Bulletin of the Seismological Society of America

This copy is for distribution only by
the authors of the article and their institutions
in accordance with the Open Access Policy of the
Seismological Society of America.

For more information see the publications section
of the SSA website at www.seismosoc.org

THE SEISMOLOGICAL SOCIETY OF AMERICA
400 Evelyn Ave., Suite 201
Albany, CA 94706-1375
(510) 525-5474; FAX (510) 525-7204
www.seismosoc.org

Bulletin of the Seismological Society of America, Vol. 101, No. 6, pp. 2579–2591, December 2011, doi: 10.1785/0120110017

On the Probability of Detecting Picoseismicity

by K. Plenkers,* D. Schorlemmer,† G. Kwiatek, and JAGUARS Research Group

Abstract Estimation of the recording completeness of seismic catalogs recorded with small networks in a heterogeneous observation volume, for example, in mines, is difficult. Local heterogeneities have a strong influence on the wave path and attenuation and must be taken into account. In order to analyze the spatially varying completeness of such catalogs in three dimensions, we present a new approach based on the probability-based magnitude of completeness (PMC) method of Schorlemmer and Woessner (2008). We demonstrate that the traditional approach of Schorlemmer and Woessner (2008) is insufficient in very complex and heterogeneous settings. To account for this problem, we extend the PMC method, taking into account the direction of incoming seismic waves. This allows us to analyze the influence of small heterogeneities on the recording completeness in high resolution. We compare the results with results obtained by a traditional Gutenberg–Richter frequency-magnitude analysis for the JAGUARS catalog: The Japanese German Underground Acoustic Emission Research in South Africa (JAGUARS) project recorded approximately 500,000 seismic events with magnitudes $-5 < M_w < -1$ in the Mponeng gold mine (Carletonville, South Africa) at −3.5 km depth. The network is surrounded by several cavities and is located partly in the Pink-Green dike, a local geological feature. We estimate that the completeness of the JAGUARS catalog varies significantly in space. In the center of the network, we estimate a magnitude of completeness of $M_P = -4.8$, whereas at stope level (approximately 100 m from the network), the magnitude of completeness is only $M_P = -3.1$. Variations due to the influence of local heterogeneities, for example, tunnels, are clearly resolvable.

Introduction

In recent years, the interest and the efforts in recording seismic events with very small magnitudes have increased (Abercrombie, 1995; Pettit *et al.*, 2002; Imanishi and Ellsworth, 2006; Boettcher *et al.*, 2009) as small-scale observations are necessary in discussing nucleation and rupture processes of earthquakes (Mendecki, 1997; Richardson and Jordan, 2002; Abercrombie and Rice, 2005). A new milestone in small-scale observations was recently reached by the Japanese-German Underground Acoustic Emission Research in South Africa (JAGUARS) project (Nakatani *et al.*, 2008; Plenkers *et al.*, 2010), which recorded seismic events inside the Mponeng gold mine in Carletonville, South Africa with magnitudes M_w −5 to −1 (Kwiatek *et al.*, 2010). Following the definition of Ellsworth *et al.* (2007) and (Bohnhoff *et al.* (2009), we call seismicity in this magnitude range picoseismicity.

Seismic networks are an essential part of seismological research. They produce earthquake catalogs that are important data sources for many seismological studies. Networks exist in different sizes and with different coverage, from global networks to very local networks. Seismic events with magnitudes $M_w \ll -1$ are only recorded underground, for example, in deep boreholes or mines, where short source-receiver distances are realized. In-mine networks represent a special case of local networks, as their design and setup is strongly determined by the local conditions in the mines, for example, the geometry of access tunnels and the mining areas (stope). Mines often encompass very complex volumes of different geological structures that lead to significant differences in the spatial distribution of static and dynamic rock properties (Cichowicz *et al.*, 1988; Milev and Spottiswoode, 2002). Geological heterogeneities and cavities, created in the mining process, can therefore strongly influence the seismic wave field locally (Maxwell and Young, 1998; Hildyard, 2001) and thus lead to local variations in recording completeness. Knowledge of the recording completeness of seismic networks is essential for almost every statistical study using earthquake catalogs, ranging from seismicity analysis to

*Now at Karlsruhe Institute of Technology, Hertzstr 16, 76187 Karlsruhe, Germany.

