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RUPTURE PROCESS OF THE 2014 ORKNEY EARTHQUAKE, SOUTH AFRICA

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ABSTRACT: An earthquake has occurred at 10:22:33 UT on 5 August 2014 in the Klerksdorp district, the North West province of South Africa. Its hypocenter is located beneath an Orkney town, where more than 10 gold mines exist. The Council for Geoscience (CGS) in South Africa reported that the magnitude and depth was M_L5.5 and 4.7 km, respectively. CGS has been operating 17 surface seismic acceleration stations with 10 km interval in average, and obtained continuous acceleration seismograms through the time of the earthquake and following aftershocks. Using these seismograms, we analyzed the mainshock rupture process of this earthquake. Analyzing these seismograms, we found the 'initial rupture' with a Richter scale approximately 4 has occurred 0.3 sec before mainshock. Furthermore, by applying detailed aftershock distribution analysis, we found most of aftershocks occurred surrounding upper and southern part of mainshock rupture area, including initial rupture hypocenter. In order to understand detailed rupture process of this event, we surveyed for strong motion generating area (SMGA) of mainshock by applying Isochrones backprojection method (IBM) to the mainshock S wave waveforms. SMGA distribution seems to fill the vacant space of the aftershock distribution and initial rupture's hypocenter. And we also found that a horizontal layered seismic vacancy exists between aftershocks with gold mine blastings. This fact implies mainshock rupture did not extent up to gold mine.

Keywords: Aftershock distribution, isochrones backprojection method, multiple rupture, strong motion generating area, tectonic earthquake.

INTRODUCTION

2014 Orkney earthquake (M_L5.5) has occurred beneath the Orkney town, Klerksdorp district in the North West province, located at south-westward of the Pretoria, capital of the Republic of South Africa (fig. 1). This town has more than 10 gold mines whose vertical mining shafts reaches to 3.6 km below the ground surface (BGS). Global CMT website [1] summarized this earthquake information that PDEW origin time was 10:22:34.00UT, 5th Aug 2014, and its hypocenter was located at 26.99°S, 26.71°E, depth 5 km, with magnitude M_S 5.4, and also reported CMT origin time was 10:22:36.20, and its hypocenter of centroid was at 26.83°S, 26.79°E, depth 12 km with M_W 5.5. CMT solution implies that fault mechanism of

Orkney earthquake is NNW trending right lateral strike fault (see also fig. 1). According to this summary, origin time and hypocenter depth is quite different with PDEW and CMT. However, these differences seem to be caused by the hypocenter estimation method. PDEW, which is the Preliminary Determination of Epicenters [2], used tele-seismic phase arrival times and their amplitude, on the other hand, CMT, centroid moment tensor solution, used broadband waveforms of body-waves. Council for Geoscience (CGS), National Institute of the Republic of South Africa, reports hypocenter depth and magnitude of the earthquake, 5 km and M_L5.5, respectively [3]. Fortunately, CGS had established and been operating seismic network with ground acceleration seismographs around the Orkney town (see small upper-left column of fig. 1) as project *'Observational Studies in South African Mines to Mitigate Seismic Risks'* of JICA-JST SATREPS [4]. CGS's hypocentral information estimation used this network seismograms data. This dense seismograph network above on hypocenter will provide us enough seismograms to understand earthquake rupture process, in spite of the fact that its magnitude is not so large and depth is quite shallow. In this paper, using these seismograms we will clarify the rupture process of the 2014 Orkney earthquake to understand the relationships among mainshock hypocenter and its strong ground motion area distribution, and aftershock distribution.

We will show a map of the Republic of South Africa (SA) in background. Star shows the epicenter of the 2014 Orkney earthquake by Global CMT (2014), and CMT solution is also shown at lower right. Upper-left small map shows close-up view around the epicenter, which near Orkney town located south-westwards from the Pretoria, capital of SA. Epicenter of aftershocks, which occurred within following 12 hours after mainshock, are shown by cross, in this map. Furthermore, ground acceleration seismographs network, which has been established by CGS, are shown by invert triangles with station codes.

