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Variations in the magnetic field arising from the propagation of teleseismic waves in magnetized crust with finite conductivity

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Variations in electromagnetic fields following large earthquakes are frequently reported. Some of magnetic variations have been observed at sites located at large distances (i.e. longer than several hundred of kilometers) from epicenters (e.g. Eleman, 1969; Taira et al., 2009). Theoretical considerations predict that changes in stress and displacement of the crust cause electromagnetic variations of various types; however, quantitative natures of them have not been sufficiently discussed. An understanding of the basic properties of signals arising from each mechanism is essential from both theoretical and applied perspectives. In the present study, we consider the piezomagnetic effect, which involves changes in the magnetization of ferromagnetic minerals under mechanical stress (Stacey, 1964; Nagata, 1970; Stacey and Johnston, 1972). Previous studies on variations in the geomagnetic field arising from the piezomagnetic effect have been performed in a framework of elastostatics (see the review by Sasai, 1994). However, to interpret co-seismic variations in magnetic fields in terms of the piezomagnetic effect, theories should be reconsidered in a framework of elastodynamics. The author derives analytical and semi-analytical solution of variations in the magnetic field arising from the piezomagnetic effect (i.e. the piezomagnetic field) corresponding to two situations, and discusse their quantitative features.

First, a situation is considered in which magnetization structure is horizontally uniform and the Earth's crust has finite conductivity. Starting from an expression of the electromagnetic field radiated from a point source in stratified conductive material (Stoyer, 1977), we can successfully derive an analytical solution of the piezomagnetic field in this situation. Using the obtained solution, quantitative aspects of the piezomagnetic field that accompanies seismic Rayleigh waves are considered. It is shown that the finite conductivity of the Earth's crust sometimes acts as an enhancer of the magnitude of the piezomagnetic field. However, the expected piezomagnetic field is substantially small. Even in the case that the initial magnetization around the observation site is as large as 5 A/m, the expected amplitudes in the piezomagnetic field are at most 0.1 nT.

Next, a situation is considered in which magnetization structure is horizontally non-uniform. A scheme is proposed for calculating the piezomagnetic fields that accompany the propagation of seismic waves through a non-uniformly magnetized crust. The calculation of co-seismic piezomagnetic fields involves laborious three-dimensional volume integrals in general, even if the magnetization structure is two-dimensional. However, the calculation is simplified by considering the Fourier transform of spatial distributions of the field. Using the obtained semi-analytical solution, the piezomagnetic field corresponding to the same seismic parameters to the uniformly magnetized case is calculated. The amplitudes of the piezomagnetic field arising from non-uniformly magnetized crust are as large as 0.5 nT, which are considerably larger than those expected in the case of uniform magnetizations. However, a highly magnetized crust ($\sim$10 A/m) is assumed to generate this value of the piezomagnetic field.

The above results imply that the piezomagnetic effect is not a reasonable mechanism to sufficiently explain variations in magnetic fields that occur synchronously with ground motions, in general. When the magnetization structure is horizontally uniform, the expected magnitude of the piezomagnetic field is too small to be observed. When the magnetization structure is non-uniform, and when the intensity of magnetization is considerably large, the piezomagnetic effect may be a reasonable mechanism; however, such situation is only seen in restricted areas including volcanic areas. Therefore, other possible mechanisms including the electromagnetic induction due to ground motions and the electrokinetic effect would be rather reasonable in many cases. The quantitative evaluations of them are required in the future studies.