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First measurement of the volcanic gas output from Anak Krakatau, Indonesia



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ABSTRACT

Anak Krakatau is the active cone that has built up in the caldera of Krakatau volcano after the 1883 cataclysmic eruption, in the Sunda Strait. Initially submarine, this new cone definitely emerged from the sea in 1930 and since then has progressively grown up through both explosive and effusive eruptions (~ one eruption every 3 years). Here we report on the first quantification of volcanic gas output from Anak Krakatau, based on airborne UV measurements of the SO₂ flux in 2014, and then discuss its implication in terms of magma degassing budget since 1930. We find that during non-eruptive activity Anak Krakatau passively emits 190 ± 40 tons per day of SO₂, which is comparable to the emission rate during lava dome extrusion at Merapi, central Java, but substantially more than those measured on few other Indonesian volcanoes (Tangkubanparahu, Slamet, Bromo and Papandayan). Anak Krakatau thus appears to be an important persistent emitter of volcanic volatiles in the Indonesian arc, even though this very active region still remains weakly documented on that aspect. Combining with available data for the composition of its high-temperature (~700 °C) crater gases, Anak Krakatau may release annually 0.07 Tg of SO₂, 3 Tg of H₂O, and 0.13 moles of ³He. Using published data for the sulfur content of its feeding magma, we estimate that about 1.3 km³ of magma may have been degassed during its subaerial growth over the past 85 years. The subaerial cone represents only 14% of this volume. Thus, a substantial fraction (1.1 km³) of the degassed magma did not extrude and may have accumulated in the plumbing system. This inference is consistent with geophysical and petrologic evidence of the presence of dense magma bodies in the shallow crustal basement of Krakatau volcano.

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1. Introduction

Krakatau volcano in the Sunda Strait, between Sumatra and Java (Fig. 1) is famous worldwide for its cataclysmic 1883 eruption, one of the two most deadliest volcanic events in historic times, after the great Tambora eruption in 1815 (Francis and Oppenheimer, 2004). Most of Krakatau death toll (36,000) was due to tsunami generated by the pulverization of the former central island and by caldera collapse, that swept across the coasts of the Sunda Strait (e.g., Francis, 1985; Yokohama, 1987). The 1883 Krakatau eruption was classified VEI 6, releasing 15 Tg of sulfur (Zielinski et al., 1996; Oppenheimer et al., 2013)

into the atmosphere that subsequently caused a global temperature fall of 0.3 °C (Francis and Oppenheimer, 2004).

The volcanic and magmatic evolution of Krakatau displays several well defined eruptive cycles (e.g., Van Bemmelen, 1942; Allard et al., 1981; Camus et al., 1987). After the 1883 climax, the birth of Anak Krakatau (“son of Krakatau” in Indonesian language) marked the onset of a new eruptive cycle. The new active vent initially grew as a submarine cone on the edge of the 7-km wide caldera formed following the 1883 cataclysm (e.g., Judd, 1889; Ninkovich, 1979; Effendi et al., 1986; Yokohama, 1987; Deplus et al., 1995). Anak Krakatau definitely emerged above the sea surface in 1930 (Zen, 1970), forming a new volcanic island that has rapidly grown up since then through both effusive (lava flow) and explosive activities. Today the insular cone is 2 km in width and 305 m in height. It is actually one of the most active volcanoes in Indonesia with at least 40 eruptions in the past 85 years (source GVP, <http://www.volcano.si.edu/volcano.cfm?vn=262000>). In the same time, the composition of its erupted products evolved from initial basalts, similar to Krakatau basalts at the onset of past eruptive cycles, to

