Precise relocation of the 2014 Orkney M5.5 main- and after-shocks to maximize scientific value of an international drilling project

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I. Summary

South Africa used to be the world’s largest producer of gold. However, most economically minable gold reefs have been mined out. Some places still untouched are not technologically minable because of depth and high level of stress in the ground. Stress increases a risk of rock burst and seismicity. The decline of gold production and increased seismic risk are serious problems of South Africa. Meanwhile, Japan has experienced and dealt with a number of earthquakes caused by approximately 10% of all seismic activities in the world. The source of seismicity occurred in Japan is too deep to be directly observed, while South African mining-site earthquakes can be explored several hundred meters from their sources by means of its advanced technology. Therefore, both countries have been involved in collaborative projects to carry out near-field seismological observation. Recently, the largest event (M5.5) of an earthquake in a mining region happened near Orkney on 5 August 2014. The upper edge of its activated fault was several hundred meters below a mining tunnel, which is 3.0km in depth. This event was recorded by underground strainmeters as well as seismometers set both on the surface and in the ground, and its data is essential to a detailed seismological analysis. A nearly real observation of a series of ongoing aftershocks is achievable by drilling to the areas around the source of the earthquake. Yet, the M5.5 main- and after-shocks of this event are not calibrated, but estimated based on a tentative seismic velocity structure. In order to set out a more precise target of drilling, I collaborated with Prof Durrheim and Dr. Manzi of University of the Witwatersrand, or Wits University and attempted to determine the velocity structure of the primary wave of the 2014 earthquake. I analyzed data gained through 3D seismic reflection survey, uncovering the location and geometry of the M5.5 fault line as well as the Vaal Reef geological structure. A set of data I used has already been processed into an image of reflective geological layers in a vertical section drawn versus a vertical time axis. In order to get data to convert the image into those drawn versus a vertical depth axis, I visited the Geology Department of Moab Khotsong gold mine and Council for Geoscience, and collected exploration drilling data which shows depths of intersections of major geological layers. This 3D seismic reflection analysis enabled me to illustrate the geological structure of the area around the source of the M5.5 earthquake in a 3D seismic reflection image. During the field work, the velocity structure of its primary wave was not fully determined, because I had to spend a lot of time on modifying the coordinate system.

This field survey included supplemental activities involving visits to two more gold mines: Savuka and Cooke4. In Savuka, I visited underground close to the source of a M3.5 earthquake located 3.3 km in depth, and participated in a stress measurement survey. This allowed me to learn overcoring technique. Cooke 4 gold mine is a site designated by the International Continental Scientific Drilling Program (ICDP). I joined an inspection of the conditions of water, compressed air and electricity necessary for drilling.
要約