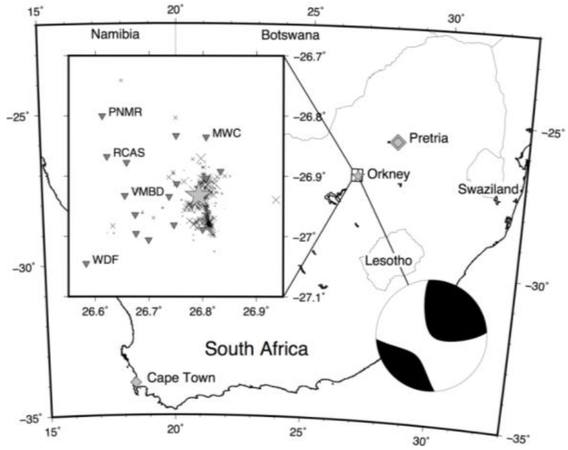

Fig. 1. Epicenters of the 2014 Orkney earthquake and aftershocks

ANALYSES

We checked all seismograms of the mainshock at first, because for shallow depth earthquake with strong motions, waveforms are sometimes saturated and/or unstable. 16 ground acceleration seismograms are shown in fig. 2. We used these seismograms for following analyses, identification for phase arrivals, hypocenter determination, estimation of magnitude, and search for strong motion generating area. Unfortunately, at two stations, KDGC and WDF, their seismograms are unstable and saturated its amplitude before S wave arrival, thus we could use these stations only for hypocenter determination. By 50 times magnified to waveform amplitude near P-wave arrival (gray colored) for all seismograms, we can find small amplitude variation approximately 0.2 - 0.4 seconds before mainshock's P wave arrival in vertical component. Additionally, their differences of arrival times seemed to be varied with their azimuth. We carefully picked up two pairs of P- and S- wave arrival times from mainshock's seismograms, by using WIN system [5]. These pairs of phase arrivals indicate two slightly distant hypocenters, with 0.3 second differences of their origin time, by applying hypoMH [6] hypocenter estimation. Comparing P wave amplitudes of vertical component in PNMR RCAS and VMBD between main large rupture with the first small event, the first one called the 'initial rupture' has only approximately 1-2% amplitude for each station.

Table 1. P-wave velocity structure for our analyses

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

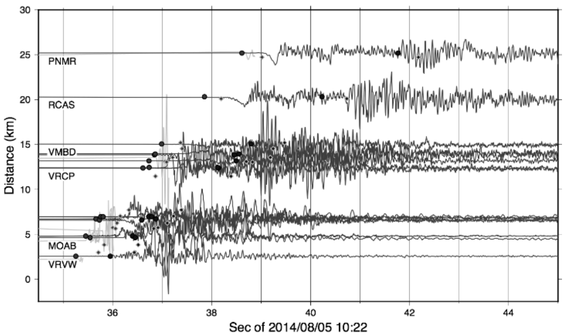

Fig. 2. Seismograms of the 2014 Orkney earthquake

Ground acceleration seismograms of mainshock are shown. In order to identify initial rupture phases, 50 times amplified waveforms were overlaid below the original waveforms of VRVW, MOAB, VRCP, VMBD, RCAS and PNMR. Solid dots laid on each seismogram indicate P- and S-phase arrival, which we had picked up. Large and small dots are corresponding to the initial rupture and main rupture, respectively.

The 2014 Orkney earthquake's mainshock, which includes the initial rupture and the main rupture, and aftershock hypocenters had been determined as absolutely and individually. Next, we would like to understand the spatial relationship of each hypocenter locations. We applied double-difference hypocenter relocation method, hypoDD [7] to initial- and main ruptures, aftershock hypocenter distribution. Appling this analysis, we can understand the distribution as relative locations to the initial rupture's hypocenter. CGS seismic event catalogue, which had been determined with Horiuchi's automatic hypocenter determination method [8], has included 337 aftershocks between approximately a half day until the end of 5 Aug. 2014. Using P- and S-wave arrival time pairs of each event in CGS catalogue and of the initial- and main ruptures, we applied hypoDD program. In order to avoid earthquake hypocenters being located above surface (i.e. air focus), we introduced following assumption for hypocenter relocation, quite slow P-wave velocity at shallow layer (< 0 km elevation, shown in table 1). After elimination for some outlier aftershock events, we analyzed 247 events, 69680 P arrival time pairs and 59777 S arrival time pairs, by minimizing weighted least squares using the method of singular value decomposition (SVD). Finally, 143 events were relocated as relatively to the hypocenter of the initial rupture of the 2014 Orkney earthquake. As the result, we obtained that a hypocenter distribution which most of aftershocks have been located on a plane with NNW trended and slightly west inclined. Furthermore, viewing in detail, almost all of aftershocks have occurred at southern and upper part of hypocenter of initial rupture. In order to understand the reason for these inhomogeneous aftershock distributions, in the other words, aftershock vacancy of northern and downward part of initial rupture, we will try to estimate rupture process of this earthquake. In general, in the case of not so large Richter's scale earthquake, detail of rupture process is quite difficult to estimate. Because the 2014 Orkney earthquake Richter's scale is also not so large, in this study we will combine some analyses, initial rupture identification, aftershock distribution and isochrones back projection (IBM) to estimate rupture process.

