006	12/06/2006
Voui colour	Light blue	Grey (eruption)	Grey (eruption)	Grey (eruption)	Light blue (post eruption)	Red (post eruption)	Red (post eruption)
pH	1.6	2.8	2.3	2.3	2.6	2.4	2.5
T(°C)	25				23		24
Cl	1064.4	1562	1906	1915	1410.7	1376	1382.5
SO4	3775.6	5409	5535	6504	4499	4763	4721.7
Ca	148.5	280	377	382	304.1	318	315
Mg	514.3	1294	1231	1263	1043.3	1346.2	1312.6
Na	160.05	241	300	300	249.5	292.1	287.4
K	40.1	42	46	60	68.1	69.5	64.8
Fe	126.6	96	329	321	409.7	310.3	262.2
Al	83.31	211.26	226.42	216.8	163.1	132.5	134.6
Si	82.1	345	309	300	233.2	217.61	205.52
Mg/Cl	0.48	0.83	0.65	0.66	0.74	0.98	0.95
SO4/Cl	3.55	3.46	2.90	3.40	3.19	3.46	3.42

recovered to pre-eruption values in January 2006 but then dropped slightly in February 2006, followed by another increase in May 2006. The ratio remained relatively constant between May and June 2006. Ca increased in 2005 though remained relative stable in 2006. Na increased in both 2005 and 2006, while K remained rather stable throughout the entire period; only a slight increase in K was observed in 2006. Meanwhile, Si strongly increased in 2005, though strongly decreased after the eruption. Cl peaked during eruption, though background levels were very stable. SO_4 strongly increased in 2005, peaked during the late stage of the eruption, and decreased then stabilized after the eruption. Mg roughly follows the same trend as Mg/Cl, increasing in 2005 with an unstable behaviour during the eruption. It increased again in 2006.

Fe shows a curious behaviour compared with the other species. It increased significantly in December 2005 along with other cations but in February 2006, while all the other cation concentrations decreased, Fe increased significantly again (Fig. 5). This second large increase in Fe took place prior to the lake's change of colour. Fe decreased in May 2006 while other cations increased in concentration. In June 2006, Fe content, like Mg, continued decreasing while other species remained relatively stable.

3.2. XRD-mineralogy

The XRD analyses of samples collected at Voui indicate a largely amorphous substance. However, the presence of several large peaks suggest the presence of jarosite, as did XRD analyses of precipitates in the water sampling tubes (Fig. 6).

3.3. SO_2 fluxes

The SO_2 emission rates (Table 3), measured on 3 and 5 December 2005, during the early phase of the eruption, reveal a 50% increase from 16 to 24 kg s^{-1}, which corresponds to the increasing eruptive activity towards a climax around mid-December. After the eruption, in February 2006, the SO_2 emission rate remained high at 22 kg s^{-1} but was higher still in June 2006, when the average emission rate reached 43 kg s^{-1} (or ~3700 t d^{-1}). Nineteen months after the November 2005 eruption, SO_2 emissions rate remain substantial at ~21 kg s^{-1}, placing Ambae at that time among the ten or so strongest volcanic SO_2 emitters worldwide (c.f., Andres and Kasgnoc, 1998).

Measurements of SO_2 burden from the OMI sensor (Krotkov et al., 2006) across a ~10°×10° box over Vanuatu (which maps also

