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Determining the rupture process of the 7 May 2001 M2 4.1 Ekofisk induced earthquake using seismological and deformation data

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On 7 May 2001, following unintentional water injection in the reservoir overburden, a moderate size (Mw 4.0-4.5) induced earthquake struck the Ekofisk oil field, North Sea. The ground shaking was strongly felt on platforms within the oil field, providing a first evidence for a source location in the vicinity. Despite of its relatively moderate magnitude, clear low frequency waveforms were recorded up to about 2500 km epicentral distance, suggesting a slow rupture at very shallow depth and propagation of seismic waves through low velocity shallow layers, consistent with the sedimentary basin surrounding the source region. The lack of stations at short distance and the poor quality of body waves at stations further away results in large uncertainties of the epicentral location. At the same time, a local GPS network operational at Ekofisk since 1985 to monitor subsidence, recorded coseismic deformation, indicating a general subsidence (up to 7 cm) and E to ENE horizontal displacements (up to 16 cm), with larger deformation in the central part of the oil field . A fourth GPS, located at the West Ekofisk field, measured only minor deformation with consistent displacement directions compared to GPS sensors at Ekofisk field. Two specific studies discussed the earthquake source process suggesting a rupture along a horizontal plane leading to a vertical dip-slip focal mechanism. However, the directions of pressure and tension axes in both works were almost inverted, providing ambiguous earthquake source models. A further investigation was thus required to provide the basis for a deeper discussion of the failure dynamics. Using these prior studies as a starting point, we improve the available seismic dataset, test different earth models and finally derive a point source model. We carefully discuss parameter uncertainties and effects related to shallow sources and wave propagation, which may explain the ambiguity of previous results. The centroid location and focal mechanisms are further investigated combining seismological data and local GPS measurements at different platforms. Thus, the polarity of our focal mechanism is confirmed, while the centroid is relocated to the Eastern edge of the field at a depth of about 2km, which is consistent with the depth of water injection. We further derive an extended kinematic source model based on the focal mechanism geometry and the observation of directivity effects. According to our model, the rupture occurred along a sub-horizontal plane and propagated towards SW. The proposed rupture model is able to explain all available geophysical observations simultaneously.