†Also at Helmholtz Centre Potsdam—GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany.

seismic-hazard assessment. Several studies demonstrated that underestimated completeness levels introduce significant biases into various analyses (Rydelek and Sacks, 1989; Schorlemmer *et al.*, 2005), while overestimated completeness levels artificially reduce the amount of available data.

Over the last decades, many seismic catalogs recorded inside underground mines have been analyzed and have proven to be a valuable source for small-scale observations (McGarr, 1971; Gibowicz and Kijko, 1994; Richardson and Jordan, 2002; Boettcher *et al.*, 2009). Nonetheless, the recording completeness of these catalogs was seldomly calculated because no applicable approach to deal with the strongly heterogeneous observational volume was available. In this study, we present an application of the newly developed probability-based magnitude of completeness (PMC) method (Schorlemmer and Woessner, 2008) to calculate in detail the recording completeness of the JAGUARS network despite the three-dimensional heterogeneous setting.

The JAGUARS network is a high-frequency (700 Hz–180 kHz), high-resolution network at 3.5 km depth inside the Mponeng gold mine. The network is situated in a complex observational volume where both geological boundaries and engineered cavities are present. Previous studies on the JAGUARS catalog discovered differences in recording quality throughout the observational space. The higher the maximum signal frequencies, the stronger the damping, and subsequently, the shorter the recording distance (Plenkers *et al.*, 2010). These studies also noted that strong local heterogeneous structures change this pattern.

Kwiatek *et al.* (2010) analyzed the frequency-magnitude distribution of data subsets of the JAGUARS catalog. They computed the magnitude of completeness, M_c, using the method of Wiemer and Wyss (2000). Like most traditional methods (e.g., Cao and Gao, 2002; Marsan, 2003; Woessner and Wiemer, 2005; Amorèse, 2007), Wiemer and Wyss (2000) estimated the magnitude of completeness as the magnitude at which the Gutenberg–Richter distribution (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944) departs from the frequency-magnitude distribution of the underlying earthquake sample. (See Schorlemmer and Woessner, 2008 for a detailed discussion and comparison of the existing methods.) The assumptions that are used in all of these methods are that earthquake samples are Gutenberg–Richter distributed and that they are representative of the completeness over their spatiotemporal extent. The latter suggests that no significant variation in recording completeness is present in the earthquake sample, which is often not true in heterogeneous observational volumes if the earthquake sample's spatial extension grows too big. If spatial variations are present, existing methods only calculate an averaged completeness, and it follows that the spatial variations in recording completeness cannot be resolved.

To account for this problem, Kwiatek *et al.* (2010) compared the magnitude of completeness, M_c, of three areas with different distance to the JAGUARS network. They found significant differences in completeness, which they explained with local damping effects. A more detailed study on the spatial completeness variations using the method of Wiemer and Wyss (2000) for underground networks is difficult because it requires earthquake samples with the same spatial extent as local heterogeneities. To overcome this problem, we present an application of the PMC method, which, unlike the most traditional methods for catalog completeness estimates, is not directly based on earthquakes samples but computes completeness from detection-probability distributions of each station in the network. These distributions are derived from empirical data only: the earthquake catalog as well as the station data. Thus, in contrast to traditional methods, the PMC method considers completeness a property of the seismic network and not of the earthquake sample, and avoids the aforementioned assumptions of the traditional methods.

Previous studies demonstrated the potential of the PMC method to analyze spatiotemporal variations in recording completeness. Schorlemmer and Woessner (2008) applied the PMC method for the first time to the Southern California Seismic Network. They showed the power of the PMC method in resolving spatial variations in completeness, in particular in areas without the necessary level of seismicity to apply the traditional methods. Nanjo *et al.* (2010) analyzed the spatiotemporal evolution of catalog completeness of the Swiss Seismic Network with the PMC method. They estimated the uncertainties in the probability-based magnitudes of completeness using a bootstrap approach and found uncertainties smaller than 0.1 magnitude units. Furthermore, the seismic network of the Japanese Meteorological Agency was studied using the PMC method (Schorlemmer, 2009) as well as the seismic networks in northern Italy (Gentili *et al.*, 2011). Schorlemmer *et al.* (2010) also applied the PMC method successfully to the network of the Instituto Nazionale di Geofisica e Vulcanologia in Italy.

