Additional File 1

A possibility of fluid migration due to the 2023 M6.5 Noto Peninsula earthquake suggested from precise gravity measurements

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Soil moisture content

Figure A1 shows a result of the simulation based on observed weather and soil data published by the National Agriculture and Food Research Organization (https://soil-inventory.rad.naro.go.jp/). The results for the lowland soil group with a high clay content at the AMeDAS Wajima station are shown. The results for other kinds of soils are also available, but they show a similar tendency.

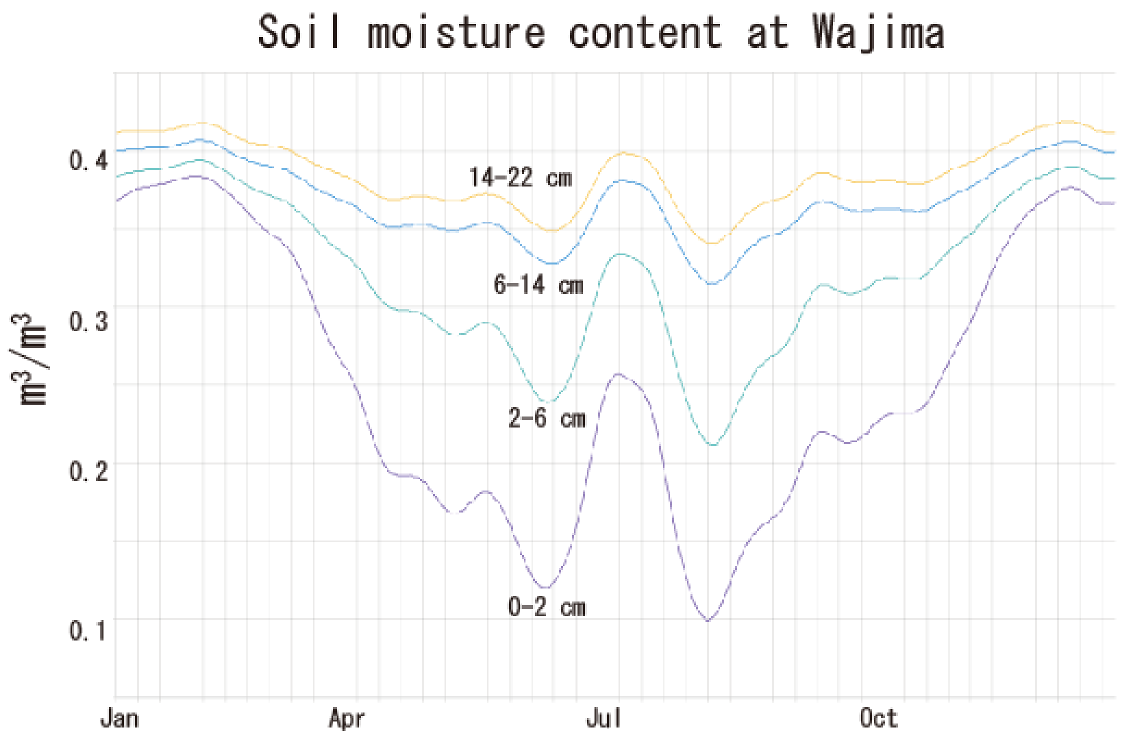

Figure A1. Seasonal changes in the soil moisture content in Wajima from 1981 to 2010 at the four depths that are shown.

Height change at SZHK

Figure A2 shows the height change recorded at SZHK that was derived from the GNSS observations. The preseismic wide-area trends and common errors are removed using the method described in Nishimura et al. (2023). The May 2023 earthquake caused an uplift of approximately 18 cm. The red circles indicate the times of the gravity observations. The uncertainty of the gravity observations is 2 μGal, corresponding to 1 cm in terms of height.