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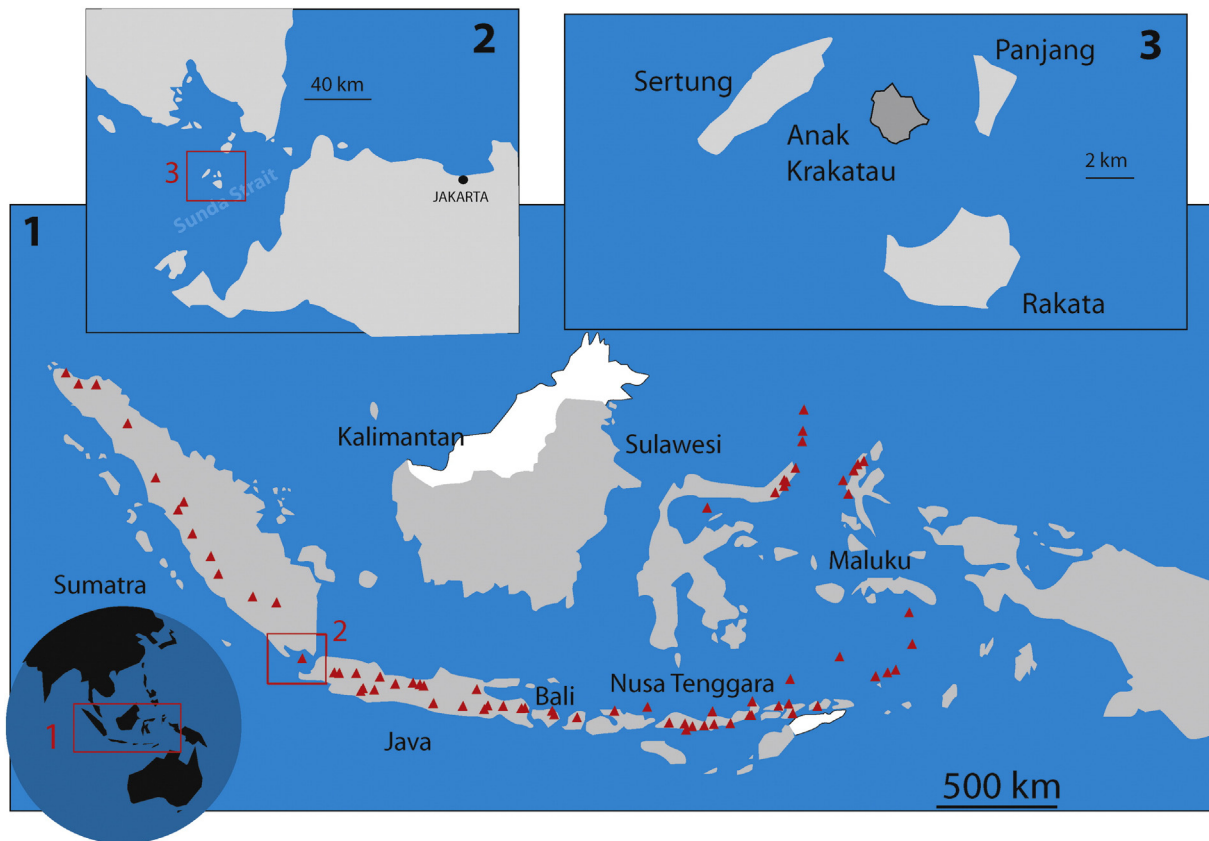


Fig. 1. Anak Krakatau, a new cone that emerged from the sea after the former Krakatau was pulverized by the eruption in 1883 (3). Anak Krakatau is located in the Sunda Strait between Sumatra and Java (2). The red triangles denote the position of every active volcanoes in Indonesia (1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

more differentiated basaltic andesites and occasionally dacits, implying crystal fractionation in a relatively shallow and/or small magma reservoir (e.g., Allard et al., 1981; Camus et al., 1987; Gardner et al., 2012). As recently imaged both through seismic tomography and petrologic studies (Jaxybulatov et al., 2011; Gardner et al., 2012), a complex feeding system underlies Krakatau and sustains the volcanic activity of Anak Krakatau. This system appears to consist of two magma reservoirs, one at only 4–6 km depth and a deeper one at 8–12 km (Jaxybulatov et al., 2011). The upper reservoir is made up of multiple discrete and small magma bodies in which crystal fractionation could rapidly occur and influence the composition of erupted products (Gardner et al., 2012). Further insight into the current evolution of Anak Krakatau and its magma supply rate can be gained by determining the emission rate of volcanic gas and, in particular of SO_2 . Indeed, gas emission rates, combined with data for magma S contents, are good indicators of the rates of magma and gas supply to active volcanoes (e.g., Allard et al., 1994; Galle et al., 2010). Volcanic fluxes of sulfur dioxide can accurately be measured using UV absorption spectroscopy (e.g., McGonigle et al., 2005; Galle et al., 2010). Paradoxically, the emission rate of volcanic gas from Anak Krakatau has never been measured, probably because of the remote insular location of the volcano. Therefore, this was the aim of our present study. We report here the first data set for the gas discharge of Anak Krakatau, based on airborne measurements of the SO_2 plume flux during non-eruptive (passive) degassing in 2014. We find that the volcano ranks amongst the strongest known volcanic gas emitters in the Indonesian arc. Moreover, combining our results with published data for the magma S content (Mandeville et al., 1996; Fiege et al., 2014) allows us to estimate the bulk amount of magma that may have been degassed over the past 85 years of subaerial growth of Anak Krakatau, as well as the fraction of this magma that remained unerupted and probably accumulated at depth in the plumbing system.