The PMC method was developed for regional seismic networks. Accordingly, earlier studies implementing the PMC method investigated networks monitoring an area up to several hundred kilometers length and width with up to a thousand seismic stations. To analyze the detailed spatial completeness variations of the JAGUARS network, a network with a few sensors monitoring a volume of only about $300 \times 300 \times 300$ m, we optimize the PMC method for underground networks by taking into account the direction of observation in order to distinguish the influence of local heterogeneities. We apply this extended PMC method to the JAGUARS network and compare the resulting spatial distribution of probability-based completeness magnitudes, M_P, with the estimates on magnitude of completeness, M_c calculated by Kwiatek *et al.* (2010). Furthermore, we demonstrate how the spatial distribution of completeness gives insights into the recording resolution of the network and how the azimuth-dependent detection capabilities of each sensor help our understanding of their performance.

Data

The JAGUARS project (Nakatani *et al.*, 2008) operated a high-frequency seismic network in the Mponeng gold mine (Carletonville, Republic of South Africa) managed by the Anglo Gold Ashanti company. The JAGUARS network is located at a depth of 3.5 km, approximately 90 m below the gold reef and next to the Pink-Green (PG) dike, which has a width of approximately 30 m and is dipping nearly vertically (see Fig. 1). Several excavations are present in the vicinity of the network, especially the development tunnels XC45 and XC46, as well as the stope, created by mining the gold reef. Mining in the gold reef above the JAGUARS network started in early 2007, as described in detail in Plenkers *et al.* (2010).

The rock properties of the quartzite host rock and the diorite dike were estimated *in situ* from seismic velocity tomography using acoustic emission transmission tests (see Naoi *et al.*, 2008) as well as in laboratory measurements (see Stanchits *et al.*, 2010). For the host rock, seismic velocities of $v_p = 6.2 \pm 0.2$ km/s for *P* waves and $v_s = 3.8 \pm 0.2$ km/s for *S* waves were estimated. The velocities within the PG dike were found to be slightly higher with $v_p = 6.9 \pm 0.2$ km/s and $v_s = 3.9 \pm 0.2$ km/s. The seismic attenuation was measured *in situ* by transmission tests (see Naoi *et al.*, 2008) as well as by Coda-Q analysis (see Plenkers *et al.*, 2009). The quality factor for shear waves varies between $Q_S = 200$–600 for frequencies ranging between 1 and 17 kHz. For *P* waves, we assumed $Q_P = \frac{5}{2} Q_S$.

The JAGUARS network consists of one triaxial (3C) accelerometer (sensitivity 50 Hz–25 kHz) and eight acoustic emission (AE) sensors (sensitivity 1000 Hz–180 kHz). All sensors were installed in boreholes of 6–15 m depth to avoid interferences with the tunnel surface and the surrounding excavation damage (Fig. 1). Events were automatically picked and localized, and event data were stored underground in a local recording system developed by the Gesellschaft für Materialprüfung und Geophysik mbH (GMuG; company for material testing and geophysics) with a sampling frequency of 500 kHz (see Nakatani *et al.*, 2008; Plenkers *et al.*, 2010). For localization, an isotropic velocity model was used with $v_p = 6.5$ km/s and $v_s = 3.8$ km/s. The JAGUARS network recorded data from May 2007 to April 2009.

For the PMC analysis, we chose data recorded from 27 December 2007 to 2 January 2008, after a seismic event with moment magnitude M_w 1.9, which occurred on 27 December 2007 close to the JAGUARS network (Yabe *et al.*, 2009). The mainshock was located about 30 m above the JAGUARS network inside the PG dike. The event was followed by more than 25,000 aftershocks (Yabe *et al.*, 2009). From these, about 11,500 events were automatically located by the JAGUARS recording system (Fig. 2). The aftershock sequence was analyzed in detail by Naoi *et al.* (2011). To insure good data quality, we reviewed all picks and hypocenter locations used in this study manually. We restricted the data for this analysis to those recorded during the Christmas closure of the mine. In this way, the data are not affected by working noises, nor by postblasting activity. Details on the effect of working noises on the JAGUARS network recording were analyzed by Plenkers *et al.* (2010). The background noise varies slightly in the period considered, but the change does not influence this analysis crucially. The final aftershock dataset used in this study consists of 9444 seismic events,

