# Feature

## Crustal volatile release at Merapi volcano; the 2006 earthquake and eruption events

**High-temperature gas in volcanic island arcs is widely considered to originate predominantly from the mantle wedge and from subducted sediments of the down-going slab. Over the decade (1994–2005) prior to the 2006 eruption of Merapi volcano, summit fumarole $CO_2$ gas $\delta^{13}C$ ratios are relatively constant at –4.1 ± 0.3‰. In contrast, $CO_2$ samples taken during the 2006 eruption and after the May 26th 2006 Yogyakarta earthquake (M6.4) show a dramatic increase in carbon isotope ratios to –2.4 ± 0.2‰. Directly following the earthquake (hypocentre depth 10–15 km), a 3–5-fold increase in eruptive intensity was observed. The elevated carbon isotope gas data and the mid-crustal depth of the earthquake source are consistent with crustal volatile components having been added during the 2006 events, most probably by the thick local limestone basement beneath Merapi. This 'extra' crustal gas likely played an important role in modifying the 2006 eruptive behaviour at Merapi and it appears that crustal volatiles are able to intensify and maintain eruptions independently of traditional magmatic recharge and fractionation processes.**

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High-temperature volcanic gas is widely considered to originate from ascending, mantle-derived magma. In the case of $CO_2$ at arc-related volcanoes, its provenance is thought to be dominated by the mantle wedge and the sediments subducted on the down-going slab. Here we report on the carbon isotope composition ($\delta^{13}C$) of $CO_2$ emitted via high-T summit fumaroles (> 200 °C) from Merapi volcano, Central Java (Figs 1, 2) over a period of approximately 25 years. During this period, notable seismic events included a deep slab earthquake with hypocentres ~150 km depth (2001) and a shallow earthquake with hypocentres between 10 and 15 km depth (2006). In addition, the 2006 events were coupled with eruptive activity at Merapi. Gas samples were collected during non-eruptive periods with the exception of the 2006 sampling period, when sampling was performed during ongoing eruptive activity of the volcano.

### The 2006 events

The 2006 eruptive events of Merapi commenced on 25 April and lasted until October of that year. On 14 June, the largest pyroclastic event of the eruptive episode occurred, destroying the village of Kaliatem on the southern flank of the volcano (Fig. 3). A magnitude 6.4 earthquake preceded this event on 26 May, along a splay of the Opak River Fault system to the south and east of Yogyakarta (Fig. 1). The earthquake caused devastating damage to the city, killing approximately 6500 inhabitants and leaving over 0.5 million people homeless for many months after the crisis. Prior to 2006, variation of fumarole carbon isotope ratios was limited with an average baseline value of –4.1 ± 0.3‰ (vs. V-PDB). This value is rather typical of subduction zones and small fluctuations have previously been thought of as reflecting the influence

  

