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COMMENT Open Access

# Reply to comment by Williams on "spatial changes in inclusion band spacing as an indicator of temporal changes in slow slip and tremor recurrence intervals"

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**Abstract**

Our recent paper (Nishiyama et al. in Earth Planets Space 73:126, 2021) suggested that the sealing time of a crack-seal event recorded in quartz-filled shear veins in the Makimine mélange may temporally increase or decrease. Nishiyama et al. (Earth Planets Space 73:126, 2021) describes the optical estimates of the vapor–liquid ratio of primary two-phase fluid inclusions between solid inclusion bands in shear veins. The variation in vapor–liquid ratio was used as an indicator of fluid pressure conditions at the time of trapping of fluid inclusions during a crack-seal event. Comment on our paper (Williams in Earth Plantes Space 10.1186/s40623-022-01599-1 2023) raised the issue that our paper neglected the error in fluid pressure associated with the uncertainties in the optical estimate of the vapor–liquid ratio of fluid inclusions. Williams (Earth Plantes Space 2023 10.1186/s40623-022-01599-1) claimed that, if a certain uncertainty in the optical estimate of the vapor–liquid ratio is considered, there is a large error in the fluid pressure. The argument by Williams (Earth Plantes Space 2023 10.1186/s40623-022-01599-1) is based on the assumption that the uncertainty of the vapor–liquid ratio can be determined accurately. An accurate estimate of the uncertainty of the vapor–liquid ratio is possible if the homogenization temperature of the fluid inclusion is measured. However, it has been a challenging issue to measure the homogenization temperature of fluid inclusions between inclusion bands in a crack-seal vein, because the spacing of inclusion bands is too small (typically, a few tens of microns or less) to measure the homogenization temperature. Therefore, it is difficult to provide a confidential discussion regarding the error in the fluid pressure during a crack-seal event. Nishiyama et al. (Earth Planets 73:126, 2021) showed the sealing time of a crack-seal vein for a wide range of fluid pressure drops and discussed that the sealing time is comparable to the slow slip and tremor recurrence intervals when the fluid pressure drop is large. We consider that such a presentation and discussion are appropriate rather than discussing the error in fluid pressure based on the ambiguous uncertainty in the optical vapor–liquid ratio estimate.

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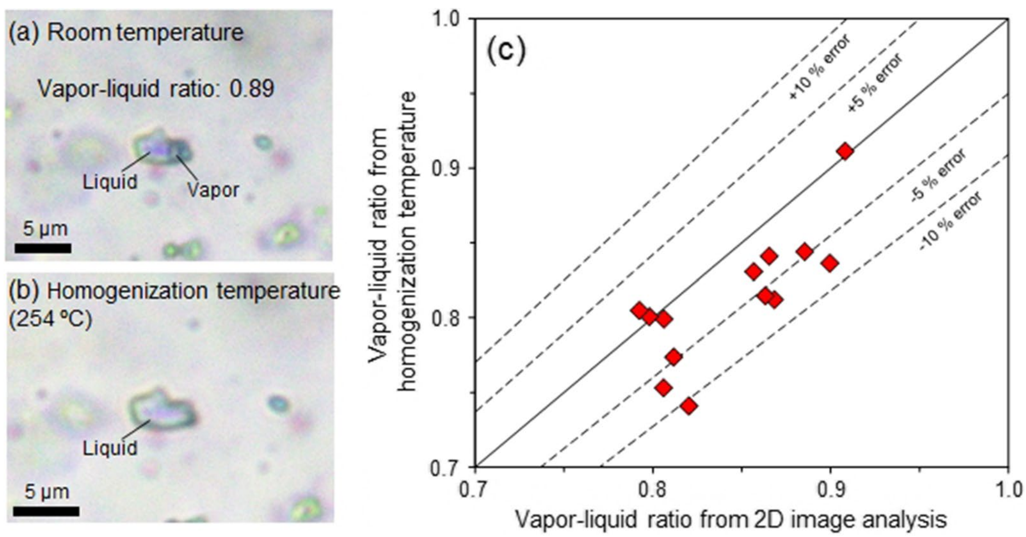
**Graphical Abstract**