南アフリカ共和国は世界有数の金の産出国であった。しかし、経済的かつ採掘可能な金鉱脈はすでに掘り尽くされてしまい、深度が大きく高ストレス状態のため採掘が難しいところだけが残されている。山はねや地震は深度やストレスに伴い活発になるためである。金の生産量が減少する一方で地震発生のリスクが上昇するのは南アフリカにとって深刻な問題である。一方日本は全世界の 10%もの地震が発生する地震大国である。地震関連の研究や技術に秀でているが、日本で発生する地震は地表から遠く、震源断層を直接調査するのが困難であった。しかし南アフリカの金鉱山では採掘レベルで地震が発生するので震源から数百メートルの位置からの至近距離観測が可能である。このような理由から日本と南アフリカは共通の目的をもって共同研究を行ってきたのである。2014年8月5日、南アフリカ共和国オークニー近郊の鉱山地帯でM5.5 の地震が発生した。この震源断層の上端部は金鉱山の地下3kmに位置する坑道の数百メートル下であり、坑道からの断層に向けて科学掘削が可能である。この地震は地上の地震計、地下の地震計と歪み計で収録された。余震活動が起こっている中で震源に至近距離で科学掘削を行うのは貴重な機会である。しかし、この M5.5 地震の本震と余震はまだ仮の速度構造において計算されているため、震源掘削にはより精度の良い絶対位置の情報が必要になってくる。そこで、今回の南アフリカ渡航ではWitwatersrand大学のDurrheim教授、Manzi博士と共に、3次元反射法地震探査データを用いてP波速度構造の決定を試みた。また、この3次元反射法地震探査データを使いM5.5地震断層地帯の地質構造解釈も行った。今回解析した地震波データは反射層の画像化を可能としたが、深さ方向の縦軸が時間であった。これを縦軸が深さのイメージに変換するためにMoab Khotson gold mineの地質部と南アフリカ共和国の国立地震観測機関であるCouncil for Geoscience(CGS)へ行き、主要な地層境界の深さの情報をもつ地質探査のドリリングデータを入手した。今回の3次元反射法地震探査解析では、滞在期間の大部分を座標系の修正作業に費やしたため、地震の速度構造を決定するまでには至らなかったが、M5.5地震の震源断層の構造を明らかにすることができた。また、補助調査として、Savukaと Cooke4金鉱山での調査を行った。Savuka金鉱山では、地下3.3kmに位置するM3.5地震の震源断層付近での応力測定調査に参加し、応力測定の手順を学んだ。Cooke4鉱山では、国際陸上科学掘削計画に指定されたドリリングサイトを視察し、電気や圧縮空気、水などが常備されているか、現場環境は適切であるか等の調査を行った。
II. Research Activity

1. Introduction

Deep South African gold mines have offered us unique opportunities to access seismogenic zones to investigate earthquake sources (e.g. Durrheim 2012) and to investigate the deep subsurface biosphere. Drilling in deep mines has the great advantage of significantly reducing the cost for boreholes that reach the actual depths (usually over 3 km) where earthquakes occur. Japanese-South African near-field seismological observational studies (Ogasawara et al. 2014) were carried out during 2009-2015 on a large scale, yielding unique near-field data elucidating the seismogenic process (Naoi at al. 2015). Some of the elucidated ruptures have already been extensively exhumed or will be exhumed by future mining operations, providing the rare opportunity to see the actual slip plane for earthquakes.

This study focuses on M5.5 earthquake occurred in a mining region near Orkney on 5 August 2014. The hypocenter location of its fore, main and aftershocks are already estimated, enabling me to predict the shape of its fault. Yet, the unknown, geological velocity structure of the epicenter makes the location of hypocenter unclear. The main aim of my South African stay was to calibrate the velocity structure of this M5.5 earthquake to accurately target for drilling and for near-field seismological observation. I studied the method of seismic reflection research and learnt how to use the software for data analysis at University of the Witwatersrand, or Wits University. Moreover, I obtained borehole drilling data from a gold mine company and Council for Geoscience, which is the outcome of seismic reflection profiling in the area. My fieldwork included some sub-activities, one of which enabled to learn how to measure stress in gold mine (Tab. 1).
<table>
<thead>
<tr>
<th>Date</th>
<th>Activity [locations or organizations visited etc.].</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/28 – 09/03</td>
<td>Attend International Geological Congress (IGC) [Cape Town] sub-activity</td>
</tr>
<tr>
<td>09/04 – 09/10</td>
<td>Bring a stress measurement system from Tohoku university and carry out measurements [Anglo Gold Ashanti] sub-activity</td>
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<tr>
<td>09/11 – 09/17</td>
<td>Field work in Savka and Cooke 4 gold mines [Anglo Gold Ashanti Ltd. and Sibanye Gold Ltd.] sub-activity</td>
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<tr>
<td>09/18 – 10/01</td>
<td>Learn seismic reflection survey in University of the Witwatersrand [Johannesburg] main-activity</td>
</tr>
<tr>
<td>10/02 – 10/08</td>
<td>Visit Council for Geoscience and Geology Department of Moab Khotson gold mine and obtain a borehole logging data [Pretoria and Klerksdorp] main-activity</td>
</tr>
<tr>
<td>10/09 – 10/12</td>
<td>Analyze seismic reflection data [Johannesburg] main-activity</td>
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Table 1. Time schedule in South Africa

