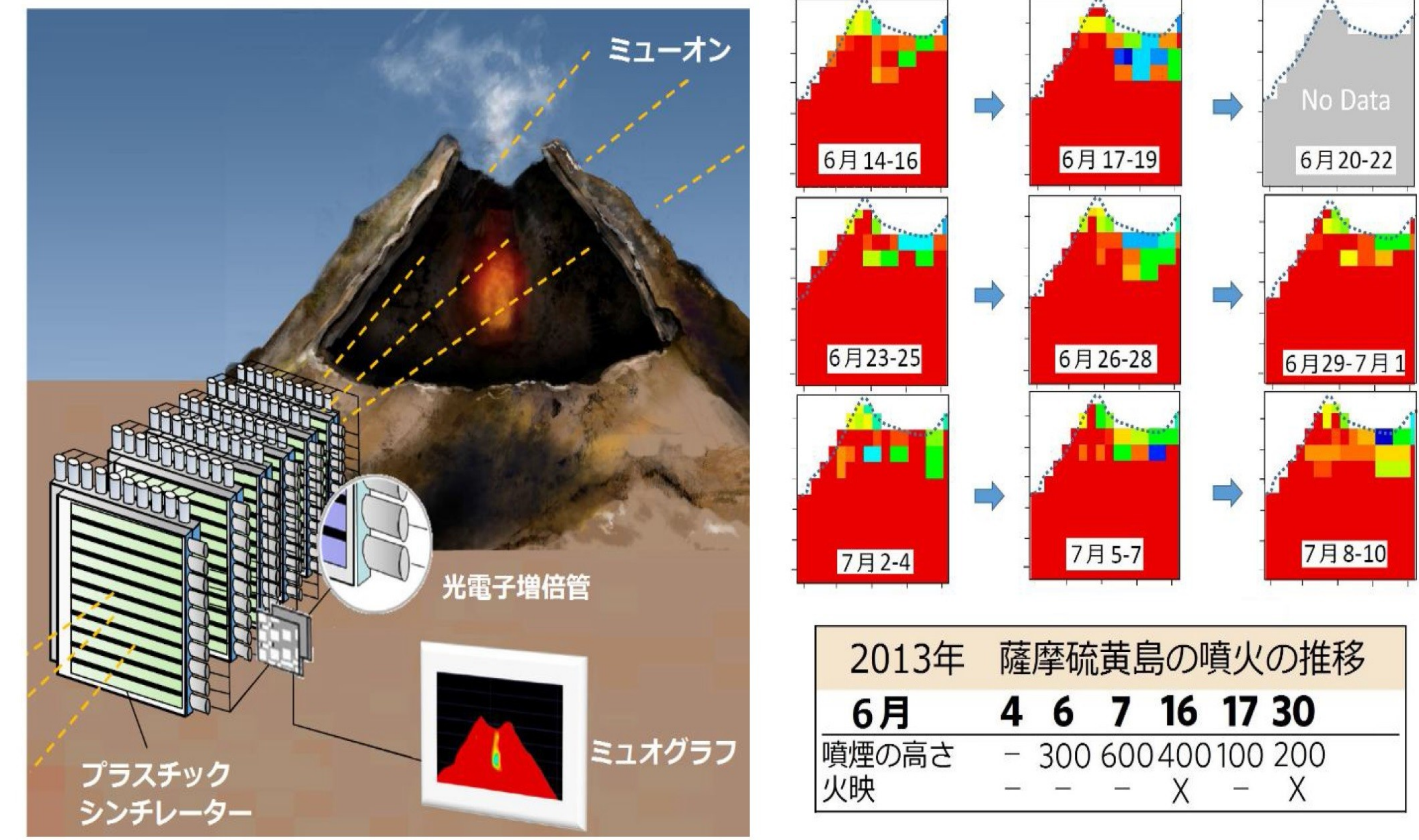


I. Cosmic-ray Muography

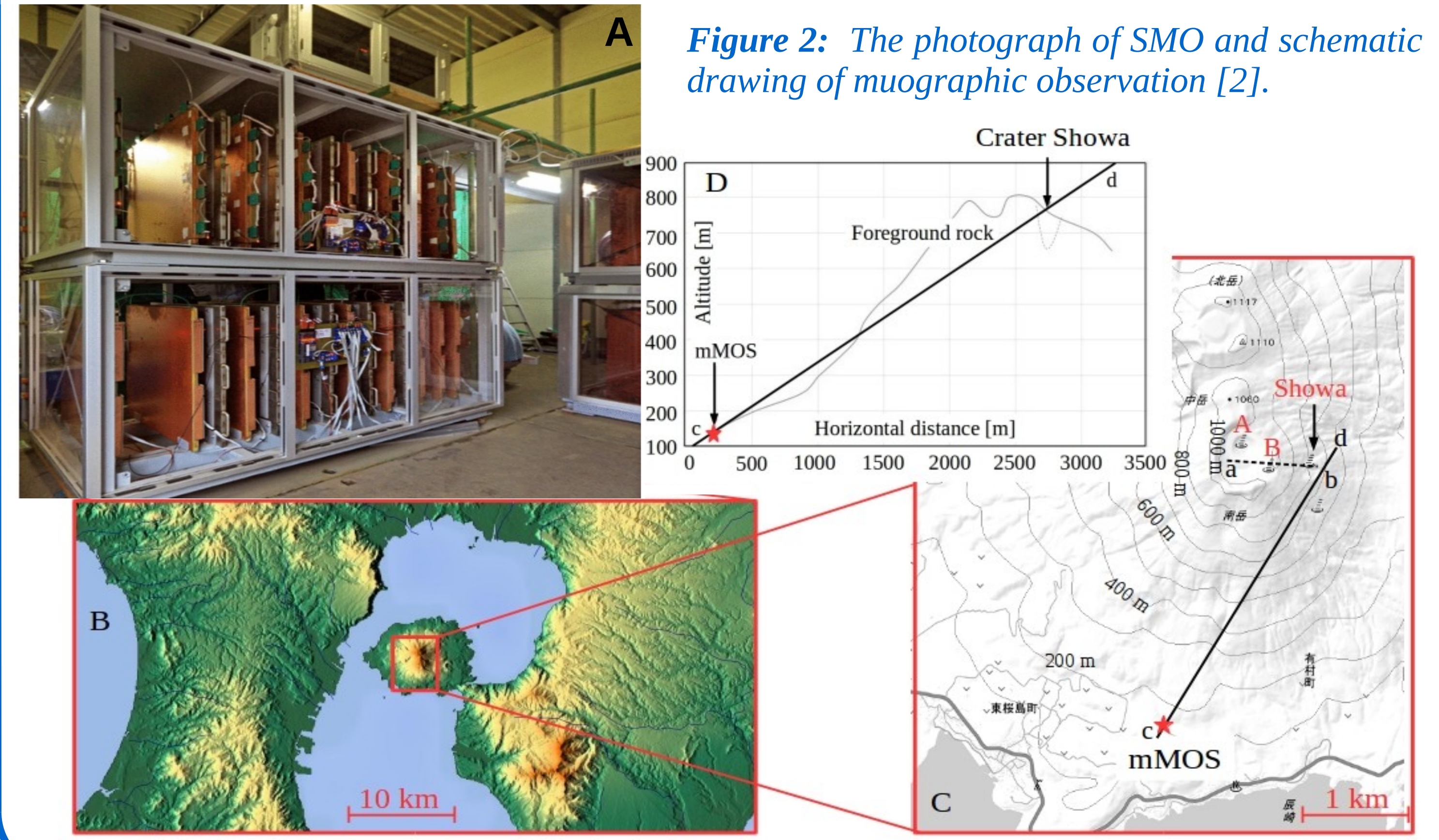
- Passive, mass density sensitive, remote imaging by muon tracking (Fig. 1) [1].
- Shallow regions (thickness <2 km, depth <200 m) are explored beneath the craters.
- High (~10 m) spatial resolution is achieved from safe (~ km) distance.

