Source Process of the 2014 M_L5.5 Orkney Earthquake, South Africa

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Abstract

In this study, we analyzed the main shock waveforms and aftershock distribution of then 2014 Orkney earthquake, South Africa, to understand the rupture process of this earthquake. We picked P and S wave arrival times of the main shock and found two sets of phases in those seismograms. One pair is radiated by earlier and smaller event (M_L<4), which is the initial rupture occurred at shallower depth and the other by main rupture occurred at northward of initial. Next, we applied double-difference relocation method to P and S wave arrival times of the aftershocks and the initial and main ruptures of the main shock. We found vacant space in the deep parts of the planarly aftershock distribution, which correspond to the mainshock hypocenter. Additionally, we applied Isochrone backprojection method to mainshock S-wave waveforms. Strong rupture distribution seems to fill the vacant space of the aftershocks distribution and main shock hypocenter.

Keywords: rupture process, aftershock distribution, strong motion generation area, Isochrone backprojection method, and initial rupture

INTORDUCTION

2014 Orkney earthquake (ML5.5) has occurred beneath the Orkney town, Klerksdorp district in the North West province, locate at south- westward of the Pretoria, capital of the Republic of South Africa (Figure 1). This town has 10 more gold mines, whose vertical shafts reached down to 3.6 km below the ground surface (BGS).

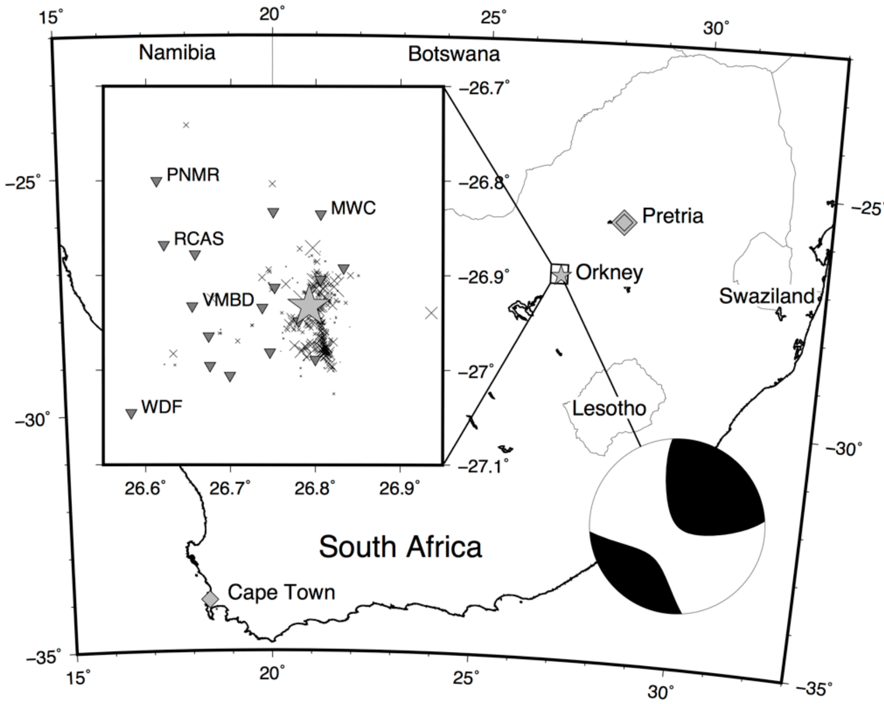

Figure 1. Seismic stations and epicenters of the 2014 Orkney earthquake (mainshock) and half-day period aftershocks occurred after mainshock. Map view of the Republic of South Africa is shown in background. Star shows the epicenter of the 2014 Orkney earthquake estimated by Global CMT website, and CMT solution is also shown at lower right. Orkney town, which nearest town of the hypocenter, is located south-westwards from the Pretoria, capital of the republic of South Africa. Ground acceleration seismographs network operated by CGS around the Orkney town and epicenters are shown in upper-left column. Invert triangles and cross indicate the seismographs and epicenter of aftershocks, respectively.