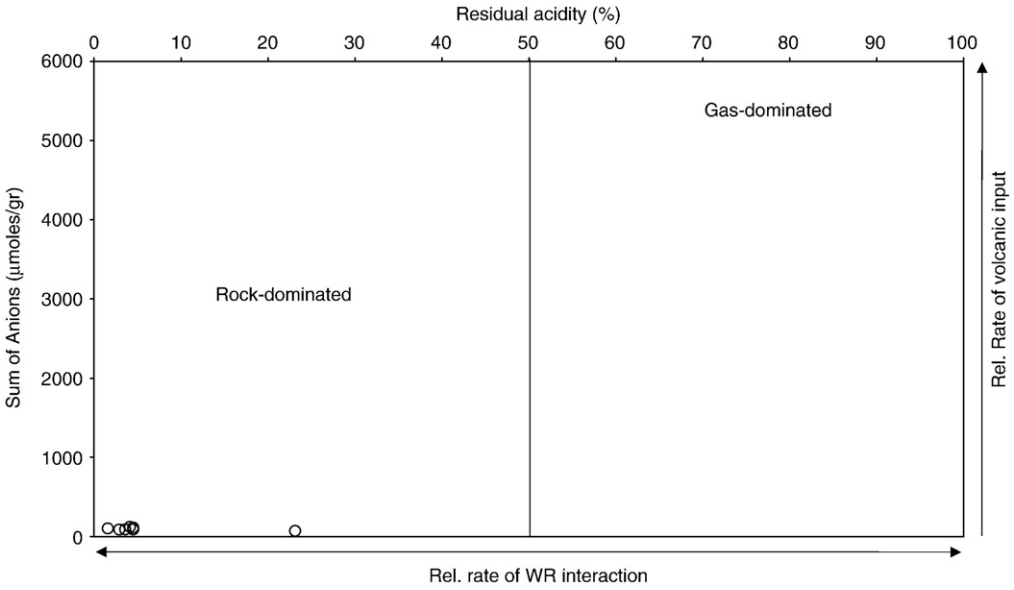
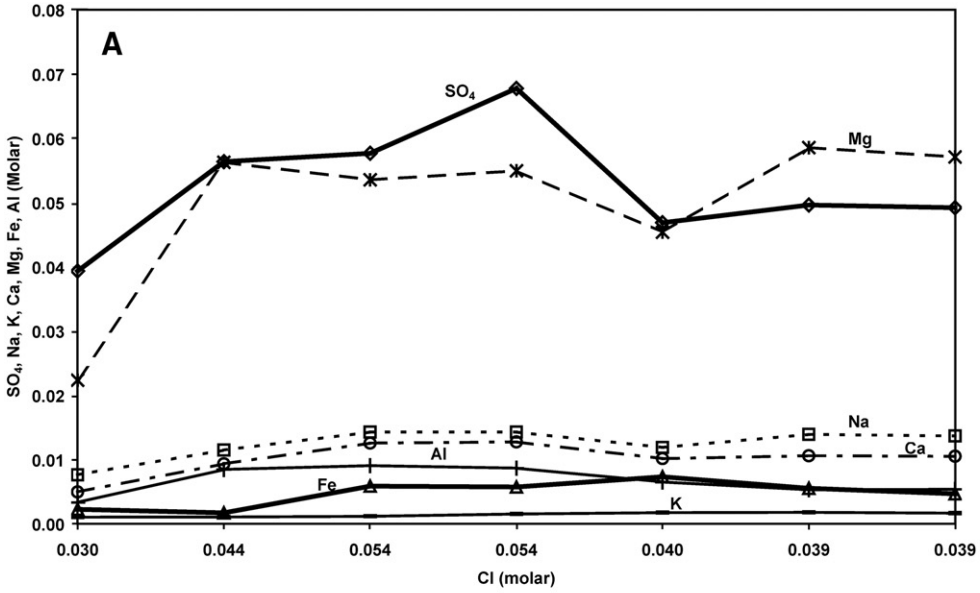