Figure 1: Schematic drawing of muography and the first time-sequential muographic images [1].



II. Sakurajima Muography Observatory

- Sakurajima is an active stratovolcano. Two craters, namely Minamidake and Showa, erupt a few hundred times per year.
- Sakurajima Muography Observatory (SMO) is continuously monitoring the yield of muons through the southern peak of the volcano from a distance of 3 km in south-west direction with an MWPC-based Muography Observation System (Fig. 2) [2,3].



III. Probing the Upper Conduit Structure with Joint Muon and Ground Deformation Monitoring

- An anti-correlation was found between the densities beneath Minamidake and Showa craters (Fig. 3A): The Pearson's coefficient was quantified as -0.52 (Fig. 3B) [4]. The inverse correlation between densities was observed for the entire period, suggesting that magma degassing occurs either in Minamidake crater or in Showa crater, acting as a preferential pathway → **a branched connection between the two conduits** [4].
- **Magma migration towards East in 2021** [5]: Deformation modelling (Fig. 3C): the deformation source moved eastward beneath the active craters at a depth of 700 m. Muography (Fig. 3D): the mass decreased beneath the Mindamidake A and Minamidake B craters, and increased beneath the Showa crater. Eruption frequency (Fig. 3D): shifted from Minamidake A to Minamidake B. → **A deep horizontal magma channel around 700 m beneath the craters feeds the two Minamidake craters.**
- **Magma rising before the 2023 eruption of Showa crater** [5]: Deformation modelling (Fig. 3C): the source of ground deformation rose about 350 m beneath the active craters. Muography (Fig. 3D): the mass increased beneath the Showa crater. Eruption frequency (Fig. 3D): the Showa crater started to erupt in early 2023. The Minamidake craters remained active. → **A shallow magma reservoir feeds all craters.**