2. Study Area

I spent a lot of time at Wits University, Johannesburg, near Central Rand Goldfield on trying to calibrate the velocity structure of the seismogenic zone of the 2014 M5.5 earthquake, which is located in the southeastern corner of Goldfield 8 in Fig. 1. Its fault took place near Orkney of Klerksdorp area, and is shown by line in Fig. 2. This earthquake is the largest event ever occurred in a gold mining district in South Africa and was felt as far as 600 km away, even in the neighboring countries. Remarkably, its hypocentral depth was significantly greater than those of usual earthquakes induced on mining horizons. One person was killed by the collapsing of a wall on surface, but there was no serious damage to underground infrastructure at the mines. They were able to resume operation within about a week after the M5.5 event; still future hazard is a great concern because a large event on the mining horizon could seriously affect mining operations, as the 2005 Stilfontein M5.3 earthquake did. Therefore, this research is crucial not only for science but also for hazard assessment in mining.

As part of my sub-activities, I visited underground at two gold mines, Savuka and Cooke4 and on surface at Moab Khotson mine. Savuka and Cooke4 are located in Carletonville, Goldfield 7, and Moab Khotson is in Goldfield 8, where the M5.5 took place.
3. Methodology

This event was recorded by the national seismometer network on surface and underground geophones of the Moab Khotsong gold mine company. The black lines in Fig. 2 are boundary lines of the mines and faults recognizable on the ground. This map shows that the main fault of M5.5 is much different from these black lines. It means that this event did not occur on the known fault lines. In the area of Fig. 2 2D seismic survey data is available from 47 observation points. 3D seismic survey data of the green, survey area in Fig. 2 can also be obtained. Both types of data are not originally calibrated with velocity structure.

During my stay, I used a software, namely KINGDOM, to convert the data of seismic waves to 3D seismic reflectivity image with actual depth information. The input data set was offered by Wits University. It has collaborated with South African gold mining companies for sharing and processing seismic reflection survey data, in order to confirm the locations as well as discontinuities of gold reefs and geological faults.

In a seismic reflection survey, a generator emits a seismic wave from the ground. The wave reflected on underground geological boundaries creates velocity contrast, which is recorded by an array of receivers on surface. In order to reduce random noise, reflected waves of multiple shots are stacked. By using KINGDOM the stacked reflected waves can be converted to vertical images of seismic reflection profiles.

A set of velocity structure data was necessary to visualize a 3D configuration of the reflection profiles of M5.5 fault lines. Therefore, I attempted to calibrate velocity structure of Klerksdorp area. Apart from the seismic reflection survey, exploration drillings have been carried out at several points to intersect the reflector planes. The data obtained through this drilling allowed me to know both the depths and travel time of seismic waves of the reflection profiles. Actually, the types of information necessary to be input into KINGDOM to calibrate velocity structure are
depths and travel time of seismic waves. Eventually, the calibration of the velocity structure will enable us to illustrate a 3D seismic reflectivity image with depth as a vertical axis. The project of Wits University in which I was involved is aiming to calibrate velocity structure in green mesh area of Fig. 2.

![Figure 2. 2014 M5.5 fault and 3D seismic survey area](image)

4. Research Findings
The collation of geological, mine maps, and the seismic survey data, which the data collection entailed, allowed me to understand the geological features of Klerksdorp area (Fig. 2). The geological map I used is available at Wits University. A red line running from north-northwest to south-southeast is a side slip fault of the 2014 M5.5 earthquake.

Through my fieldwork the data necessary to calibrate the velocity structure of the green area in Fig. 2 was largely collected. On 26 September 2016, Prof Durrheim, Dr. Manzi and I visited the Geology Department of Moab Khotson gold mine, and obtained the exploration drilling data of over 39 boreholes in the area. On 3 October 2016, a visit to the Council for Geoscience took place, allowing me to get the exploration drilling data of 80 boreholes around the northern part of the area near the M5.5 fault.