In ordinary IBM analysis, we will investigate locations that have large rupture velocity on assumed fault plane by using S wave amplitude time variation [9]. However, for the case of not so larger earthquake, its rupture duration (c.f. Global CMT half duration: 1.3 sec) and spatial rupture extension (< 2 km) will be not enough for rupture velocity distribution estimation. Therefore, we only investigated the location of large amplitude S wave generating around the initial rupture hypocenter using with main rupture S wave amplitude variation. We consider that this distribution corresponds to the spatial strong motion generating area (SMGA) distribution. Practically, SMGA distribution will be masked by main rupture's first S wave with mostly maximum amplitude arrival. Therefore, we assumed ideal S wave amplitude variation (fig. 3), and we calculated ideal SMGA spatial distribution by using this amplitude variation. Finally, we applied deconvolution to these two results calculated from observation and ideal waveform. We can evaluate where excess S wave amplitudes generated around the initial rupture's hypocenter in this process. Additionally, because we did not assume a fault plane, we will be able to find SMGA distribution off the fault plane, too. We used the S-wave velocity of 3.25 km/s, which is calculated from the P wave velocity (5.78 km/s) corresponding to hypocenter depth (2 - 17 km) and assumed Poisson's ratio (1.78) for this IBM analysis. And we also assumed rupture duration and velocity not to exceed the Global CMT's half duration (1.3 s) and 90 % of S-wave velocity, respectively. We considered grid size should not be shorter than observed wavelength, 200 Hz S-wave wavelengths (~ 17 m), we defined grid size as 50 m. Relocated hypocenters distribution and the SMGA spatial distributions were shown in fig. 4. SMGA distribution is spatially averaged, final spatial resolution will be 250 m (5 by 5 grid average). This grid length corresponds to the wavelength of 15 Hz S wave variation.

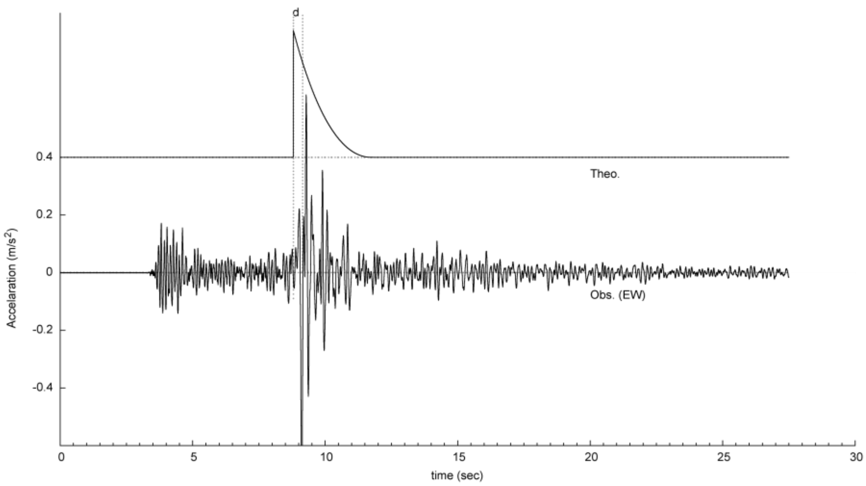

Fig. 3. Hypothesis of the ideal S-wave amplitude variation for our IBM analysis

Seismogram, observed with the other earthquake, (Obs. EW) and ideal S-wave amplitude variation (Theo.) are shown as an example. Maximum amplitude of ideal S-wave appears at the same time on phase arrival, and decays by time ($e^{-t/2}$). On the other hand, maximum amplitude of Obs. EW appearance will be delayed with d from phase arrival. d implies the spatial and temporal extension of rupture from initial hypocenter. In spite of without fault plane assumption, we can see a SMGA distribution on and along the aftershock distribution on a fault plane. In normal view to fault plane fig. 4c, we can see the SMGA distribution at (1) northward, (2) southward, and (3) upper ward of initial rupture's hypocenter. And most of the aftershocks are located at the edge of the southern (2) and upper (3) SMGA distribution. Upper ward SMGA (3) spatial extension is different from two deeper distributions. Upper ward SMGA (3) seemed not to extend until -1000 m, but (1) and (2) will reach 1500 m. 1500 m rupture extension means until the end of the maximum calculation grid.

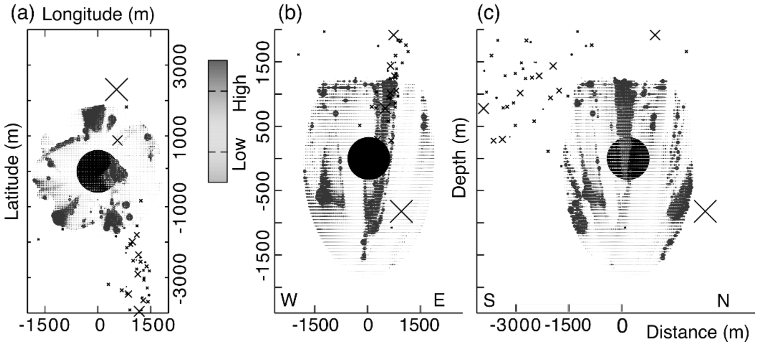

Fig. 4. SMGA and aftershock distribution of the 2014 Orkney earthquake

We showed map view (a), view along the fault plane (b), and view from normal to the fault plane (c), which was estimated by aftershock distribution (NNW trending and west dipping). We masked initial rupture's extended area as centered filled circle. Aftershock hypocenters are shown by cross at the place of relative to the initial rupture's hypocenter and its size is proportional to its Richter's scale. SMGA is indicated by grey scaled circle; when becoming strong, its color will change toward black.