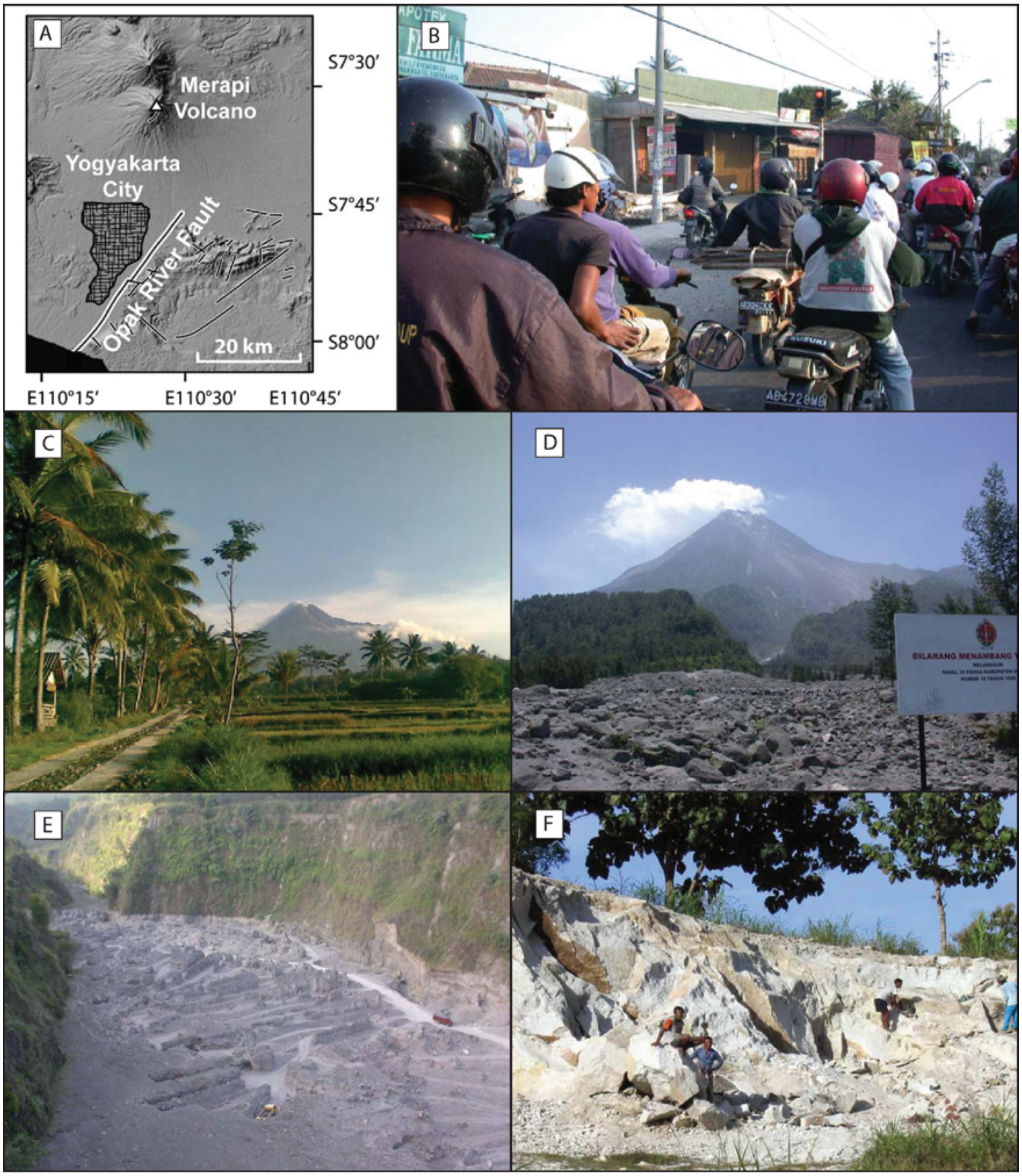


**Fig. 1. A.** Map of Merapi volcano and Yogyakarta city (after Walter et al., 2008). The Opak River Fault System is indicated to the south and east of Yogyakarta. **B.** Impression of the busy Yogyakarta city street. Yogyakarta had a recorded 3880 888 habitants in 2010, and thus 4 million people live within ca. 25 km of the volcano. **C, D.** Views of Merapi Volcano from the south. **E.** Older valley-filling pyroclastic flow deposit that is quarried for gravel which creates sediment traps for future flows in order to reduce their runout distance. **F.** Limestone quarry west of Yogyakarta. Limestone forms the local sub-volcanic bedrock and is presumed to dominate the upper 7–8 km of the local crust beneath Merapi.

of the local limestone basement underneath Merapi. Carbon dioxide collected after the earthquake and during the 2006 eruptive events, however, showed a dramatic increase from this baseline value, reaching up to $\delta^{13}C = -2.4 \pm 0.2‰$. In 2007 and 2008, the $\delta^{13}C$ fumarole values returned to the previous background levels (Fig. 4). Notably, for several weeks after the May 26th earthquake, there was a marked rise in eruptive intensity in the form of accelerated dome growth (by a factor of three) and a dramatic increase of dome collapse events (by a factor of five).