Global CMT website (Global CMT, 2014[1]) summarize this earthquake information, PDEW origin time is 10:22:34.00, 5th Aug 2014, and its hypocenter is 26.99°S, 26.71°E, depth 5 km, with magnitude M_S 5.4 and CMT origin time is 10:22:36.20, and its hypocenter of centroid is 26.83°S, 26.79°E, depth 12 km with M_W 5.5. And its fault mechanism is NNW trended right lateral strike fault (Figure 1). According to this report, origin time and epicenter is quite different with PDEW and CMT. These difference seem to be caused by the hypocenter estimation method, PDEW, which is the Preliminary Determination of Epicenters (USGS, 2014[2]), used phase arrival times and their amplitude, the other hands, CMT, centroid moment tensor solution, used full waveforms of body-wave. Council for Geoscience (CGS), which is National Institute of the Republic of South Africa, have established a ground acceleration seismographs network around the Orkney town (see small upper-left column of Figure 1) with the project ‘Observational Studies in South African Mines to Mitigate Seismic Risks’ of JICA-JST SATREPS (e.g. Ogasawara et al., 2012[3]), which is one of the scientific collaboration projects between South Africa and Japan. Using with this network seismograms, CGS reports depth and magnitude of the earthquake, 5 km and M_L5.5, respectively (*e.g.* okubo *et al.*, 2015[4]). In spite of this earthquake magnitude is not so large, its depth is quite shallow and additionally we have dense seismograms network above its hypocenter. In this paper, we clarified the rupture process of the 2014 Orkney earthquake to understand the relationship among mainshock hypocenter, aftershock, and simultaneous strong ground motion.

ANALYSES:

We checked all waveforms of the mainshock at first, because waveforms sometimes saturated and/or unstable for shallow depth earthquake. 16 ground acceleration seismograms are shown in Figure 2. Two stations, KDGC and WDF, are unstable and saturated its amplitude bore S wave arrival, thus we use only P wave arrival time. By 50 times zooming up amplitudes of P-wave arrival, small amplitude vertical component variation (gray colored) was appeared approximately 0.2 - 0.4 second before significant P-wave variations, additionally their time differences seemed to have been varied with direction toward stations. Thus, we carefully picked up two pairs of P- and S- wave arrival time from mainshock seismograms, by using WIN system (Urabe and Tsukada, 1992[5]). These pairs of phase arrivals show two slightly distant hypocenters with 0.3 second different origin time, which estimated by hypoMH (Hirata and Matsu'ura, 1987[6]). Initial rupture's hypocenter is located at the depth of 4.3 km, in the other words, 5.8 km below the surface. For this determination, we used the P-wave velocity structure listed in Table.1 and V_P/V_S ratio (1.78). In this study, we call the initial rupture for earlier and small variation, and the following main rupture for significant one. By comparison initial rupture vertical component P wave amplitude and main rupture's of PNMR, RCAS and VMBD, P-wave amplitude approximately 50 times smaller than main's.

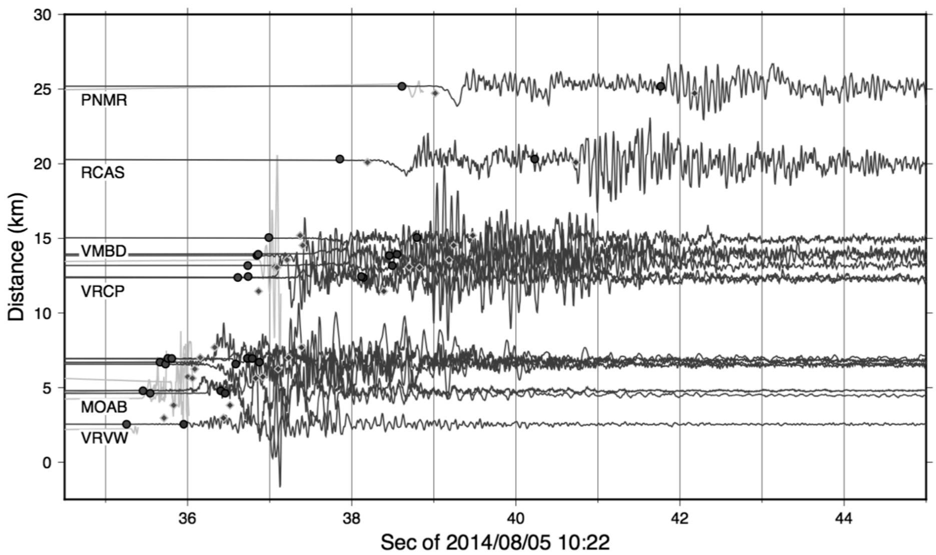

Figure 2. Solid cirlcles layed on each seismograms indicate P- and S-wave arrival time of initial rupture. in order to identified initial P- wave arrival, 50 times amplified waveforms are shown below the original waveforms of VRVW MOAB, VRCP VMBD RCAS and PNMR. Small diamonds show phase arrivals of main rupture.