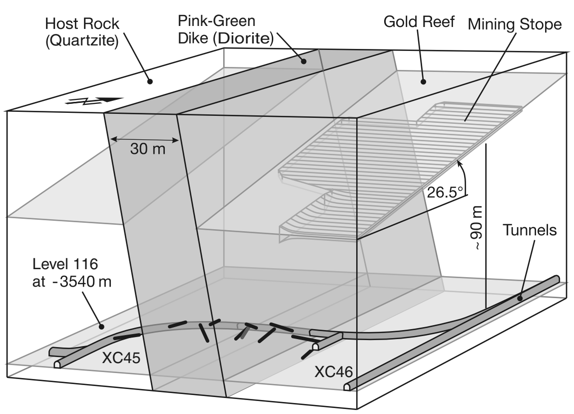

Figure 1. Sketch of the location of the JAGUARS network in the Mponeng gold mine and its surrounding geologic formations. The JAGUARS network is located at 3540 m depth. The sensors are located in boreholes that are shown as bold black lines. The PG dike is shown in gray. The gold reef with active mining located above the JAGUARS network is shown in light gray. The mining stope width is 0.5–1 m. The development tunnels XC45 and XC46 are shown in dark gray.

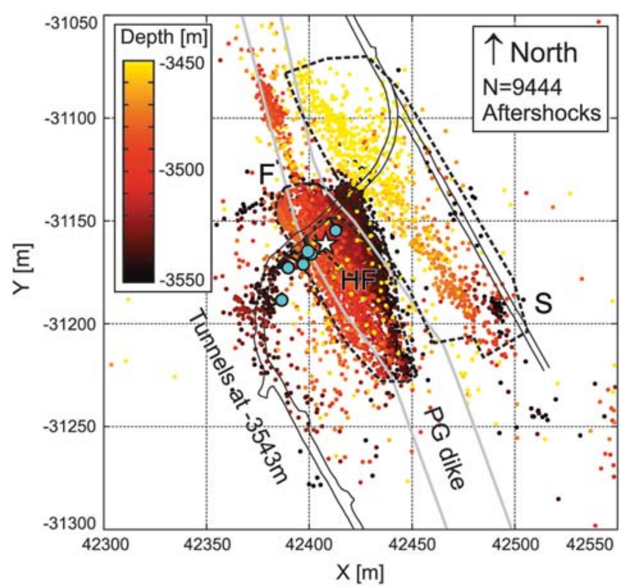

Figure 2. Spatial distribution of the aftershock sequence of the M_w 1.9 mainshock (location is marked by a star). The zones Fault (F), Center of Network (HF; with highest sensitivity as shown by Plenkers *et al.*, 2010), and Stope (S) as defined by Kwiatek *et al.* (2010) are shown using dashed lines (see Data section for details). The events in zones F and S are clearly separated in depths and do not overlap. For orientation, the sensors, the tunnels XC 45 and XC46, and the PG dike at stope level are shown.

representing 82% of the automatically located aftershocks. The same 9444 events were used by Kwiatek *et al.* (2010) to analyze the frequency-magnitude distribution of this dataset.

The magnitudes of the events were estimated as described in Kwiatek *et al.* (2010). The magnitude calculation was corrected for damping using the quality factors given at the beginning of this section. The magnitudes range from M_w −0.9 to M_w −5.0. The uncertainty in magnitude estimation is smaller than ±0.5, as discussed by Kwiatek *et al.* (2010). Temporal variations in the completeness distribution, introduced by changes in the network setup, are not studied in this analysis, as the performance of the JAGUARS network did not change in the period considered.

The majority of events analyzed occurred in the proximity of the network where location precision and detection probability are highest. In the network's focus, inside the PG dike, data availability is highest (cluster 1 in Fig. 3) and allows for a high-resolution statistical analysis. Cluster 1 is located in zone F as defined by Kwiatek *et al.* (2010). The extended PMC method introduced in this study requires a large dataset because the varying azimuth of incoming waves needs to be taken into account.