## Source of 'extra' $CO_2$

High carbon isotope gas values, such as those observed in 2006 at Merapi, are not produced by decompression- or fractionation-induced degassing in either an open or closed system mode, suggesting an addition of $CO_2$ from a non-magmatic, high-$\delta^{13}C$ source. The abundant skarn-type xenoliths (metamorphosed limestone) found in eruptive deposits at Merapi (Figs 4, 5) suggests that the sedimentary carbonate basement underneath Merapi provides such a source. The significant increase in $\delta^{13}C$ in 2006, its transient duration, the crustal depth of the earth-


**Fig. 2.** Impressions of Merapi's summit region (2968 m.a.s.l.; 9737 ft). **A.** Transition of older lava dome rocks on the left to the active dome on the right. **B.** Spine-like dome remnant that marks the last safe point before the active dome. **B, C.** Gendol fumarole field on the active dome. **D, E, F.** Woro-fumarole field and active gas sampling. (images from 2003–2008).

quake hypocentres, and the link with eruptive and seismic intensity are consistent with the addition of $CO_2$ from mid- to upper-crustal depths. This creates a picture of intense magma-crust interaction in the top few kilometres of the crust beneath Merapi during eruptive episodes. Such additions of crustal $CO_2$ to subduction zone baseline fluxes may modify volatile budgets of ascending magmas at Merapi considerably during eruptive events (> 50 percent based upon the shift in $\delta^{13}C$ values). $CO_2$ liberation from long-term crustal storage reservoirs, such as the thick limestone basement of Merapi, may thus sustain or even amplify ongoing eruptive activity, especially when aided by external seismic events which can act to fracture country rock creating new reaction surfaces and/or releasing trapped gas pockets.

## Chicken or egg?

Recently, it has been advocated that $CO_2$ lubricates the slip planes of crustal faults, thus aiding fault rupture. It is therefore conceivable that volcanic activ-

  