DISCUSSIONS

We clarified that the 2014 Orkney earthquake includes the initial- and main-ruptures, their origin time difference is 0.3 second, by careful P- and S- phase arrival picking. Main rupture's relative location subsequent to initial rupture is 1.0 km distant from initial one toward the north and slightly deep. These facts imply quite fast rupture velocity (>3.0 km/s). Thus, main rupture might have been dynamically triggered by the initial rupture's S waves. In order to trigger dynamically such as in this case, we are considering that tectonic stress around the hypocenter should have been high.

From SMGA distribution, upper ward rupture reached 1.0 km above the initial rupture hypocenter. Initial rupture's hypocenter depth, which we determined, is 3.9 km below the sea level. Thus, this means that rupture extends to 2.9 km below the sea level. On the other hand, this area mining is reaching 3.6 km below the surface. Since Orkney town's altitude is 1000 m to 1500 m, the deepest mining leaf will reach 2.6 - 2.1 km below the sea level. Therefore, more than 500 m spatial gap exists, mining will not affect the occurrence of the earthquake, we considered. Additionally, ordinary mining releases tectonic stress and makes smaller from initial condition. High environment stress condition around the hypocenter implied by high rupture velocity is inconsistent with this feature.

Comparing with the maximum P wave amplitudes in vertical component of each stations for initial- and main ruptures, we could see the initial rupture's seismic magnitude will be approximately 1 / 50 times smaller than the main rupture’s one. Therefore, Richter scale magnitude of the initial rupture should be smaller 1.2 (= $\log_{10}(50/1.5)$) than that of the main rupture. On the other hand, we determined the Richter's scale for main rupture of the 2014 Orkney earthquake is M5.6 estimated with the maximum amplitude of vertical component [10]. Watanabe's scaling law was developed only for small or micro seismic events, sometimes its absolute value may be overestimated. However, their relative magnitude is correct. Therefore, we considered that the initial rupture of the 2014 Orkney earthquake has approximately 4 as local magnitude scales.

Applying double-difference hypocenter relocation method, we obtained detailed aftershock distribution with most events located on a NNW trending and slightly west inclined plane. If we considered this plane as the fault plane of the 2014 Orkney earthquake, this plane is consistent with one of nodal planes that are reported by Global CMT solution. Upper part of aftershock distribution is located on a different nearly horizontal plane. We think these hypocenters corresponding to blastings and mine induced earthquakes. It seems that the vacancy of hypocenter between these distributions, minings and aftershocks exists. By this vacancy area existence, tectonic earthquakes and mining earthquakes seem to be separated. And no earthquake hypocenters were determined around the initial rupture area.

Small amplitude SMGA distribution, which is located off the plane, may be artifacts. These distributions are quite limited and strength is not high. Thus, we should mention to the SMGA distributions (1), (2), and (3), only. SMGA distributions (1), (2), and (3) are located on the plane, especially, the location of SMGA (1) is just corresponding to the main rupture’s hypocenter. We consider that SMGA distribution (1), at least one, should have to exist on the 2014 Orkney earthquake occurrence. SMGA distributions (2) and (3) are corresponding to the vacancy of aftershock distribution, however, some more evidences for existence of SMGA distributions (2) and (3) must be investigated in future study.

CONCLUSION

We clarified that the 2014 Orkney earthquake is multiple earthquake, which includes the initial- and main-ruptures. Their origin time difference is only 0.3 second, and main rupture hypocenter relative location is 1.0 km distant toward the north and slightly deep. By comparison of the maximum P wave amplitudes, we concluded that the initial rupture of the earthquake has approximately M~4. This earthquake has been followed by many aftershocks, these distributions show a fault plane, which is NNW trending and slightly west dipping. Three strong motion generating area (SMGA) distributions, which are obtained by IBM analysis, are located on the plane. Especially, one of the SMGA (1), which is located northward, is corresponding to the main rupture's hypocenter. Two remaining SMGA distribution are corresponding to the vacancy of aftershock distribution, however, some more evidences for their existence will have to be investigated in future study.

Finally, fast rupture velocity of this earthquake, vacancy of upper area aftershock distribution, and so on implied that this earthquake is tectonic earthquake, not a mine induced earthquake, we considered.

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