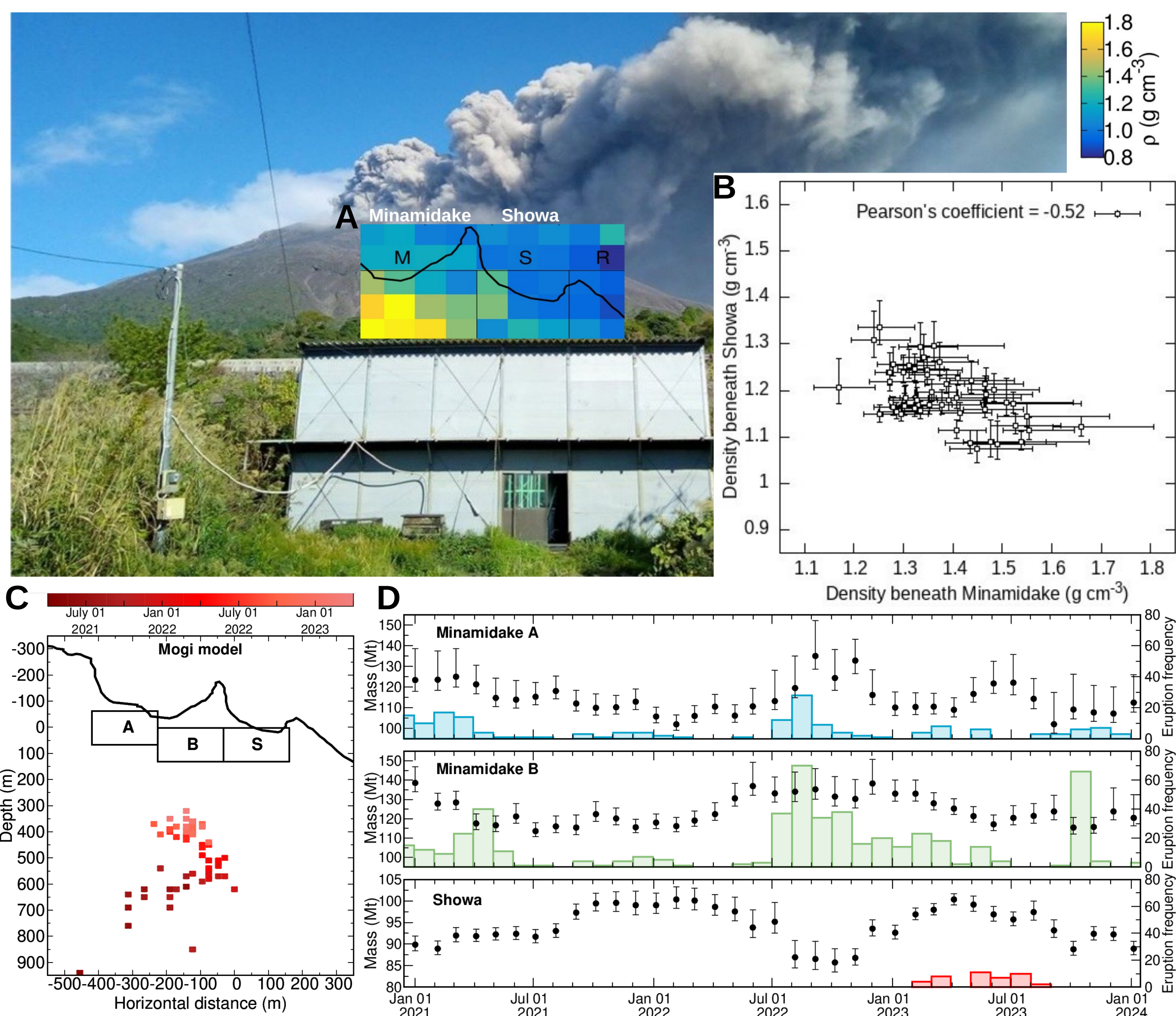
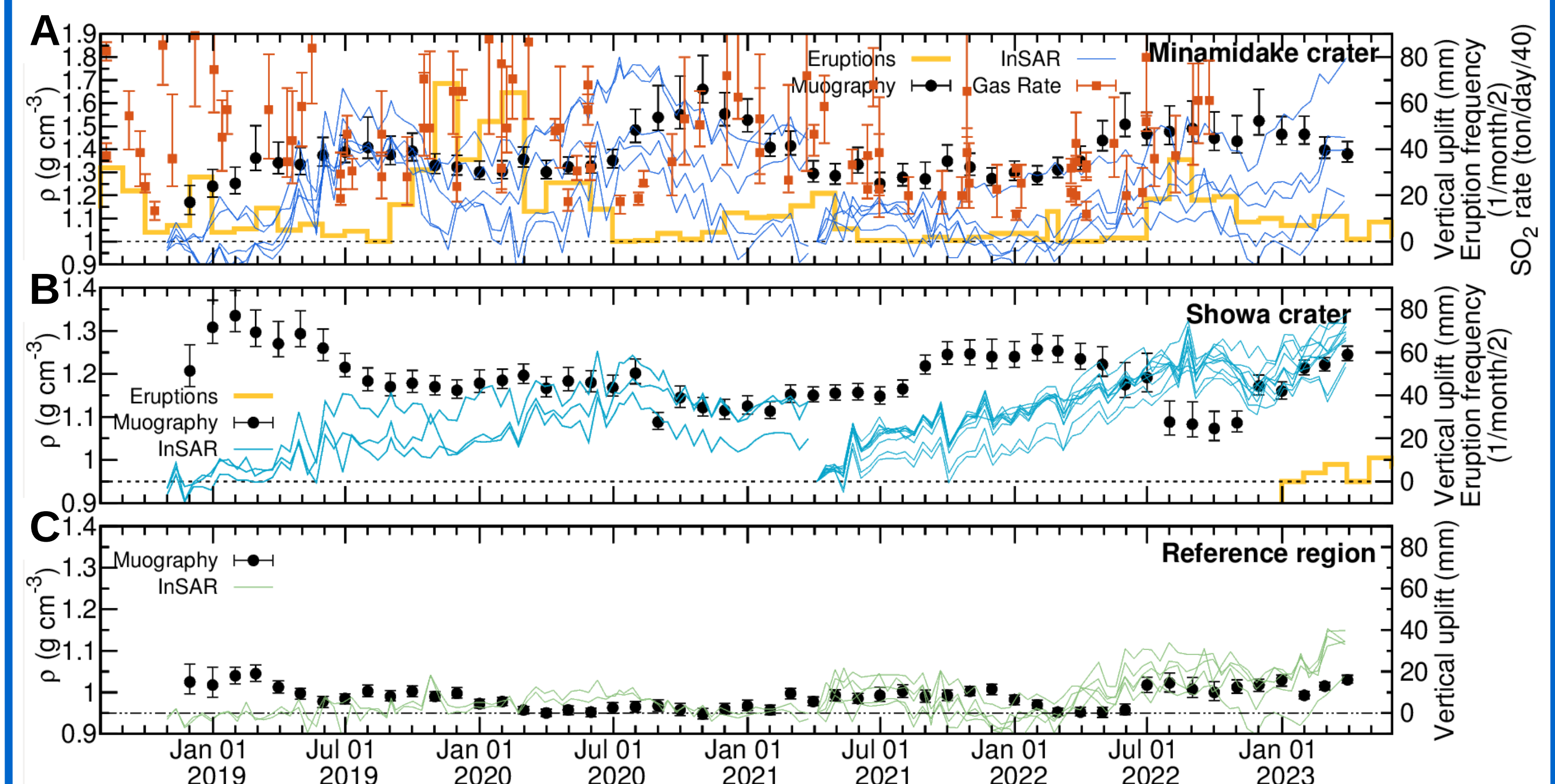