2. Methodology

To retrieve the SO_2 plume flux from Anak Krakatau volcano, we used an Ocean Optic USB4000 ultraviolet spectrometer with a spectral range of 290–440 nm and a spectral resolution of 0.3 nm FWHM (full width at half maximum). The instrument set was embarked on board a Pipistrel Virus 912 light aircraft flying beneath the plume at altitudes varying between 110 m and 250 m above sea level with an average speed of 160 km/h. The wind was to the north during our measurements, so our traverses were in the east–west direction, perpendicular to plume transport (Fig. 2). Twelve successive traverses under the plume were carried out, at distances ranging from 0.6 km to 5 km from the crater. The wind speed at the plume elevation was obtained from the difference in the aircraft velocity while repeatedly flying along with and against the wind (Fig. 2).

The spectrometer was connected via an optic fiber bundle to a vertically pointed telescope of 8 mrad FOV, fixed outside the aircraft, which transmitted the solar light into the UV spectrometer. Spectra were acquired using Jscript executed by DOASIS software (Tsanev, 2008). Exposure time for each individual spectrum was 200 ms and we co-added 4 spectra to enhance the signal-to-noise ratio. The position of each recorded spectrum was obtained using a 1-Hz continuously recording GPS.

SO_2 column amounts (ppm m) were later retrieved using standard DOAS calibration and analysis procedures (see Platt and Stutz, 2008). Reference spectra included in the non-linear fit were obtained by convolving high-resolution SO_2 (Bogumil et al., 2003) and O_3 (Voigt et al., 2001) cross sections with the instrument line shape. A Fraunhofer reference spectrum and ring spectrum, calculated in DOASIS, were also included in the fit. The optimum fitting window was defined at 302–325 nm from a near random fit residual with minimum deviation. Uncertainty of each flux value is given in Table 1.