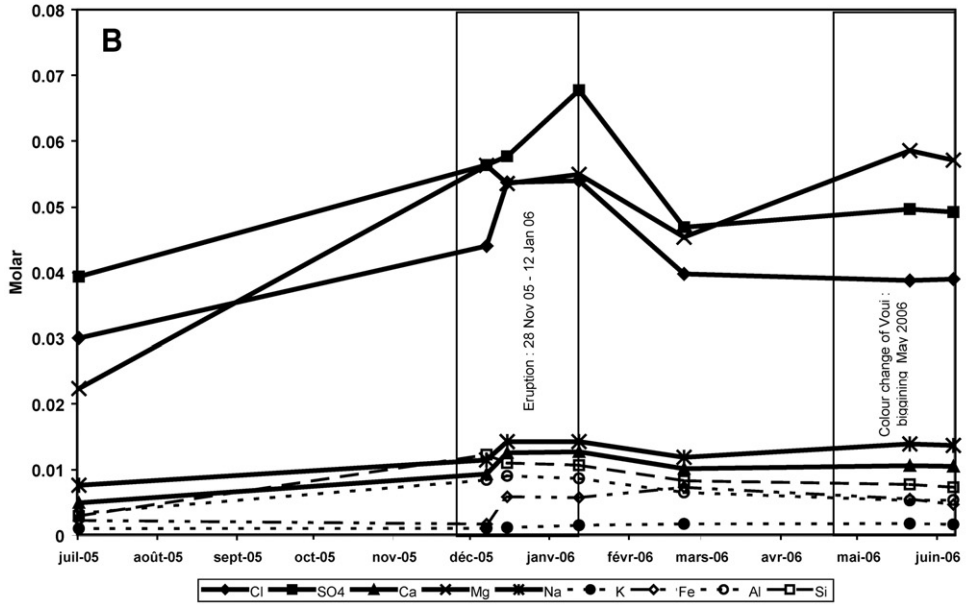
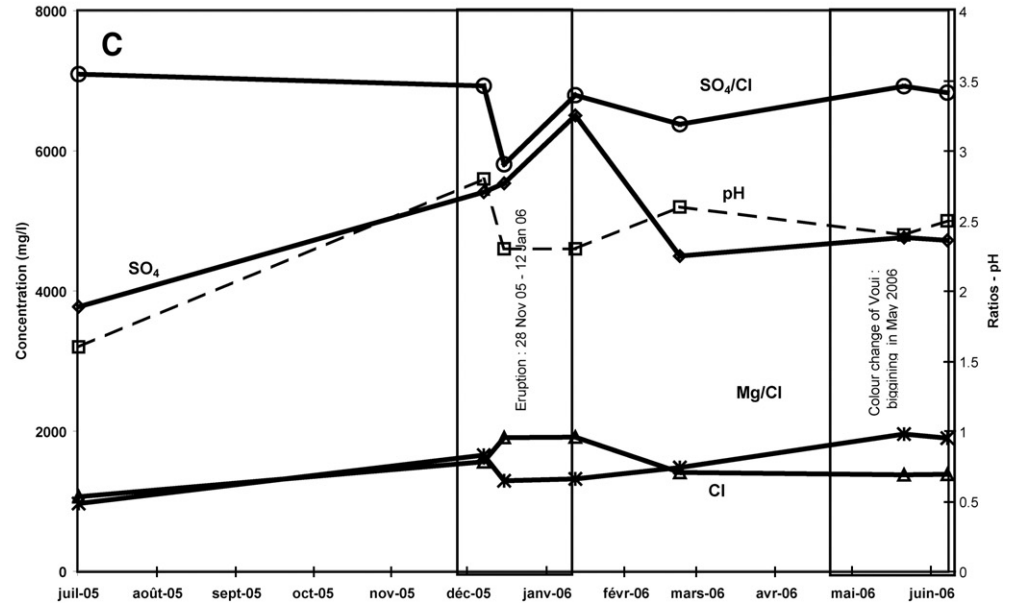


