Effect of seismic fault slips at various depths on the E_1' center in quartz

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A fault dating using electron spin resonance (ESR) is a developing method to estimate the age of the last fault movement. This method assumes that natural radiation-induced ESR intensity, which is proportional to the concentration of charges trapped in defects accumulated in the interseismic period, is completely reset due to fracturing, loading, and frictional heating by a seismic fault slip (Ikeya et al., 1982 *Science*). This is called ESR signal zeroing, and the incomplete zeroing can result in age overestimation, hence, the deep understanding of the mechanism and conditions for complete/incomplete zeroing is required. We have performed high-velocity friction (HVF) experiments under various normal stresses to investigate the possibility for the signal zeroing by seismic fault slips at various depths. Moreover, to reveal factors enhancing/impeding the signal zeroing, we conducted microstructural observations on the experimental products and temperature estimations within the gouges during the HVF experiments.

HVF experiments were performed for coarse-grained, synthetic quartz grains as the starting material, at an equivalent slip rate of 1 m/s, normal stresses (σ) of 1–3 MPa, and displacements (D_{eq}) of 10–40 m. ESR measurements to detect the E_1' center in quartz (≡Si$^\bullet$, where – is an electron pair and $^\bullet$ is an unpaired electron) were conducted for the starting material and simulated-fault gouges. We observed the microstructures of the starting material and gouges using a scanning electron microscope (SEM). The temperature within the gouges during experiments was measured by the thermocouple located at the gouge surface and estimated by finite element method (FEM) with COMSOL Multiphysics.

In the HVF experiments at $\sigma = 1$ MPa, the ESR intensity of the E_1' center tended to increase with displacements and were more than 2 orders of magnitudes higher than that of the starting material. In this series of HVF experiments, the maximum temperature estimated by FEM modelling, which was consistent with the measured temperature, was dependent on displacements. Up to $D_{eq} = 30$ m, the maximum temperature in the gouges was estimated to be about 250°C. At $D_{eq} = 40$ m, the estimated temperature reaches 300–500°C due to significant frictional heating. Even though the E_1' center is generally thermally unstable above about 200–300°C (e.g., Toyoda and Ikeya, 1991 *Geochem. J.*), the ESR intensities increased in all of these experiments. It indicates that grain fracturing effect on the E_1' center was more dominant than frictional heating effect for cases at $\sigma = 1$ MPa as shown in the results that grain fracturing during the low-velocity friction increases the intensity of the E_1' center (Tanaka et al., 2021 *Geochronometria*).

In the HVF experiments at $\sigma = 2$, 3 MPa, the ESR intensity of the E_1' center only increased by 1 order of magnitude compared to that of the starting material. SEM observations on the experimental products indicated more significant grain size reduction than those of the HVF experiments at $\sigma = 1$ MPa. Thus, ESR intensity was weakened contrary to our expectation that grain fracturing effect would impede the ESR signal zeroing as shown in cases at $\sigma = 1$ MPa. The FEM modeling showed that small sections near the friction surfaces in the gouges were over 500°C within ten seconds in the experiment. The intensity of the E_1' center is generally completely zeroed by heating at 500°C or higher within a few ten seconds (e.g., Hataya and Tanaka, 1997 *CRIEPI Report*). Hence, frictional heating effect began to be predominant at $\sigma = 2$, 3 MPa. Locally high temperature over 500°C in the gouge zone might play a role to reduce the ESR intensity partly and yield incomplete ESR signal zeroing.

From these results, it could be concluded that ESR signal zeroing mechanism of the E_1' center by high-velocity frictional slip is not simple, but a competition between two opposite effects, grain fracturing and frictional heating, controls the ESR intensity.

Keywords: High-velocity friction, Electron spin resonance, Grain fracturing, Frictional heating, E1′ center, Quartz