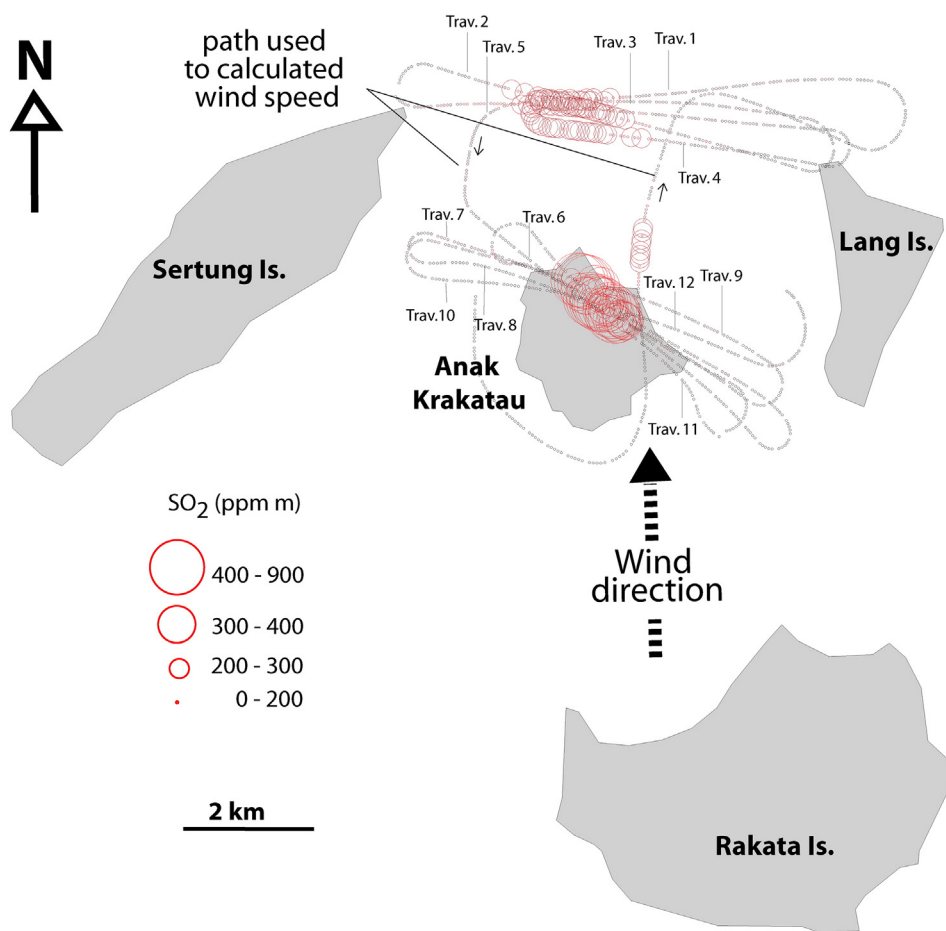


Fig. 2. Airborne measurement path. The 12 traverses from which the mean SO_2 flux was retrieved are indicated. The SO_2 concentrations encountered during traverses are highlighted. The plume dispersed to the north.

3. Results and discussion

Our results are summarized in Table 1 and the SO_2 profiles from our 12 traverses across the plume are displayed in Fig. 3. The volcanic plume was about 1 km at ~600 m from crater but widened to 5–6 km at ~5 km downwind. Fluxes were obtained by scaling the total SO_2 column amount in each plume cross section to the plume speed. The later

Table 1
 SO_2 flux measurement results.

Traverse number	Start time (LT = UT + 6)	Dist. from source (km)	Traverse projected distance (km)	Mean SO_2 column amount (mg/m^2)	SO_2 flux (kg/s)	t/d	Flux error (%) ^a
Trav. 1	10:11:45	3.3	4.4	43.0	2.1	184	31
Trav. 2	10:13:34	2.9	4.0	90.4	2.6	227	31
Trav. 3	10:15:15	3.2	5.6	67.0	3.8	332	31
Trav. 4	10:17:43	5.1	5.2	75.5	3.3	282	31
Trav. 5	10:19:48	3.7	5.7	54.3	3.0	258	30
Trav. 6	10:22:41	0.6	1.1	77.3	1.0	91	30
Trav. 7	10:23:59	0.7	1.8	97.7	2.0	169	32
Trav. 8	10:25:35	0.7	1.8	113.6	2.3	197	31
Trav. 9	10:28:10	0.8	1.5	73.4	1.2	103	31
Trav. 10	10:30:14	0.7	1.2	102.4	1.3	117	31
Trav. 11	10:32:10	1.0	1.5	128.3	2.2	190	31
Trav. 12	10:34:06	0.8	1.6	66.4	1.2	103	30
Mean SO_2 emission rate = 2.2 ± 0.7 kg/s (190 ± 40 t/d)							

^a Determined according to Mather et al. (2006), from estimated relative errors in SO_2 column amounts, distance measurements and plume direction (± 0.4 – 1.8%) and plume transport speed ($\pm 30\%$).

averaged 9.7 m s^{-1} deduced from the flight (difference between flying with and against the wind) implying plume aging of 1 to 8 min at the measuring position. The altitudes of the traverses are given in Fig. 3.

The SO_2 plume flux values vary between 1.0 and 3.8 kg s^{-1} and define a mean SO_2 flux of $2.2 \pm 0.7 \text{ kg s}^{-1}$ or 190 ± 40 tons per day.