## Main text

We thank Dr. Williams for his comments (Williams 2023) on our paper (Nishiyama et al. 2021). One of the major issues raised by Williams (2023) is that Nishiyama et al. (2021) neglected the uncertainties in the vapor–liquid ratio of fluid inclusions estimated from 2D images and did not include any consideration in subsequent calculations of the sealing time of crack-seal veins. Given that the density of water at room temperature is 1 g cm$^{-1}$, the volume fraction of liquid water ($V_r$) is related to water density at the time of vein formation ($\rho_h$) (Nishiyama et al. 2021; Williams 2023):

$$\rho_h = V_r \tag{1}$$

Hereafter, the volume fraction of liquid water is referred to as vapor–liquid ratio. Nishiyama et al. (2021) estimated the vapor–liquid ratios using 2D images of fluid inclusion. The fluid pressure at the time of vein formation can be estimated from the $\rho_h$ value with isochore. Williams (2023) estimated possible errors in fluid pressure associated with the 2D vapor–liquid ratio estimates based on the results of Bakker and Diamond (2006) and unpublished data (shown below). Williams (2023) suggested that uncertainties in 2D vapor–liquid ratio estimates generate large errors in fluid pressure (Fig. 1 of Williams 2023). When the error in fluid pressure is included, the fluid pressure drop during a crack-seal event for the Makimine mélange can be interpreted as almost zero (Williams 2023).

The above argument by Williams (2023) is based on the assumption that the uncertainty of the vapor–liquid ratio can be determined accurately. Precise uncertainty can be determined by comparing the vapor–liquid ratio estimated optically with that evaluated based on the homogenization temperature of fluid inclusion, because the homogenization temperature gives a true vapor–liquid ratio (or a true $\rho_h$). However, it is currently a challenging issue to measure the homogenization temperature of small fluid inclusions between inclusion bands, because the spacing of inclusion bands is too thin (typically, a few tens of microns or less) to measure using a heating and cooling stage mounted on a microscope. As described in Williams (2023), Bakker and Diamond (2006) reported that the relative uncertainty of the 2D vapor–liquid ratio estimates is 20%. Bakker and Diamond (2006) used ~ 10–20 μm-size fluid inclusions synthesized in quartz that has no inclusion bands. We also evaluated the uncertainties of the optical estimates of the vapor–liquid ratio using thin sections of crack-seal shear and extension veins collected from the Makimine mélange, which are the same samples used in Nishiyama et al. (2020, 2021). The uncertainties were evaluated by comparing the vapor–liquid ratio estimated optically (Fig. 1a) with that determined from the homogenization temperature using microthermometry (Fig. 1b). The fluid inclusions analyzed were outside the inclusion bands where a relatively large fluid inclusion was available (Fig. 1). The results showed that 2D image analysis of fluid inclusions