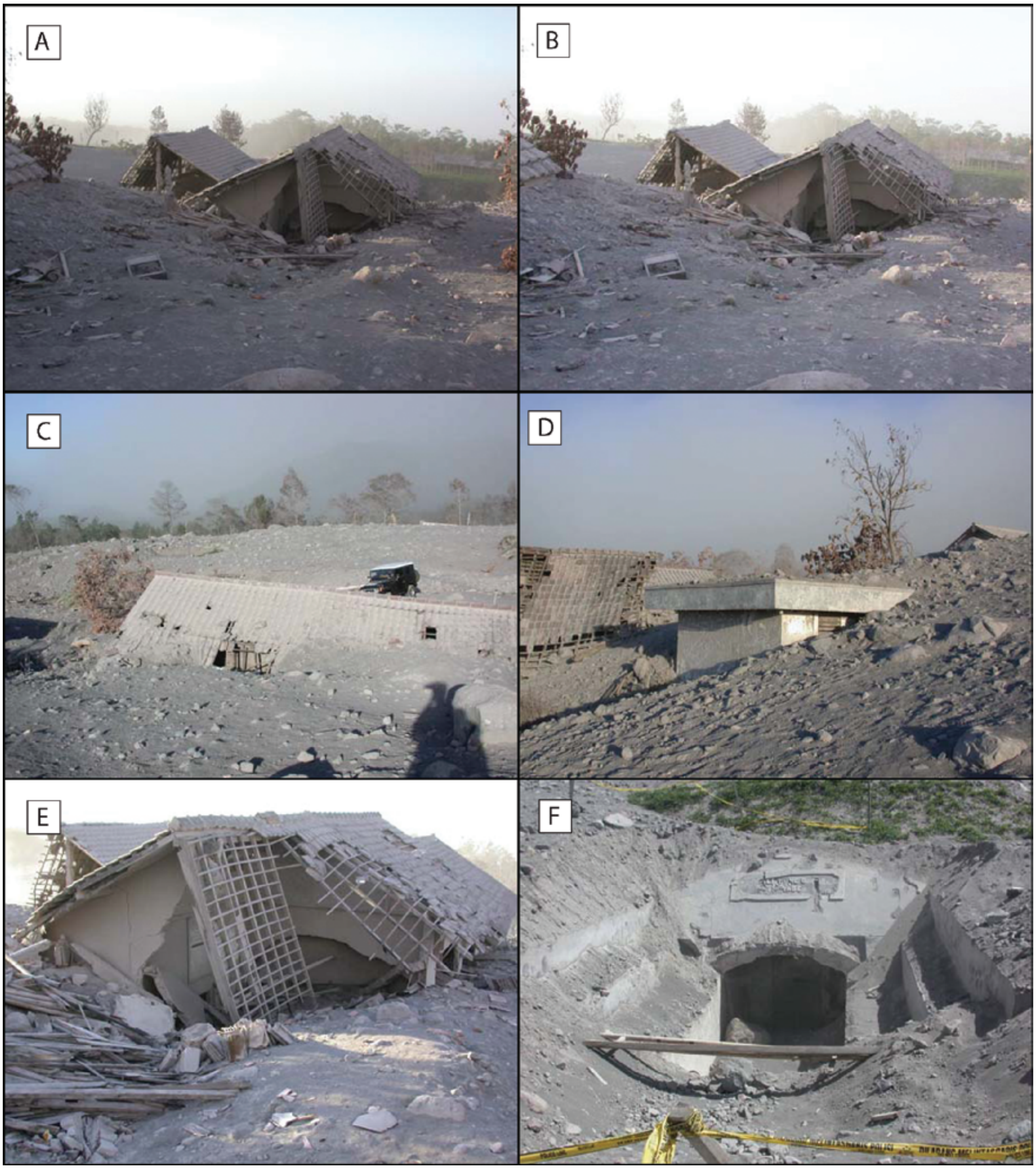


**Fig. 3. A–F.** Kaliatem village, ca. 6 km south of Merapi summit, was destroyed by the June pyroclastic event. **F.** Shows the observatory bunker near the village that became a death trap for two observatory staff on 14 June (see Gertisser *et al.* 2012b, for details).

ity may, in turn, represent a potential trigger for increased regional seismicity. As the 2006 eruption was already ongoing for six weeks prior to the 26th May earthquake, it is possible that high crustal $CO_2$ degassing at Merapi volcano could have released $CO_2$ into crustal weak zones, thus changing the regional stress regime and promoting the 2006 Yogyakarta earthquake. This would be consistent with slightly elevated $\delta^{13}C$ values in fumarole gas in the year prior to the eruption (2005). Irrespective of the final cause of the 26 May earthquake, we envisage a chain of events whereby the volcano and earthquake interacted in a positive feedback loop. We conclude that crustal volatiles intensify on-going eruptions independently of magmatic recharge and fractionation processes at Merapi and may even be a factor in promoting regional seismic activity.