Such an emission an emission rate, for non-eruptive (passive) degassing, is comparable to that from Merapi volcano, central Java, during lava dome extrusive activity ($\sim 150 \text{ tons d}^{-1}$ on average; e.g., Surono et al., 2012; Allard et al., 2011) but is much higher than SO_2 fluxes measured at few other Indonesian volcanoes: Tangkubanparahu (0.9 kg s^{-1}) and Slamet (0.7 kg s^{-1}) (Andres and Kasgnoc, 1998), Bromo (0.3 kg s^{-1}) and Papandayan (0.02 kg s^{-1}) (Bani et al., 2013). If one accepts that our measurements are representative for time-averaged passive degassing rate of Anak Krakatau and that the passive degassing contributes most in the long-term SO_2 emission of the volcano, then Anak Krakatau's emission would amount to $0.07 \text{ Tg year}^{-1}$ of SO_2 . The volcano thus ranks not only amongst the strongest known volcanic gas emitters in Indonesia (even though the Indonesian arc still remains poorly documented on that respect) but also within the top-40 passive degassing volcanoes on a global scale (Andres and Kasgnoc, 1998). Otherwise, in terms of gas fluxes, Anak Krakatau is representative of typical arc volcano emitters, whose single contribution to global emission budgets remains relatively modest (e.g., Andres and Kasgnoc, 1998; Halmer et al., 2002).

Melt inclusion data indicate a pre-eruptive sulfur content of ca. 900 wt ppm in Krakatau basaltic andesite magma (Mandeville et al., 1996; Fiege et al., 2014). 90% of this content being outgassed at the surface (Mandeville et al., 1996), our measured SO_2 flux of 2.2 kg s^{-1} or $0.07 \text{ Tg year}^{-1}$ implies the degassing of $1.6 \times 10^7 \text{ m}^3 \text{ year}^{-1}$ of basaltic

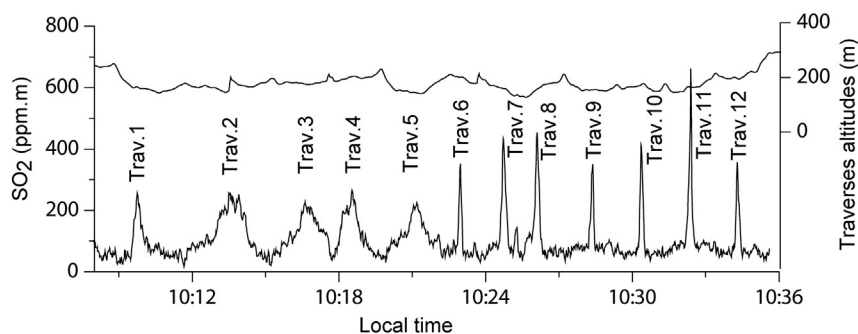


Fig. 3. SO₂ column amounts obtained during traverses. Individual plume traverses are indicated, as well as the measurement altitudes.

andesitic magma with density of 2700 kg m⁻³. It is interesting to compare this quantity to the average magma extrusion rate during the sub-aerial growth of Anak Krakatau since 1930. With a diameter of 2 km and a height of 305 m above sea level, the sub-aerial volcanic cone has an approximate volume of 0.32 km³. Its average growth rate over 84 years is thus $3.8 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ ($0.12 \text{ m}^3 \text{ s}^{-1}$) which, corrected for ~40% bulk porosity of erupted tephra and lava flow, reduces to $2.3 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ of dense (DRE) magma. This represents only 15% of the magma degassing rate computed above. This percentage may be minimal since we neglect here the totally unknown proportion of magma that could have been erupted under sea water. Nevertheless, if the SO₂ flux measured in 2014 is representative for the time-averaged degassing regime of Anak Krakatau in the past 85 years, at least 6 times more magma may have been degassed than erupted in that time laps. Such a substantial difference implies either extensive differential gas transfer across the magma column (given a prevalent contribution of passive degassing to the volatile budget) or/and efficient convective overturn of this column, with downward recycling of the unerupted, denser degassed magma, such as observed at other open-conduit volcanoes (e.g., Kazahaya et al., 1994; Allard, 1997; Shinohara, 2008; Beckett et al., 2014). Whatever the dominant process, the conclusion is that a substantial amount of degassed magma ($\sim 1.4 \times 10^7 \text{ m}^3 \text{ year}^{-1}$) may have accumulated beneath the volcano since the onset of its sub-aerial stage in 1930. The underground storage of unerupted degassed magma, at probably shallow crustal level, could be one mode to form the solidified plutonic bodies of magma seismically detected within the shallow basement of Krakatau (Jaxybulatov et al., 2011). A similar conclusion was inferred, for instance, at Mount Etna basaltic volcano (Allard, 1997). Furthermore, we emphasize that, at the present rate of 0.07 Tg/year, the cumulated SO₂ emission of 5.9 Tg over the 85 years of sub-aerial growth of Anak Krakatau would be equivalent to the lower (petrologic) estimates for the total amount of sulfur released as SO₂ during the 1883 cataclysmic eruption (Mandeville et al., 1996). This further illustrates how continuous passive degassing at open-vent volcano can widely prevail in long-term degassing budget with respect to eruptive events of very high magnitude but much rarer occurrence.

