Geophysical Research Abstracts
Vol. 18, EGU2016-5340, 2016
EGU General Assembly 2016

Imaging hydraulic fractures at Median Tectonic Line, Japan using multiply generated and scattered tube waves in a shallow VSP experiment

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Tube waves are low frequency guided waves that propagate along a fluid-filled borehole. The analysis of tube waves is a promising approach to image and characterize hydraulic fractures intersecting a borehole. It exploits tube waves generated by an external seismic wavefield which compresses fractures and injects fluid into the borehole. It also utilizes the attenuation of tube waves due to fluid exchange between the fracture and the borehole, which creates scattered waves (reflection and transmission).

Conventional approaches consider tube waves due to a single fracture. However, when the spacing between multiple fractures is short relative to the wavelength of the tube waves, the generated and scattered tube waves interfere with each other, making it difficult to isolate the effect of a single fracture. The analysis of closely spaced fractures is important in highly fractured areas, such as a fault zone.

In this study, we explore the possibility of prediction and utilization of generated and scattered tube waves due to multiple fractures. We derive a new integral equation of the full tube wavefield using 1D wavefield representation theory incorporating nonwelded interfaces. We adapt the recent developments in modeling tube wave generation/scattering at a fracture. In these models, a fracture is represented as a parallel wall or a thin poloelastic layer. This allowed us to consider the effects of a dynamic fracture aperture with fracture compliances and the permeability. The representation also leads to a new imaging method for the hydraulic fractures, using multiply-generated and scattered tube waves. This is achieved by applying an inverse operator to the observed tube waves, which focuses the tube waves to the depth where they are generated and/or scattered. The inverse operator is constructed by a tube wave Green's function with a known propagation velocity.

The Median Tectonic Line (MTL) is the most significant fault in Japan, extending NE-SW for over 1000 km across the Japanese Islands. We observed multiple tube waves in a P-wave VSP experiment in a 250 m deep, vertical borehole located on the MTL at Shikoku, Japan. The borehole televiewer and the core studies show that below 40 m depth, the Sambagawa metamorphic rocks contain highly fractured zones which consist of more than 100 open fractures and more than 30 cataclasites.

We predict the full tube wavefield using the values of fracture depth and thickness known from the borehole televiewer. We model the open fractures as parallel-wall fractures and the cataclasites as thin poroelastic layers. Furthermore, we estimate the depth of the hydraulic fractures by applying the inverse operator. The results show that the tube waves could be generated and scattered at these permeable structures. Our preliminary results also indicate the possibility that the effect of the open fractures is more dominant in the generation and scattering of tube waves than that of the cataclasites in this field. The formulation and the results presented in this study and the following discussion will be useful in analysis of tube waves in highly fractured zones, in order to localize and characterize hydraulic fractures.