Fig. 4. Voui is a rock-dominated lake due to reactive hot and freshly erupted material (Varekamp et al., 2000).


A
SO4
Mg
Na
Ca
Al
Fe
K
SO4, Na, K, Ca, Mg, Fe, Al (Molar)
Cl (molar)
0.030
0.044
0.054
0.054
0.040
0.039
0.039


B
Molar
Eruption : 28 Nov 05 - 12 Jan 06
Colour change of Voui : biginning May 2006
juil-05
août-05
sept-05
oct-05
nov-05
déc-05
janv-06
févr-06
mars-06
avr-06
mai-06
juin-06
Cl
SO4
Ca
Mg
Na
K
Fe
Al
Si


C
SO4/Cl
pH
SO4
Mg/Cl
Cl
Concentration (mg/l)
Ratios - pH
Eruption : 28 Nov 05 - 12 Jan 06
Colour change of Voui : biginning in May 2006
juil-05
août-05
sept-05
oct-05
nov-05
déc-05
janv-06
févr-06
mars-06
avr-06
mai-06
juin-06

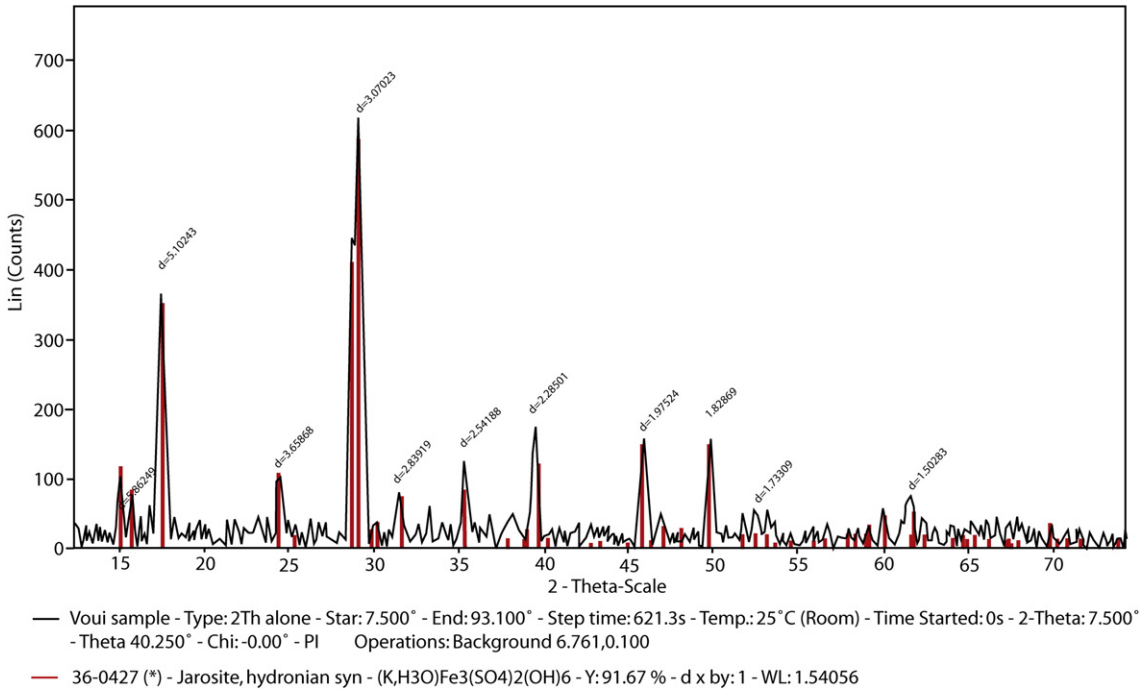


Fig. 6. X-ray diffraction results — the diffractogram of the products best matches the reference diffractograms ICDD (JCPDS) 36-0427 "jarosite".

contributions from Ambrym, Aoba, Lopevi and Yasur volcanoes) were also inspected. These cover the period November 2005 to June 2006 and confirm strong degassing from Ambae volcano (Fig. 7), with a peak of emission in April–May 2006, immediately prior to the colour change of the lake. MODIS imagery acquired on 3 June 2006 and 31 August 2006 indicates that in the intervening period, some 15–20 km^2 of vegetation was destroyed, revealing a substantial impact on terrestrial ecology due to the acidic plume (GVP 12/2006 BGVN 31:12).

4. Discussion

4.1. The 2005–2006 eruption: a comprehensive model

Fig. 8 provides a conceptual model for the 2005–2006 eruption. Variations in the Mg/Cl ratio are widely recognised as diagnostic of changes in magmatic activity at highly acidic lakes (e.g., Ruapehu, Poás, Kawah Ijen). During the Ambae eruption, Lake Voui is less extreme (lower pH, Cl, and SO_4) than other known crater lakes but its Mg/Cl ratio does show two significant increasing trends — between July 2005 and December 2005, and between January 2006 and May 2006. The first of these trends heralds a new magmatic intrusion and associated degassing. The strong Mg increase (along with most other cations) indicates a phase of water–rock interaction (WRI) with fresh rock. WRI consumes H^+ through rock dissolution (Delmelle and Bernard, 2000) leading to an increase of pH in the early eruption phase. Lake water circulation and magmatic degassing through the new tuff cone constructed by the eruption resulted in strong WRI with the freshly comminuted tephra. During this early eruptive phase, significant SO_2 emission rates were recorded indicating that even with a lake that might provide ample opportunities for gas scrubbing, SO_2 fluxes can be substantial (Fig. 7).

The magma rising beneath Voui was largely degassed by the time it erupted. Sulphate concentrations initially did not increase, while Cl concentrations do, resulting in a SO_4/Cl drop just after the arrival of the magma batch. The corresponding Mg/Cl fall is due to a Cl increase rather than to Mg decrease (which is weak). The preferential Cl release with respect to SO_4 (20 December 2005 sample) probably reflects exsolution of chlorine closer to the surface due to its higher solubility in the melt compared with sulphur. Besides this, the stable SO_4/Cl ratio before the eruption shows that the degassing regime (and thus magma depth) did not vary significantly. Subsequently, SO_4 increased significantly (peaking on 17 January 2006), the SO_4/Cl ratio increased sharply, Mg/Cl (and all cation contents) remained stable suggesting the predominant control of gas emissions on the lake chemistry (Fig. 5). The Si peaks coincident with very high Mg/Cl ratio is likely to reflect increased hydrothermal temperatures associated with magma ascent.