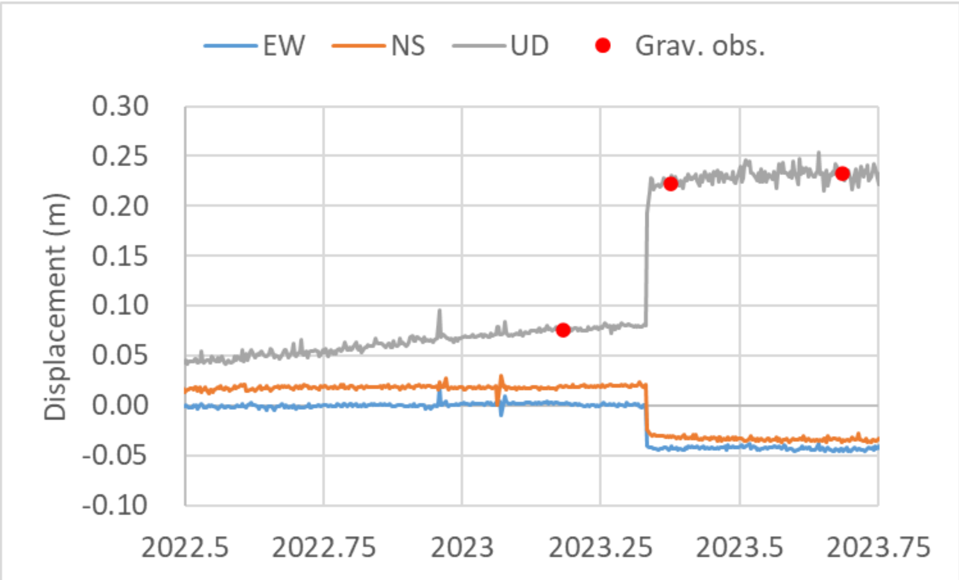

Figure A2. Daily displacements at SZHK. EW, NS and UD denote the east–west, north–south and up–down components, respectively.

Coseismic stress changes within the crust

Figure A3 shows the *N*–*N* component of the coseismic stress tensor computed by the formula of Okada (1992), where *N* denotes northward. The fault parameters are those for Case I in Table 1. The top edge of the fault is located at X=0–7.1 km, Y=7.4 km and Z=6 km. At depths of 0 km and 2 km, the stress change promotes north–south extension above the entire fault plane. At depths of 3 km and 5 km, similar stress changes occur over the southeastern half of the fault plane. The change in volumetric strain also shows a similar tendency. These results indicate that the coseismic stress change tends to open cracks and dykes in the east–west direction.

References

Okada Y (1992) Internal deformation due to shear and tensile faults in a half-space, Bull. Seism. Soc. Am., 82, 1018-1040.

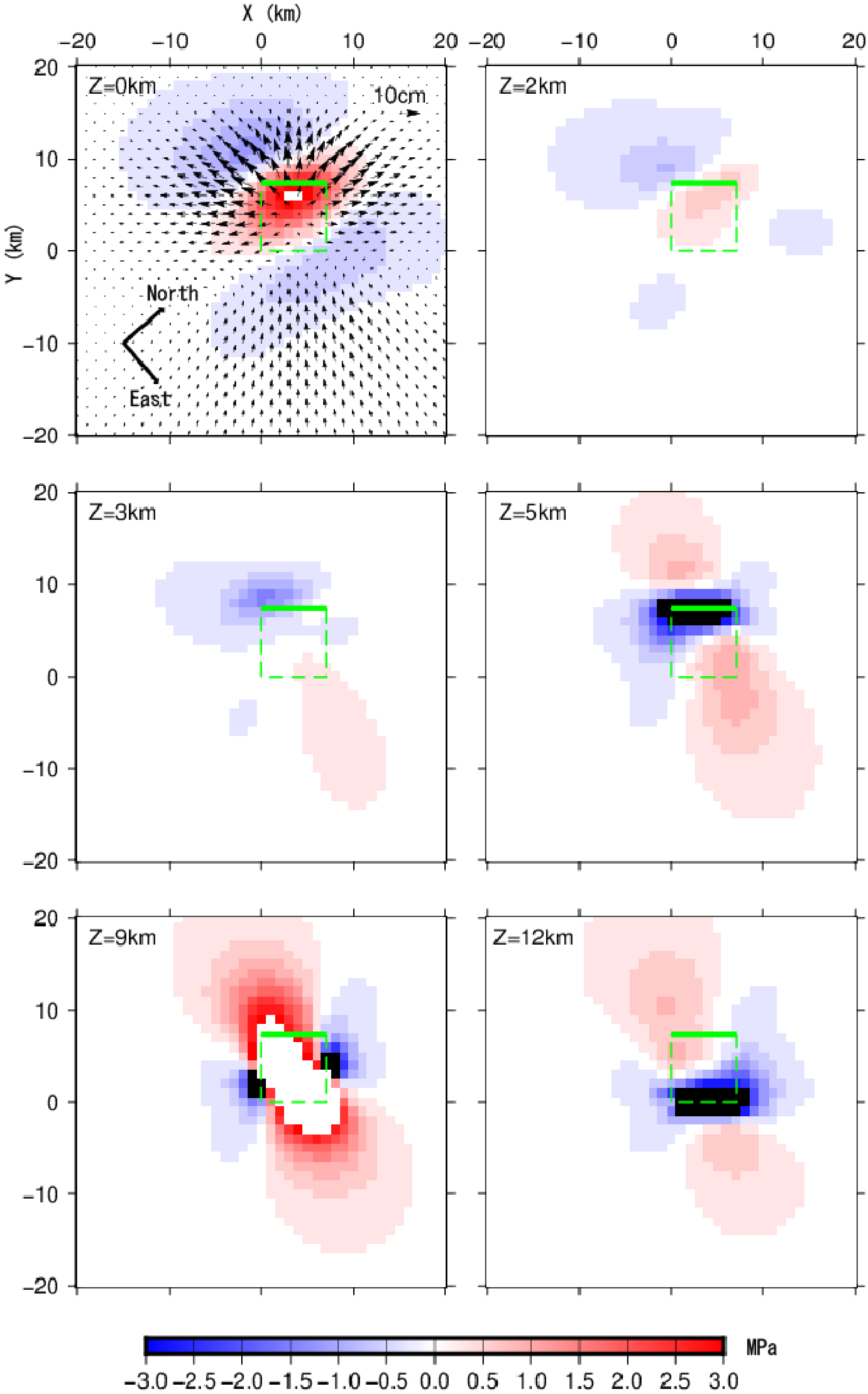
X (km)
Y (km)
Z=0km
10cm
North
East
Z=2km
Z=3km
Z=5km
Z=9km
Z=12km
MPa
−3.0 −2.5 −2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0