A second cluster with high event density is located at the stope face (cluster 2 in Fig. 3). Cluster 2 is located in zone S as defined by Kwiatek *et al.* (2010). The clusters within the PG dike and at stope level are clearly separated in depth. A third cluster of high event density is observed in the dike offshoot (cluster 3 in Fig. 3). Because it is located far from the network ($R \geq 200$ m) on the edge of the observational space and because the travel paths are complex, we do not consider this cluster for the PMC analysis. The areas with low event density are not appropriate for an application of the PMC method. Therefore, the analysis of the full observational space is not possible due to a lack of input data in areas outside the recorded clusters.

Method

The PMC method, as described by Schorlemmer and Woessner (2008), consists of two steps. In the first step, detection capabilities of each station in the network are derived, and in the second step, these capabilities are translated into spatial completeness. Each station's detection capability is described as a probability distribution, P_D, of detecting events of given magnitude at given distance. Each distribution is derived from empirical data only, namely, the earthquake catalog, station information, and processing information of the network. The latter information includes the attenuation relation used to estimate magnitudes of detected and localized events and the trigger information of each station. Only stations that trigger the localization procedure contribute to recording completeness. The pick distribution, $\boldsymbol{k}$, describes at which sensor i an earthquake j was picked or not:

$$\boldsymbol{k}_{ji} = \begin{cases} 0, & \text{if event } j \text{ is not picked at station } i \\ 1, & \text{if event } j \text{ is picked at station } i \end{cases}. \quad (1)$$

Schorlemmer and Woessner (2008) calculated detection probabilities $P_D(M, R)$ taking into account only the earthquake magnitude and the distance of the event from the station. From the pick distribution $\boldsymbol{k}$ of all events, data triplets $\boldsymbol{K}_i$ were prepared for each station that summarize the event magnitude M, the source-receiver distance $R(\mathbf{x}_j, \mathbf{x}_i)$, and the pick-distribution $\boldsymbol{k}$ of each event j in the catalog:

$$\boldsymbol{K}_i = [M_j; R(\mathbf{x}_j, \mathbf{x}_i); \boldsymbol{k}_{ji}]. \quad (2)$$

For this task, detailed information about the operational times of each station is necessary; missed events should not count at stations that were not in operation when the earthquakes occurred (Schorlemmer and Woessner, 2008). This effect is especially crucial in seismic networks containing only a few sensors, like the JAGUARS network.

Detection probabilities, P_D, were then calculated as a function of magnitude, M, and source-receiver distance

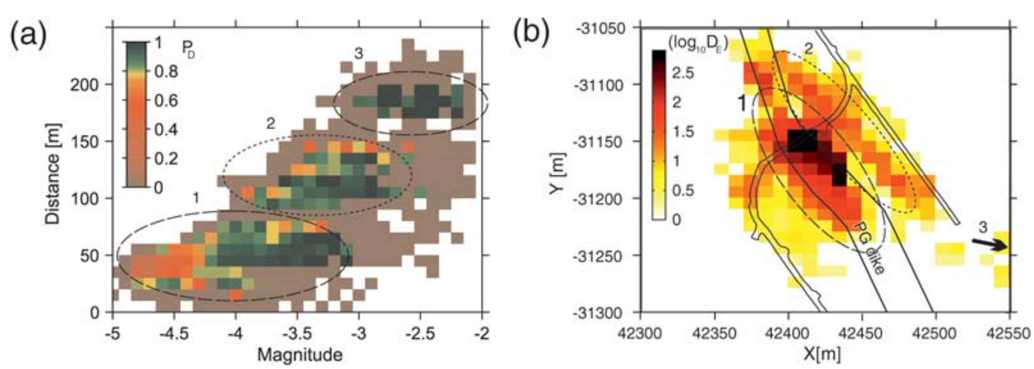

Figure 3. The effect of local heterogeneities. (a) Detection probabilities, $P_D(M, R)$, as defined by Schorlemmer and Woessner (2008) for sensor AE8. The direction of the incoming wave is not taken into account. Note: data bins with fewer data points than required are automatically set to zero probability. Black dashed lines mark three data clusters that correspond to data with different ray paths, as discussed in detail in the text. (b) Event density in map view. The three clusters observed in Figure 3a correspond to the three areas of increased event density. Clearly, the ray paths of the three clusters differ. The PMC analysis is possible only in areas of high event density. Clusters 1 and 2 are analyzed in this study. For orientation, we show the tunnel positions and the location of the PG dike.