The 2014 Orkney earthquake's mainshock, which included the initial rupture and the main rupture, and aftershock hypocenters have been determined absolutely and individually. Relationship of each hypocenter locations seems to be preliminary results. Therefore we applied double-difference hypocenter relocation method, hypoDD (Waldhauser and Ellsworth, 2000[7]) to understand hypocenter distribution of events relative to the initial rupture.

Table 1. P-wave velocity structure for our analyses

hypoMH (km/s)	5.10	5.10	5.78	6.10	
hypoDD (km/s)	2.00	5.10	5.78	6.10	
Depth (km)	-3.0	0.0	2.0	17.0	25.0

A CGS event catalogue, which have been determined with Horiuchi's automatic hypocenter determination method (e.g. Horiuchi et al., 2005[8]), includes 337 aftershocks between approximately a half day until the end of 5 Aug. 2014. This catalogue records P- and S- wave arrival times for each event. We used these phase picked up data and the initial- and main rupture phase picked up data. We assumed quite slow P-wave velocity at shallow layer (< 0 km, shown in Table 1) to avoid earthquake hypocenter locates in air. After elimination of some outlier aftershock events, we analyzed 247 events, 69680 P arrival time pairs and 59777 S arrival time pairs, by minimized weighted least squares using the method of singular value decomposition (SVD). Finally, 144 events were relocated their hypocenters relative to the hypocenter of the 2014 Orkney earthquake initial rupture. We obtained that detailed aftershock distribution with most events located on a NNW trended and slightly west inclined plane. Viewing in detail, most of aftershocks are occurred at southern and upper part of hypocenter of mainshock.

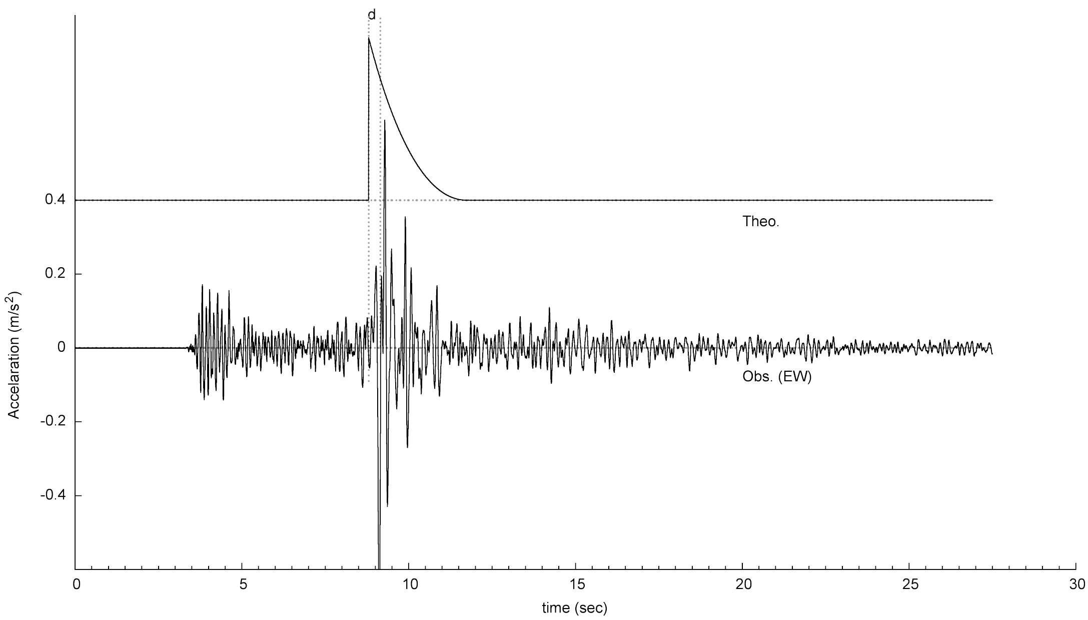

Figure 3. Hypothesis of the ideal S-wave amplitude variation for IBM analysis. Example seismogram and ideal S-wave amplitude variation is shown. maximum amplitude of Ideal S-wave appears at the same time on phase arrival, and decays by time. On the other hand, the maximum amplitude of observational seismogram is sometimes delayed(t) and its variation is not smooth.