The Mg/Cl ratio peaked again in May 2006, while Cl, as well as SO_4 and most of the cations, remained relatively constant. This Mg/Cl increase does not reflect pure water–rock interaction, and the magma continued to degas through the conduit of newly formed cone — by this stage, lake Voui was largely isolated from the magmatic–hydrothermal system. In mid-December 2005, the new cone was about 500 m across and 50 m high, supporting direct emission of SO_2 into the atmosphere (22 kg s^{-1} in February and 43 kg s^{-1} in June). These strong emissions were observed by the OMI sensor and were responsible for the damage to vegetation around the crater.

4.2. Voui colour change and chemical speciation modelling

Volcanic lakes display a variety of colours, which result from absorption and scattering of solar radiation by inorganic and organic materials that are dissolved and/or suspended in the water (Oppenheimer, 1997; Delmelle and Bernard, 2000). Chemical precipitation rates, particle sizes and the convective circulation in crater lakes can also enhance changes in colour of the water body. At Ruapehu, a transition in the lake's colour from blue–green to pale grey indicates remobilisation of lakebed sediments due to vent activity. Similar cases have been reported in other crater lakes including Kawah Ijen, Kelut

Fig. 5. (A) Mixing plots of Cl *vs.* SO_4, Na, K, Ca, Mg, Fe, Al define the hydromagmatic end-member. Note the connection with the time variation plots. (B) Time series of cation and anion concentrations in Voui crater lake. (C) pH, Mg/Cl, SO4/Cl for the period July 2005–June 2006. Eruption and colour change periods are highlighted in (B) and (C).

Table 3
SO_2 fluxes measured between December 2005 and June 2006.

Date	Start time (UT+11)	Length of the plume (km)	Average concentration (ppm)	Flux (kg/s)	Flux error %	Mean fluxes (kg/s)
03/12/05	07 :59	8	575	22.9	+51/−68	16
	08 :04	7	533	10.6	+42/−21	
	08 :08	3	489	13.9	+4/−20	
05/12/05	16 :03	15	171	15.6	+44/−60	24
	16 :16	13	282	32.8	+8/25	
26/02/06	08 :47	18	308	28.5	+34/−52	22
	09 :03	19	278	24.1	+49/−66	
	09 :08	20	183	13.8	+53/60	
10/06/06	10 :39	10	538	46.5	+10/−27	43
	10 :43	14	272	45.0	+10/−36	
	10 :49	11	349	37.0	+22/−39	
12/08/07	9 :31	8	120	18.1	+28/−45	21
	9 :34	9	180	29.8	+24/−41	
	9 :39	9	117	20.2	+29/−46	
	9 :42	11	82	17.5	+24/−41	
	9 :48	11	86	18.2	+26/43	

and Poás (e.g., Delmelle and Bernard, 2000). Temporary colour changes, from blue to grey, or green to yellow, have been observed in many volcanic lakes. In some cases, for instance at Ruapehu, changes in colour have been used to infer changes in volcanic activity. Nevertheless, it is unusual to observe rapid (<2 weeks) colour change from blue to red affecting an entire crater lake, especially considering the vast volume of Lake Voui of ($40\times10^6\,m^3$, Lardy et al., 1997; Bani et al., 2009) and surface area of ~2 km^2. The most comparable example of colour change that we are aware of is for Keli Mutu, Indonesia (Pasternack and Varekamp, 1994), whose lakes reportedly change colour between green/blue and red.

During the field survey in June 2006 on Ambae, we acidified Voui water samples with H_2SO_4 — a few drops of acid in sample tubes led to an instantaneous disappearance of the red colour, indicating that the colouration had nothing to do with a phytoplankton bloom but rather reflected physico-chemical processes.