(Euclidian distance), R. To simplify the computation, magnitudes and distances were binned, and the distributions of P_D were precomputed. In order to ensure statistical relevance, it is important to collect large datasets to compute the detection probabilities. Schorlemmer and Woessner (2008) proposed a minimum number of $N_{min} = 10$ per bin. To account for data gaps and statistical fluctuations, they proposed to smooth the probability distributions such that probabilities for all values of M and R are given. P_D is computed as

$$P_D(M, R) = \frac{N_+}{N}, \quad (3)$$

where $N = N_+ + N_-$ is the number of data triplets per bin, and N_+ and N_- are the number of successful and missed picks, respectively.

As discussed in the Introduction, the approach was developed for regional networks, where local heterogeneities in the observational space do not significantly alter the overall recording. The JAGUARS network is situated in a volume with strong, three-dimensional heterogeneities and records very high frequencies. Because recording of high frequencies is especially sensitive to attenuation caused by local heterogeneities, the detection probabilities depend noticeably on the ray paths of seismic waves and are therefore dependent not only on the distance but also on the direction of observation.

This effect is demonstrated in Figure 3a. Here, the detection probabilities $P_D(M, R)$ are calculated for sensor AE8. Clearly, three clusters of data are visible. In each cluster, the same probability pattern is found; higher magnitudes and shorter distances have a better probability for detection than small events or events from larger distances. This is in agreement with the theory of attenuation. However, we see deviations from this pattern. We observe that the detection probability decreases in one cluster as the distances become larger but is suddenly better in the next cluster although the distances are even larger. These irregularities cannot be explained as artifacts, for example, due to sparse input data. On the contrary, in the case of the JAGUARS network, the fluctuations display important information about differences in recording events from different directions. The three clusters observed in Figure 3a correspond to seismic events that occurred in very different geological settings. The first cluster of events with source-receiver distances between 30 and 80 m can be assigned to events that occurred within the PG dike (Fig. 3b, group 1). The second cluster, which occurred in distances from 100 to 150 m, is found to be located close to the stope front on the stope level above the network (Fig. 3b, group 2). The third cluster, located more than 170 m from the sensor, represents events that occurred in the dike offshoot to the east (Fig. 3b, group 3). The observed nonlinearity of detection probabilities is directly correlated with the locations of the three clusters and the differences in ray paths. Traveling waves, depending on the source origin, cross different rock settings and are affected accordingly by local attenuation.

We conclude that the sensor detection probabilities, $P_D(M, R)$, as proposed by Schorlemmer and Woessner (2008), taking into account only magnitude and source-receiver distance, are not sufficient in the case of very complex geological settings. We therefore propose that the direction of incoming waves must be taken into account when calculating the sensor detection probabilities and introduce the extended detection probability $P_D^*(M, R, \phi, \delta)$ as a function of source-receiver distance R, magnitude M, and the direction's azimuth ϕ and incidence angle δ. Hence, we also define the extended data triplets $\boldsymbol{K}_i^*$ as

$$\boldsymbol{K}_i^* = [M_j; R(\mathbf{x}_j, \mathbf{x}_i); \phi; \delta; \boldsymbol{k}_j^i]. \quad (4)$$

$P_D^*(M, R, \phi, \delta)$ is computed like $P_D(M, R)$, except that the pick information is not only constrained by magnitude and distance but additionally by azimuth and incidence angle. Here, we further substitute the incidence angle, δ, in equation (4) by a specific depth interval z and calculate $P_D^*(M, R, \phi, z)$. We do this because we are interested in certain depth levels inside the mine. As proposed by Schorlemmer and Woessner (2008), we require a minimum number of 10 data triplets per bin during the calculation to insure statistical relevance. We avoid smoothing of the distribution, as many bins contain no input data.

In the second step of the PMC method, detection probabilities for events of certain magnitude at a certain location and time, $P_E(\mathbf{x}, M, t)$, are computed from the precomputed detection-probability distributions P_D or P_D^* per station as described in detail by Schorlemmer and Woessner (2008). For each event location, we calculate the distance and azimuth to each station and, defining a certain magnitude, we gather the detection probabilities, P_D^*, from each station. We combine these probabilities to the joint probability, requiring at the same time that at least as many stations have detected the event as are needed for the location procedure (here, four stations). Repeating this procedure for the full range of magnitudes provides a full set of probabilities for each location. In order to extract the probability-based magnitude of completeness, a probability level is defined, according to the confidence level required for further analysis. In many applications, probability levels of 0.95, 0.99, or 0.999 are used.