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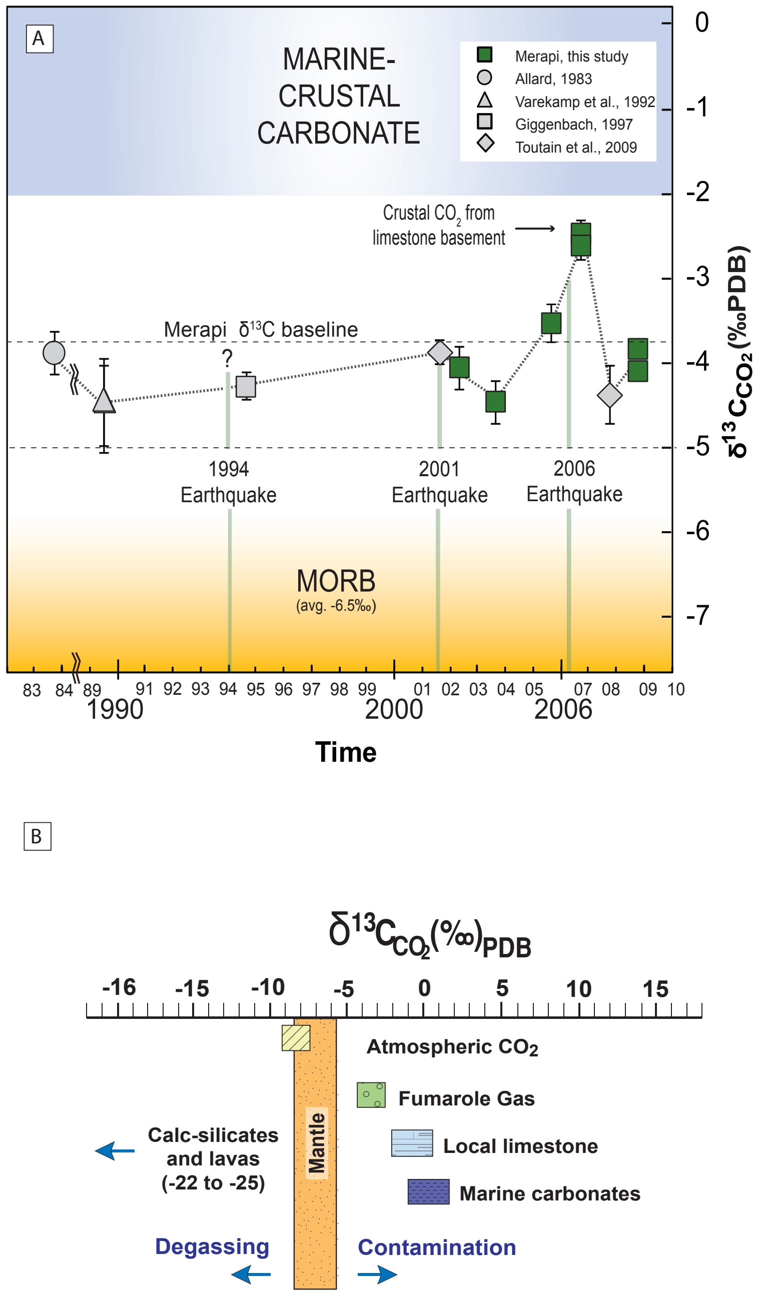


**Fig. 4. A.** Variations in $\delta^{13}C_{CO2}$ in high-T Merapi fumarole gas from the 1980s to 2008. Carbon isotope ratios are in ‰ (permil) relative to V-PDB. Green squares represent data from Troll *et al.* (2012), grey symbols are other literature values. The $\delta^{13}C_{CO2}$ values of baseline samples are considerably more positive than pure mantle values and are quite typical of subduction zones (Hilton *et al.* 2002). There is a marked increase in $\delta^{13}C$ in 2006 after the 26 May 2006 earthquake, where values rise sharply relative to the baseline. This implies that a high $\delta^{13}C_{CO2}$, i.e. a non-magmatic, volatile input is associated with the 2006 Merapi earthquake and eruption. **B.** Plot of $\delta^{13}C_{CO2}$ of Merapi fumarole gas samples, limestone basement, calc-silicate xenoliths and lavas from Merapi. The low isotope values for calc-silicates and lavas are a function of intense degassing, whereas Merapi fumarole samples are displaced towards the local limestone crust.