Simple speciation–saturation models using the 'phreeq' code (Saini-Eiducat and Yahin, 1999), which applies extended Debye Huckel expressions for activity–composition relations, leads to the following insights. Crater lake waters prior to the eruption (6 July 2005, blue lake) are the most acidic, close to charge balance under oxidizing conditions — only a small adjustment in the measured pH yields complete charge balance (pH of 1.6–1.73). These fluids are close to saturation (with the saturation index, S, within one order of magnitude) for anhydrite/gypsum and amorphous silica, while both goethite and haematite are oversaturated with $S>1$. On 17 January 2006 (grey lake), the lake fluids were less acidic (pH = 2.3) but more concentrated by a factor of ~2 for the main cations, and very close to charge balance under oxidizing conditions. The aqueous silica concentrations jumped by a factor of almost four, suggesting the input of much hotter fluids. Anhydrite and gypsum were still close to saturation, and goethite, haematite, amorphous silica, and now also jarosite, were all oversaturated.

The post-eruptive lake waters (12 June 2006, red lake) had a pH of 2.5 and sustained high cation concentrations. Gypsum and anhydrite were close to saturation, whereas silica, goethite, haematite and jarosite were all oversaturated. The occurrence of jarosite as a suspended phase was observed, but the saturation with Fe-oxides for water samples collected during the blue, grey, and red periods suggest that these simulations do not cover the observations. Most likely, the redox potential, pe, of the lake varied over the observation period, and the lake became more oxidizing during the 'red period' in May–June 2006. We re-ran the models for the pre-eruptive and eruptive lake compositions selecting pe such that neither haematite nor goethite were saturated prior to the red period. A pe value of 9 generates a solution close to charge balance with no saturation of Fe-oxides, and a pe value <7 still yields charge balance and no saturation in Fe-oxides or jarosite. After the eruption, the lake turned red and precipitated jarosite, while the composition was slightly changed from the syneruptive state. Most likely, the process of oxygenation changed in the post-eruptive lake, taking into account the hydrodynamic repercussions of the formation of the islet and the tephra/tuff deposits.

Voui had a maximum depth of around 150 m before the formation of the new islet (Bani et al., 2009) and had resumed activity only in the early 1990s, after more than 300 years of dormancy. A burst in Fe (27 January 2006 sample) combined with a light blue colour, indicating reduced Fe^{2+}, surged into the surface waters. Subsequent Fe loss arose by oxidation and sedimentation to deeper waters. Thus, the surface waters lost Fe, but remain coloured. A strong Mg/Cl increase on 26 May 2006 (Fig. 5), which was unaccompanied by new magma since Cl and SO_4 remained relatively constant, suggests that Mg could have been enriched in bottom waters and then moved to surface waters like Fe. Si remained constant during this period, indicating that WRI reached steady-state, and no new hot fluids or magmas entered the system. Na, Ca and K slightly increased, which could reflect the kind of stratification observed at Nyos and Monoun lakes (Cameroon) in terms of cations (Kusakabe et al., 2000). Al loss is possibly due to oxidation, as for Fe. It is thus possible that Voui underwent a limnic overturn shortly after the eruption. We speculate that the formation of a new cone and the high volcanic gas emissions in April–May–June could have been the triggering mechanism.

5. Conclusions

Lake Voui on Ambae displayed spectacular and unusual volcanic activity between July 2005 and June 2006. Surtseyan eruptions (December 2005–January 2006) were followed by an extraordinary colour change of lake water from blue to red in less than 2 weeks (May 2006). This colour change event is exceptional considering the $40\times10^6\,m^3$ water volume. Voui water chemistry and dynamics over this period yield explanations for these events — a degassed magma reached the surface and triggered the surtseyan eruption. Once the eruption started, pressure dropped allowing an undegassed magma batch to rise to deeper plumbing system. The growth of the cone within Voui during eruption and the high degassing destabilised the lake stratification leading to a limnic event and subsequently the spectacular colour change. Voui thus evolved from a Nyos type lake (prior to 2005 eruption) to a rock-dominated lake (during eruption) then to a gas-dominated lake (towards the end of eruptive period).

The first measurements of SO_2 fluxes for Ambae volcano indicate high sulphur emission into the atmosphere during 2005–2006, even when the active vent was submerged. SO_2 release through the vent in the new cone led to significant vegetation damage around the crater.

With more than 5 m of annual rainfall, the newly formed islet is expected to be rapidly eroded. Water from the lake may reinvade the active crater leading to the recovery of the Voui blue turquoise acidic water — unless the cone continues to isolate the Voui water from acidic gas inputs.

