Low-frequency earthquakes in close vicinity of repeating earthquakes in the brittle upper crust of Hakodate, Hokkaido, northern Japan

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Pore pressure changes at depth affect fault strength and thus play an important role in the generation of earthquakes (e.g. Hubbert & Rubey 1959; Nur & Booker 1972; Rice 1992; Sibson 1992, 2020; Hasegawa 2017). The occurrence of deep low-frequency earthquakes (LFEs) is suggested to be closely related to fluid behaviour (e.g. Ukawa & Ohtake 1987; Hasegawa & Yamamoto 1994; Aso *et al*. 2013). In this study, we conducted a detailed investigation of an earthquake cluster distributed from the lower crust to the upper crust beneath Hakodate, Hokkaido, which included both semi-volcanic low-frequency earthquakes (LFEs) and regular earthquakes.

We first relocated the hypocenters of 212 earthquakes (MJMA 0.0–2.7) listed in the JMA unified catalogue from this region of Hakodate, Hokkaido, for the period from January 2003 to October 2018. Of these earthquakes, 189 and 23 were classified as LFEs and regular earthquakes, respectively, in the JMA unified catalogue. Relocated hypocenters clearly show that both the LFEs and regular earthquakes occurred close to each other in the brittle upper crust of this non-volcanic area, while only LFEs occurred in the lower crust. Inspection of the observed earthquake waveforms has shown that some of LFEs that occur in the shallow upper crust were misclassified as regular earthquakes in the JMA unified catalogue.

The observed differences between LFEs and regular earthquakes might be related to differences in pore pressure and/or fluid volume: larger pore pressure and/or fluid volume for LFEs than regular earthquakes. However, a reduction in effective normal stress alone cannot explain some characteristics of LFE waveforms, including their significant CLVD components and long-lasting high-amplitude codas. These characteristics may be explained by incorporating other fluid effects, such as fluid movement (Hasegawa & Yamamoto 1994), nonlinear self-excited oscillations induced by a fluid flow (Julian 1994), or oscillations of fluid-filled resonators (e.g. Kubotera 1974), which were proposed to explain the characteristics of volcanic long-period (LP) events.

Regular earthquakes that occur in close vicinity of LFEs have very similar waveforms and nearly overlapping source regions, which indicate that they reflect the repeated rupture of the same asperity patch on a fault. Temporally, the intervals between events in the repeating earthquake sequence were very short, thus suggesting that they were caused by a sudden increase in pore pressure. The deep cluster of earthquakes, composed of LFEs, in the lower crust seems to connect with a shallower cluster of earthquakes composed of both LFEs and regular earthquakes. As a whole, the earthquakes have a rod-like distribution extending from the bottom of the crust to near the surface and dipping slightly eastward. This continuous eastward-dipping zone that extends through the entire crust might represent a pathway of aqueous fluids originally sourced from the subducting slab.

Keywords: deep low frequency earthquakes, repeating earthquakes, fluid supply