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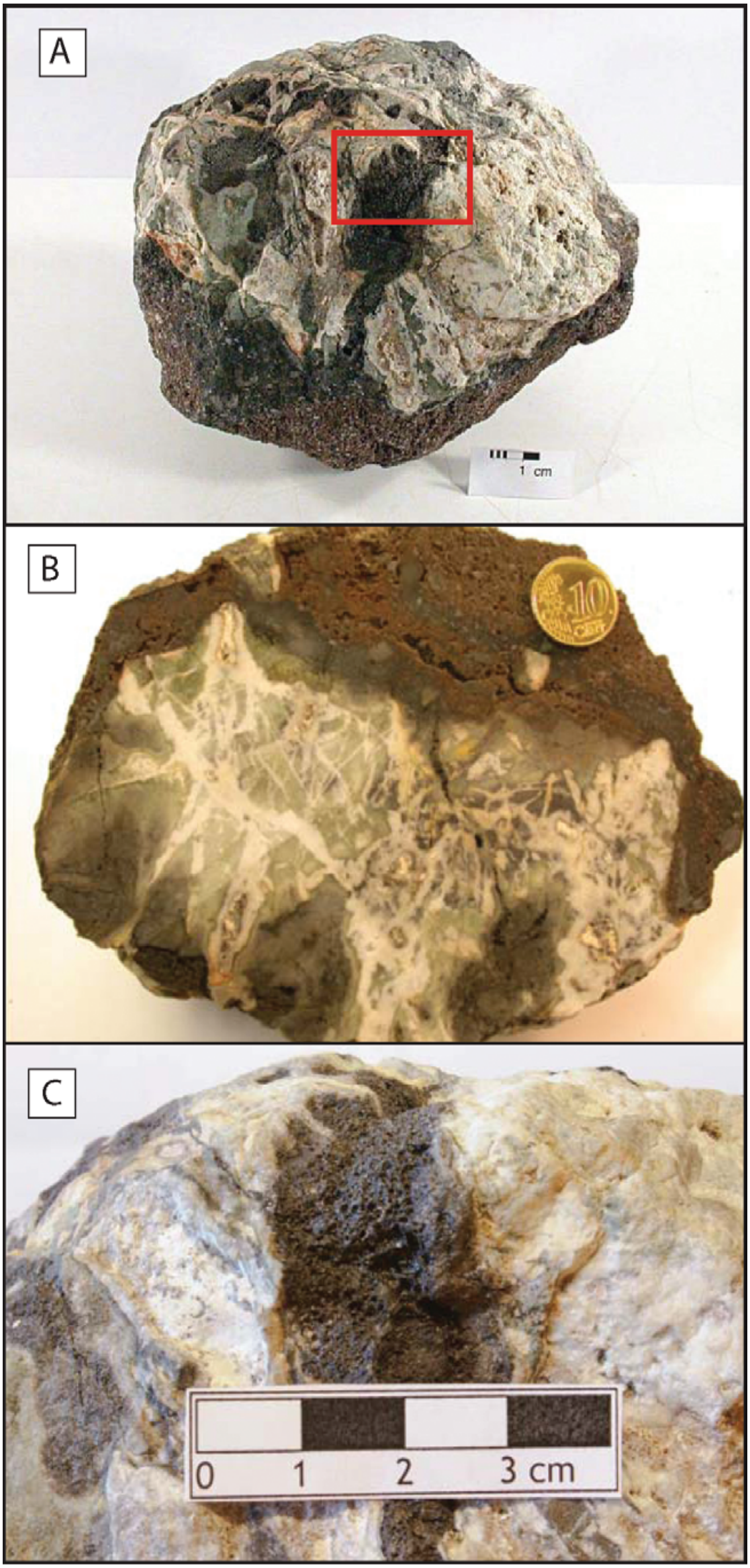


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**Fig. 5. A.** Example of Merapi calc-silicate xenolith made up dominantly of wollastonite and diopside with minor tremolite, grossular and quartz. This mineral assemblage is characteristic of the contact-metamorphic reaction of limestone with magma. Note the infiltrating andesite vein in the centre of the image. **B.** Same calc-silicate xenolith sectioned, showing a macroscopic network of diopside (green) and wollastonite (white). **C.** Close up of (**A**) (red square) shows the infiltrating magma to be strongly vesicular at the magma-xenolith contact, indicating gas liberation due to chemical interaction between magma and xenolith.