Figure 3: (A) Density image of Sakurajima volcano is shown. (B) The scatter plot of densities measured beneath Showa and Minamidake craters [4,7]. (C) Ground deformation source was localized by forward modelling [5]. (D) Results of muographic mass monitoring are shown [5].

IV. Determining the Volcanic Unrest Index from multi-parametric monitoring data

- **The Volcanic Unrest Index (VUI) semi-quantitatively evaluates the intensity of volcanic activity by comparing it with historical activity levels** [6]. The uses of the VUI: (1) Communicates complex observational data to society, and (2) provides input information for event-tree models used to assess hazard levels.
- We calculated the VUI based on the rates of change in density, the vertical component of ground deformation, and sulfur dioxide gas flux (Fig. 4).
- In Table 1, **low activity (VUI2) marks the period during which all observational datasets reached their maximum values (September 2019 to December 2020)** [7]. The VUI2 is associated with the time period having the highest eruption probability.
- The less active (VUI1) and inactive (VUI0) states were linearly scaled relative to VUI2.
- In future works, we aim to add the results of ground surface deformation source modelling to the above-presented data sets. The determined VUI levels are planned to be incorporated into probabilistic hazard models to improve eruption forecasts and risk mitigation strategies.



	0: no unrest	1: negligible unrest	2: minor unrest
Mass density rate	No change in the density	Low rate of density increase (<0.05 g/cm ³ /month)	Moderate rate of density increase (0.05–0.15 g/cm ³ /month)
Vertical ground displacement rate	No deformation	Low rate of deformation (<10 mm/month)	Moderate rate of deformation (>10 mm/month)
SO ₂ gas flux rate	Low levels of gas flux rate (<1000 t/day)	Moderate levels of gas flux rate (1000–2500 t/day)	Moderate levels of gas flux rate (2500–5000 t/day)

Figure 4: Densities are shown for the region beneath the Minamidake (A), Showa (B) craters and across a reference region (C). Eruption frequencies are shown by the orange histograms. The SO₂ emission rates are shown with brown-coloured rectangles with error bars [4,7]. Table 1: The framework of the volcanic unrest index was constructed from monitoring data.

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