Finally, our SO₂ flux results provide the first basis to estimate the fluxes of other magma-derived gas species from Anak Krakatau. Allard et al. (1981) measured H₂O/SO₂, CO₂/SO₂, and He/SO₂ molar ratios of 1.57, 0.34 and 1.2×10^{-5} in high-temperature (687 °C) gas directly collected at the bottom of Anak's crater. Converting into weight ratios and scaling to an SO₂ flux of 0.07 Tg year⁻¹, we derive annual fluxes of 3 Tg of H₂O, 16 Gg of CO₂ and 100 moles of ⁴He. The low CO₂ release simply reflects the low CO₂/S ratio of the measured gases, typical for a late-stage degassing of feeding magma batch at the time of crater sampling (Allard et al., 1981). It is thus a likely underestimated figure for the time-averaged CO₂ emission rate from the volcano. On the contrary, the estimated flux of H₂O may overestimated the true magmatic emission as D-¹⁸O isotopic data indicated a probable dilution of the crater gases by heated meteoric or marine water (Allard et al., 1981). Instead,

helium at Anak Krakatau is typically mantle-derived with a ³He/⁴He ratio ~7 times the atmospheric ratio (Gasparon et al., 1994), and our estimate for the flux of ³He from Anak Krakatau (0.13 moles year⁻¹) is truly magmatic origin. It represents only 0.2% of estimated global emissions from sub-aerial arc volcanism ($\sim 68 \text{ moles year}^{-1}$; Allard, 1992).

4. Conclusion

Anak Krakatau is the new active vent of Krakatau volcano, formed after the disastrous 1883 eruption. It constitutes the onset of a new eruptive cycle and has been one of the most active volcanoes in Indonesia since its emergence above the sea surface in 1930. Strikingly, however, no information was yet available for its volcanic gas emission rate, despite the interest of that parameter to get deeper insight into its magma supply rate and its plumbing system. In this study we report the first data set for the SO₂ emission rate from Anak Krakatau during non-eruptive (passive) degassing in 2014. We find an average SO₂ flux of $190 \pm 40 \text{ t d}^{-1}$ or $0.07 \pm 0.015 \text{ Tg year}^{-1}$ which reveals Anak Krakatau as one of most powerful persistent gas emitters in Indonesia. Coupled to previous data for high-temperature crater gases of the volcano, we estimate a maximum release of 3 Tg of H₂O, 16 Gg of CO₂ and 0.13 moles of mantle-derived ³He. Furthermore, based on melt inclusion data for the magma sulfur content and degassing rate, we estimate that about 1.3 km³ of basaltic andesitic magma could have been degassed at Anak Krakatau since it started to erupt at the open air in 1930. The present-day sub-aerial cone represents only ~15% of this bulk volume, suggesting that 1.1 km³ of unerupted degassed magma may have accumulated beneath the volcano in the past 85 years. This observation fits with recent detection of several solidified magma bodies in the shallow crustal basement of the volcano, implying that the current activity of Anak Krakatau does represent a continuum of its past eruptive regime. Regular SO₂ flux measurements at Anak Krakatau should complement the existing geophysical monitoring system for a better understanding and monitoring of the variations in its eruptive activity.

Finally, our study further outlines the great need of improved quantification of volcanic volatile fluxes from the very active Indonesian arc region.

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