Measurements of Voui water chemistry and dynamics have proved very useful to constrain some of the physic-chemical, surficial behaviour of the 2005–2006 eruptive event at Ambae volcano — we strongly encourage future, sustained monitoring of this unusual volcano, especially in respect of the lahar hazard it presents to the population.

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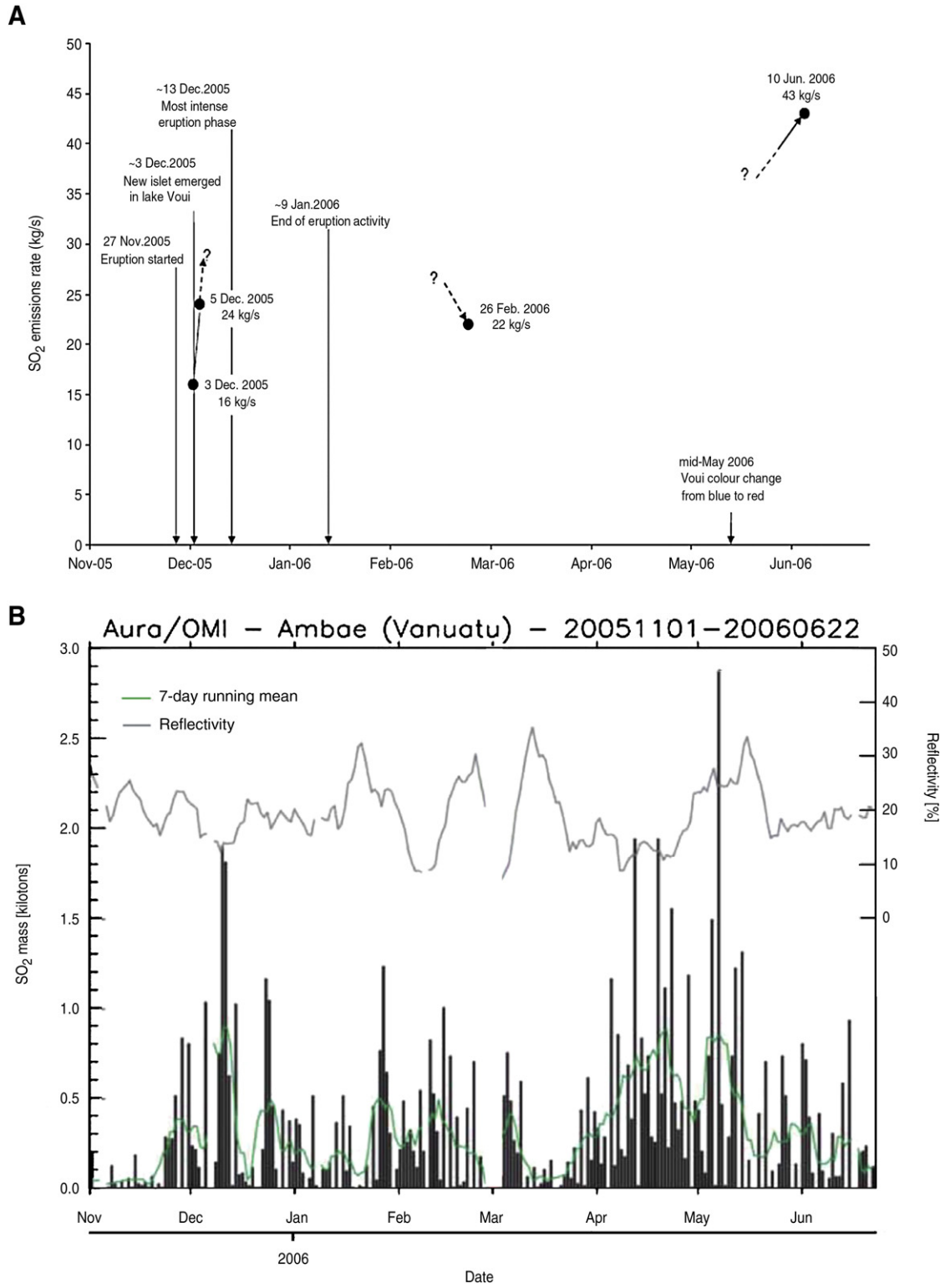

Fig. 7. SO_2 release from Ambae Volcano. (A) UV-DOAS measurement results. Periods of related manifestations in Voui crater lake are indicated. (B) Total SO_2 burdens measured by OMI in a region ($\sim 10^\circ \times 10^\circ$) centred over Ambae from November 2005–June 2006 (vertical bars). We assume that all SO_2 in this region is sourced from Ambae. We stress that these amounts are not SO_2 fluxes and are therefore not directly comparable with the DOAS measurements reported here. Also indicated is the average scene reflectivity at 360 nm (grey curve; data have been smoothed using a 14-day centred moving average); this provides a proxy for cloud cover, which can obscure the SO_2 plume. Note the OMI data gaps from 28 February to 4 March 2006.