Fig. 3 (left) is the enlarge view of the meshed, green area of Fig. 2, showing one of the E-W travers line (thin red horizontal line). Fig. 3 (right) demonstrates the sectional view of reflection profiles along the travers line, where seismic velocities are under analysis. This image was not made by using a calibrated, accurate velocity structure. The depth information is not correct, but it is still useful to understand the subsurface structure of the area. For example, the strong reflective boundary can be seen at about 1300 m below ground, which corresponds to the bottom of basaltic lava. On the mining horizons (circled in Fig. 3) ranging from 2 to 3 km in depth, there are some reflection profiles multiply intersected, which can be recognized as the fault. Interestingly, it can be considered that there was unlikely to be disturbance to the M5.5...
rupture (which is at least 5 km long and 3 km wide in direction of dip). A dyke (near vertical lava intrusion) does not offset bedding vertically, which does not seem to affect the reflection profiles.

![Figure 3. E-W traverse line and its sectional view](image)

5. Discussion
To assume the velocity structure of the surveyed area theoretically, I created and explored Fig. 3, whose depth information is still uncertain. When I left South Africa, Prof. Durrheim and Dr. Manzi gave me a license of KINGDOM. This allows me to continue to work for data analysis in Japan. In the next step, I will carefully compare Fig. 3 with the borehole logging data, in order to calibrate the seismic velocity of the M5.5 earthquake. After this calibration, I plan to plot the seismic reflection data of the aftershocks on the map.

6. Conclusion
My fieldwork was part of the attempts to understand the subsurface structure of Moab Khotsong mine by using 3D seismic reflection data. The collected data included geological and mine maps, as well as 2D and 3D seismic survey data in the study area. The exploration of them enabled me to show the fragment of the complex structure in the seismic zone of the M5.5 earthquake. During this South African stay, I could not complete the calibration of seismic velocities necessary for making an 3D seismic reflectivity image with actual depth information. I want to keep contact with South African researchers and complete the calibration work.
• Acknowledgement

I really appreciate Prof. Raymond Durrheim and Dr. Musa Manzi whose comments and suggestions were of great value during my South African stay. Special thanks also for Dr. Artur Cichowicz who gave me invaluable comments and warm encouragements at Council of Geoscience. Finally, I would like to express my gratitude to Global Leadership Training Program for their financial support.

• References


10) Musa S. D. Manzi, Raymond J. Durrheim, Kim A. A. Hein, and Nick King 3D edge detection seismic attributes used to map potential conduits for water and methane in deep gold mines in the Witwatersrand basin, South Africa

Appendix
III. Reflection to the GLTP in Africa

The reason why I applied for GLTP in Africa is that the program enables me to stay for a long period in South Africa. The laboratory for which I work does research on earthquake taking place in gold mining area of South Africa. Therefore, I have always been interested in a mining technology and the safety measures in South African mines. I wanted to see South African gold mines and learn the relevant technology. I fully appreciate this program, which let me stay there for a two-month period. One of the most important things I obtained through this program is self-confidence. My English skill was not necessarily good, and I was worried about hotel reservation, rental car booking, shopping, and so on. At first, I could not understand English at all, but my listening skill became gradually better throughout the period of field work. Information about the serious state of crimes in Johannesburg made me spend two months in the university and hotels. However, my South African friends asked me to go out and taught me many things in Johannesburg. The visit to the Nelson Mandela House in a township, Soweto was a good opportunity to learn South African history. I realized that there is still racial discrimination among local people including Wits students. During my stay, some students did demonstrations involving violence against the annual increase in tuition fees. This made me witness a fragment of a history of conflicts which South African has experienced. I learnt that communication with local people is significant in developing my capability to judge what is safe or dangerous.

I want to go for industry to exploration resources. In Japan, resources are not rich, which will result in the fragment opportunities of overseas business trip. I believe my experience of being involved in this program will become crucial in my future carrier. It allowed me to engage in the International Drilling Project and learn what I am expected to do in such an international project. I met many people joining the Project during my stay, and all of them kindly helped me. Through GLTP program, this always reminded me of the importance of warm human relationship.