In order to understand the reason of the vacancy of aftershock distribution, we applied Isochrone backprojection method (e.g. Pulido et al., 2008[9]) to S-wave waveforms of mainshock. Because the 2014 Orkney earthquake is not so large earthquake, we did not assume a fault plane for concentrating strong motion generating area (SMGA) for our analysis. Instead, we calculated observational spatial SMGA distribution using with observational waveforms and ideal spatial SMGA distribution assumed ideal S wave amplitude variation and travel time (see Figure 3). Finally, we applied deconvolution to these calculation (e.g. Okubo and Saiga, 2014[10]). In this calculation, we used the S-wave velocity as 3.25 km/s, which corresponding to 2 – 17 km depth, and rupture velocity does not excess for 0.9 of S-wave velocity. We also assumed rupture duration does not excess the Global CMT's half duration of earthquake (1.3s). Calculation grid size as 50m, which we define, does not beyond for wavelength of S-wave on 200 Hz. We show the relocated hypocenters and SMGA distribution spatially averaged (5 by 5 grid) in Figure 4. In map view and fault parallel view, some significant SMGA are located on a plane, nevertheless we did not assumed fault plane. Small SMGA distributed off plane, these are not so large amplitude. Thus, these may be artefacts. In fault normal view, SMGA distributed at (1) northern part, (2) southern part, (3) and upper part of initial rupture hypocenter and northern part of distribution (1) is corresponding to the main-rupture. Thus, SMGA located at the vacancy of aftershock distribution around the initial rupture's hypocenter. It seems that aftershocks occurred at the upper and southern edge of SMGA.

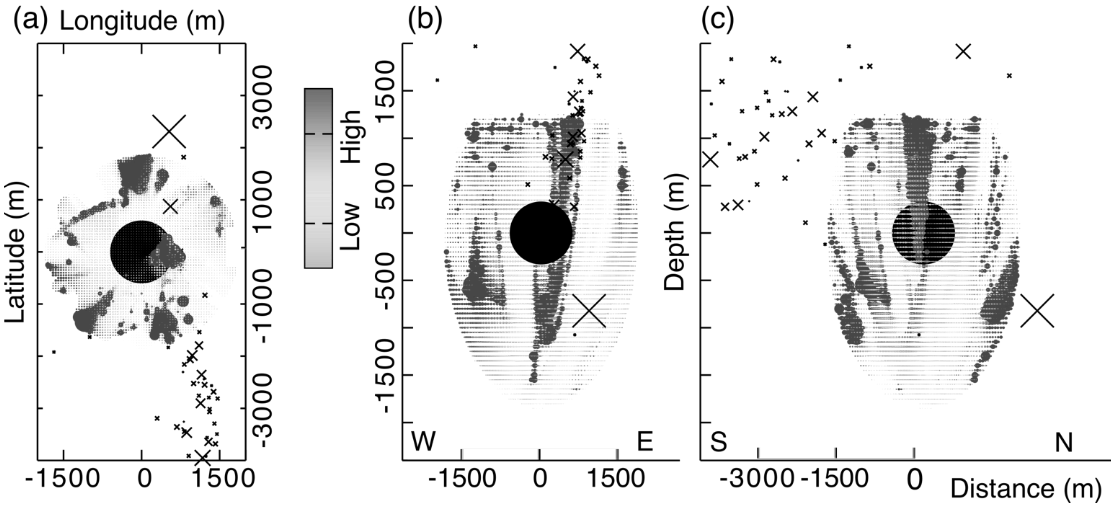

Figure 4. Strong motion generating area (SMGA) distribution of the 2014 Orkney earthquake. Map view around the initial rupture's hypocenter, which indicated by center circle is shown in (a). Aftershock hypocenters are shown by cross and its size is proportional to its magnitude. SMGA are indicated by grey scaled circle. Figure (b) and (c) is vertical section view of fault (NNW trended) parallel view and fault normal view, respectively.