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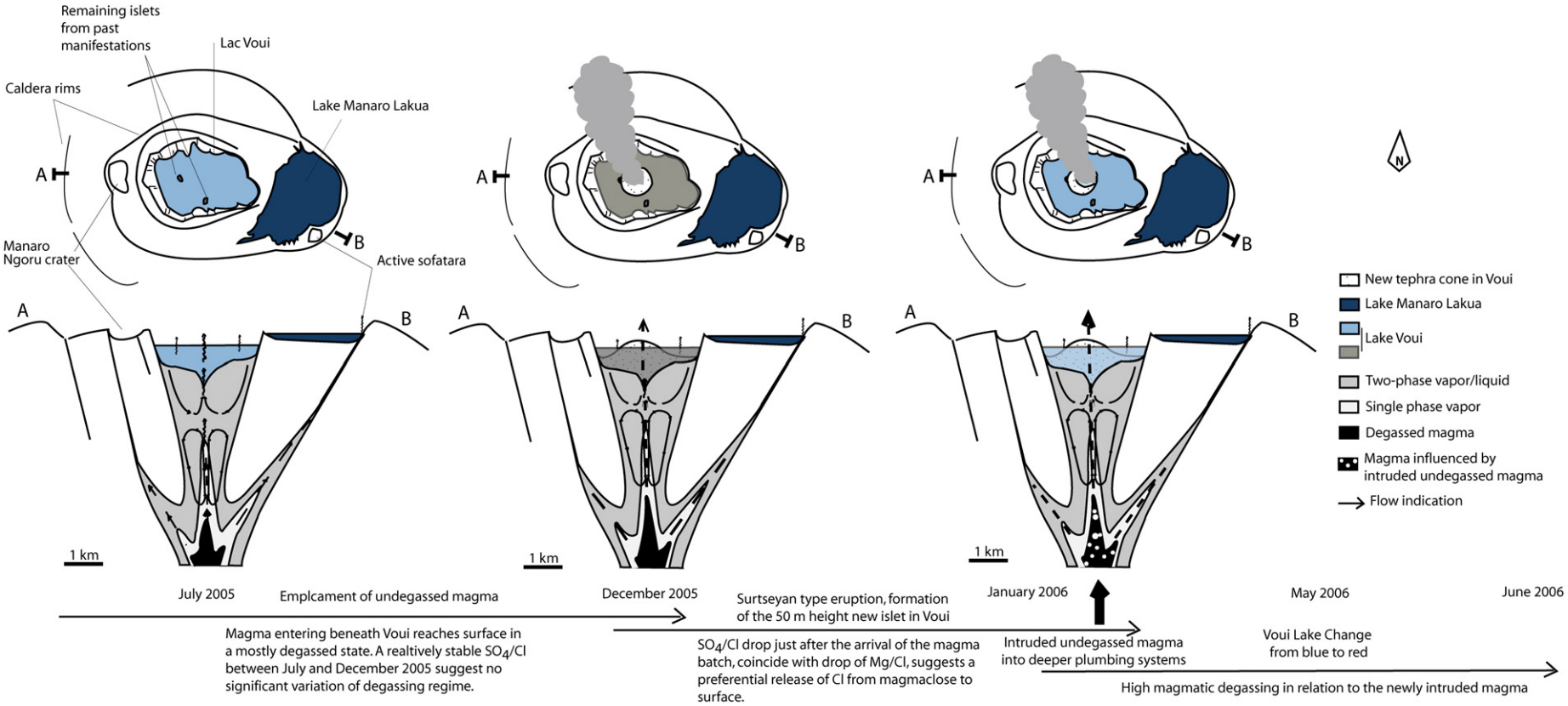

Fig. 8. Conceptual model of the 2005–2006 eruption sequence, commencing with the initial ascent of degassed magma followed by volatile-rich magma, which then sustained the high degassing over the period of January–June 2006.

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