Figure A3. The coseismic stress changes in the north–south direction (extension positive) on the horizontal cross-section at depth Z. The units are MPa (the rigidity is assumed to be 30 GPa). The horizontal displacement at the surface is superimposed in the figure for Z=0 km. The N–E axes are tilted 49 degrees clockwise with respect to the X–Y axes. The location of Fault A is shown by the green lines.

Effects of heterogeneities in the structure of Earth and slip distribution

The impact arising from the adoption of a different Earth model is expected to have a negligible effect on the conclusions of this study for the following reasons.

i) According to seismic tomography, heterogeneities in density and elasticity structures reach a maximum of ~10% in the source area (e.g., Nakajima 2022). These differences exhibit a maximum of ~10% surface displacement and total gravity change in forward modeling.

ii) By performing the inversion, the effects of heterogeneities are eventually adjusted by the fault slip and/or the other fault parameters.

iii) In our analysis, we focused on reproducing a “relative” ratio of gravity anomaly to total gravity change. The dislocation models that assume shear slip show that the gravity anomaly is smaller than 10% of the total gravity change, which is irrelevant to the employed Earth models. The effects of employing different Earth models on the gravity anomaly are therefore 1% or less of the total gravity change.

iv) As long as we model crustal deformation assuming shear slip only, the observed large ratio of the gravity anomaly to the total gravity change (>15%) cannot be reproduced. Uncertainties in the Earth model parameters slightly increase the errors in estimating the displacement and gravity changes in an absolute sense. However, if we focus on the ratio of the gravity anomaly, the effects of the errors are small, and a half-space model, as the first approximation, is sufficient to show that an additional source is necessary for shear slip.

In our modeling, a rectangular fault with uniform slip was employed. Heterogeneities in the slip distribution may cause changes in the gravity anomaly. However, this effect is considered to be small for the following reasons.

The M6.5 rectangular fault produced a gravity anomaly of ~2 μGal, as shown in Figure 3 (d). This implies that, to produce a gravity anomaly of -6 μGal at SZHK, twice the amount of slip would be required in addition to the rectangular fault. As an extreme case, one could add localized shear slip to the area below SZHK with a moment magnitude twice as large as the M6.5 fault slip. This local slip would cause extremely large displacement and total gravity changes at SZHK, which would disagree with the observations.

Therefore, the rectangular fault is sufficient to achieve the objective of the current study.