DISCUSSSIONS:

This earthquake includes the initial- and main-rupture, difference of each origin time is 0.3 second, and its spatial distance is 1.0 km. By comparison vertical component P wave amplitude, we can see the initial rupture's amplitude is approximately 50 times smaller than main's. Therefore, Richter scale magnitude of initial rupture should be 1.7 smaller than main rupture. Therefore, initial rupture of the 2014 Orkney earthquake has approximately 4 by local magnitude scale.

We obtained detailed aftershocks distribution with most events located NNW trended and slightly west inclined plane. This distribution is consistent with one of nodal plane that reported by Global CMT solution. Viewing in detail, most of aftershocks are occurred at southern and upper part of initial rupture's hypocenter. Thus, we could have found a seismic vacant around the initial rupture – main rupture area. These vacancies of aftershocks are corresponding to the SMGA distribution, estimated by IBM. Especially, northern part of SMGA on fault plane is consistent with main rupture's hypocenter.

CONCLUSION:

We analyzed dense ground acceleration seismograms of the 2014 Orkney earthquake (M_L5.5), South Africa. This earthquake includes the initial- and main-rupture, difference of each origin time is 0.3 second, and its spatial distance is 1.0 km, at 4.3 km depth. By comparisons of initial motion amplitudes, we concluded the initial rupture of the 2014 Orkney earthquake has smaller than M_L4. Primary Strong motion generating area (SMGA), which obtained by spatial IBM, of this earthquake is locate at northern part of the initial rupture hypocenter, is corresponding to the main rupture. Two more SMGA area distributed on a same plane. Aftershock distribution also located on a same NNW trended, west inclined plane, and this seems to be consistent with one of nodal plane of Global CMT solution of this earthquake. SMGA surrounded around the initial rupture, and aftershock distributed around these, concentrically.

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REFERENCES:

Global CMT (2014) Global CMT Catalog, http://www.globalcmt.org/, accessed 21 Aug. 2016. [1]

Hirata N, and M. Matsu'ura (1987) Maximum likelihood estimation of hypocenter with origin time eliminated using non-linear inverse technique. Phys Earth Planet Int Vol. 47, pp 50–61. [6]

Horiuchi, S., H. Negishi, K. Abe, A. Kamimura, and Y. Fujinawa (2005), An automatic processing system for broadcasting earthquake alarms, Bull. Seismol. Soc. Am., 95, 708–718. [8]

Okubo, M., A. Cichowicz, D. Birch, H. Ogasawara, O. Murakami, S. Horiuchi (2015) Source Process of the 2014 ML5.5 Orkney earthquake, South Africa, JpGU 2015, 2015/05/26 S-SS30-27. [4]

Okubo, M. and A. Saiga (2014) Source dynamics of the Philippine Sea intra-slab earthquakes -Isochron back projection analysis for the 2011 eastern Mino earthquake-, AOGS 2014 Meetings, SE15-D5-AM2-CA-013(SE15-A001). [10]

Ogasawara, H., T. Katsura, G. Hofmann, Y. Yabe, M. Nakatani, M. Naoi, H. Ishii, D. Roberts, S. Nakao, M. Okubo, J. Wienand, P. Lenegan, A.K. Ward. and H. Kawakata (2014) In situ monitoring of rock mass response to mining in South African gold mines using the Ishii strainmeters, The Southern African Institute of Mining and Metallurgy 6th South African Rock Engineering Symposium SARES 2014. [3]

Pulido, N., S. Aoi, H. Fujiwara (2008) Rupture process of the 2007 Notohanto earthquake by using an isochrones back-projection method and K-NET/KiK-net data, Earth Planet Sp, Vol.60, 1035-1040, doi:10.1186/BF03352865. [9]

Urabe, T. and S. Tsukada (1992) win – A Workstation Program for Processing Waveform Data from Microearthquake Networks (in Japanese), 1992 Fall Meeting, Seismol. Soc. of Jpn, P41. [5]

USGS (2014) The Preliminary Determination of Epicenters (PDE), http://earthquake.usgs.gov/data/pde.php, accessed 21 Aug. 2016. [2]

Waldhauser F. and W. L. Ellsworth (200) A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, Bull. Seism. Soc. Am., Vol. 90, pp1353-1368. [7]

Wessel, P. and W. H. F. Smith (1991) Free software helps map and display data, EOS Trans. AGU, 72, 441. [11]