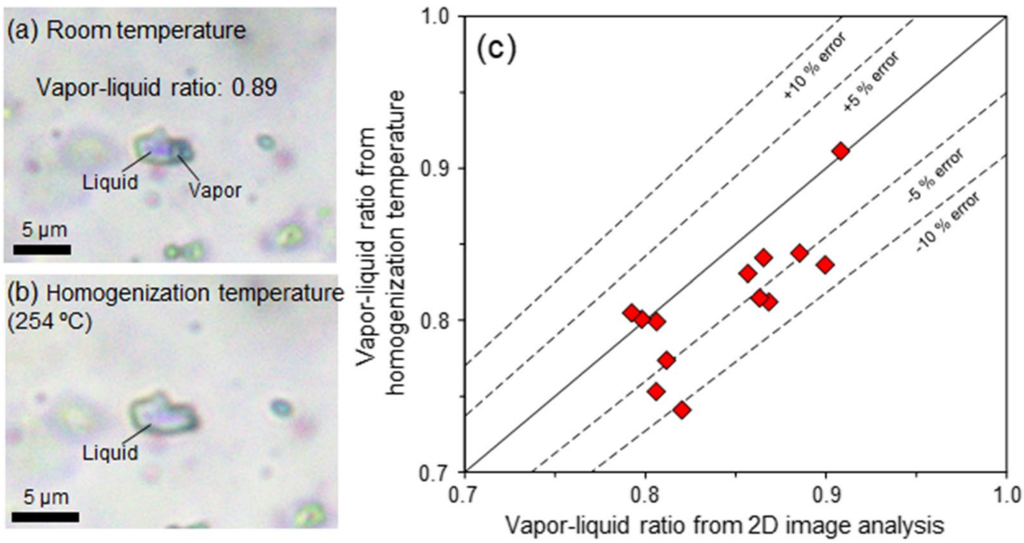



**Fig. 1** Photomicrographs of primary two-phase fluid inclusion at room temperature (**a**) and at homogenization temperature (**b**). Water density (liquid–vapor ratio) of the fluid inclusion was calculated to be 0.89 and 0.84 g $cm^{-3}$ from 2D image analysis with Eq. (1) and homogenization temperature of 254 °C with LonerHGK (http://fluids.unileoben.ac.at). (**c**) Comparison of vapor–liquid ratio calculated from 2D image analysis and homogenization temperature for fluid inclusions trapped in shear and extension veins

in the shear and extension veins provides uncertainties in the range of 2% underestimation to 10% overestimation of the vapor–liquid ratio (Fig. 1c). The difference in the uncertainty between the results of Bakker and Diamond (2006) and our analysis suggests that the uncertainty of the 2D vapor–liquid ratio estimate is not constant and may change depending on the size, shape, and vapor–liquid ratio of fluid inclusions. The error in fluid pressure changes significantly depending on the value of the uncertainty adopted (Fig. 1 of Williams 2023). Therefore, it is difficult to provide a convincing discussion on the error in fluid pressure during a crack-seal event, because the precise uncertainty of the vapor–liquid ratio for fluid inclusions between inclusion bands is unknown.

Another issue raised by Williams (2023) is that assuming a certain uncertainty of the vapor–liquid ratio, the lower-bound pressure during a crack-seal event for the Makimine mélange would be more than 100 MPa less than the hydrostatic value. However, such a low fluid pressure seems to be unrealistic. Williams (2023) raised another question: given a certain uncertainty of the vapor–liquid ratio, the upper-bound fluid pressure during the crack-seal event may be equal to the hydrostatic pressure, which means almost no change in fluid pressure during the crack-seal event. Such a situation is unlikely because the crack-seal shear vein subparallel to mélange foliation and the foliation-parallel extension vein form fault-fracture mesh in the mélange deformed under a vertical lithostatic stress, indicating that the shear vein developed under near-lithostatic fluid pressure (Ujiie et al. 2018 and Fig. 1a of Nishiyama et al. 2021).

In our paper, we first provided a figure showing how the sealing time of the crack-seal vein changes if the fluid pressure drop varies (Fig. 5 of Nishiyama et al. 2021) and then discussed that the sealing time is comparable to the recurrence intervals of slow slip and tremor when a large fluid pressure drop is considered. Such a large fluid pressure drop is not surprising because the homogenization temperatures of large fluid inclusions across multiple inclusion bands for the shear vein in the Makimine mélange indicates the fluid pressure drop from lithostatic pressure to hydrostatic pressure (Nishiyama et al. 2020). Considering the technical difficulty in determining the precise uncertainty of 2D vapor–liquid ratio estimates for fluid inclusions between thin inclusion bands, we consider that it is an appropriate presentation style to provide the figure showing the change in sealing time as a function of fluid pressure drop, rather than to discuss possible errors in fluid pressure based on ambiguous uncertainties of vapor–liquid ratio. The readers can readily understand that the sealing time becomes short when a large fluid pressure drop occurs. Williams (2023) and this reply suggest that technique to accurately estimate vapor–liquid ratio of small fluid inclusions between inclusion bands needs to be developed in the future. Such technique enables us to accurately estimate the sealing time of a crack-seal quartz vein, leading to more robust discussion of whether crack-seal vein in a subduction mélange is linked to slow slip and tremor.

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## Declarations

**Competing interests**
The author declares no competing interests.

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## Publisher's Note