Results and Discussion

Sensor Detection-Probability Analysis

We calculate the extended sensor detection probabilities $P_D^*(M, R, \phi, z)$ as described in the previous section. We group the data for the analysis according to their magnitude M, their source-receiver distance R, the depth z, and the source-receiver azimuth ϕ using static binning. The magnitude interval used is $\Delta M = 0.5$, the distance interval is $\Delta R = 10$ m, and the azimuth interval is $\Delta\phi = 10°$. The depth is restricted to intervals of $\Delta z = 20$ m. In the analysis, we consider only detection probabilities calculated from at least 10 data points.

We calculate the extended detection probabilities for all sensors and gain in this way insights into the local variations of recording sensitivity. Detection probabilities for the depth interval 3520–3540 m are shown in Figure 4. We are able to estimate detection probabilities in the PG dike at source-receiver distances between 10 and 80 m and with magnitudes ranging from M_w −5 to M_w −2.5. As expected, small magnitudes ($M_w < -4$) have a lower detection probability than larger magnitudes, as events with high dominant frequencies are more strongly affected by damping. The influence of attenuation is clearly seen in the results, as the detection probabilities decrease with distance. More importantly, we can see that the extended detection probabilities reflect the expected damping from the local heterogeneities. We point out that results for larger magnitudes ($M_w \geq -3.5$) are sparse because an insufficient number of such events were recorded. Additionally, magnitudes $M_w \geq -2.5$ often exceed the network's dynamic range because the JAGUARS network was designed for high sensitivity towards small events; therefore, these events are not analyzed.

The detection probabilities of sensors differ significantly (Fig. 4). These differences can be attributed for the most part to their location and performance. For example, the detection probabilities of AE11 are very high ($P_D^* > 0.8$), even for very small magnitudes. This is because sensor AE11 is located inside the dike and therefore closest to the focus of the network. The sensor detects events from all distances and all magnitude intervals. Most of the data are located at small azimuth angles. It follows that sensor AE11 is very important in the recording process. The detection probabilities of sensor AE10 are very low ($P_D^* < 0.6$) regardless of magnitude. This demonstrates that this sensor does not play a considerable role in the detection process. The result is easily explained, as the preamplifier of this sensor was broken during the period studied. Sensors AE7 and AE8 are located at the far west side of the network, close to each other. For magnitudes $M > -4$, the detection probabilities of both sensors are high and often exceed 0.8 in the whole observational space. Smaller magnitudes on the other hand have low detection probabilities. Small events are less likely to be recorded owing to the longer source-receiver distances. The damping is significant, as signals occurring inside the PG dike have to cross the dike-host rock boundary to reach these sensors. The detection probabilities reveal that sensor AE7 has a slightly lower sensitivity than sensor AE8 and is also located closer to the network's focus. This is because sensor AE7 has a poor rock-sensor coupling. We conclude that the detection probabilities are a useful tool for analyzing the performance of individual sensors. Broken sensors are recognized as well as sensors with lower sensitivity due to poor coupling to the rock.

Detection probabilities depend on the ray paths and are influenced by local heterogeneities. This is shown in Figure 4, where the detection probabilities of sensor AE7, AE8, and AE14 are reduced for magnitudes $M - 4 \pm 0.25$ in the vicinity of the access tunnel XC45. The detection probabilities are higher inside the dike south of the tunnel but lower north of the tunnel, although the distance to the sensor is identical.

We suggest that the decrease in detection probabilities in the northern part is due to the extensive fracture zone around the tunnel. Fracture zones around excavations were shown to lead to significantly increased attenuation of seismic waves (Cichowicz and Green, 1989; Maxwell and Young, 1998; Hildyard, 2001). Sensors located further away, which consequently receive more attenuated signals, are noticeably affected by the local damping zone. Signal detection at sensors AE11 and AE13 is not affected, owing to the proximity of the sensors to the events. We point out that the effect of spatially varying detection probabilities is not explained by the directivity of sensors, because the orientations of sensors do not coincide with high detection probabilities. It follows that the effect of local heterogeneities on the recording is significantly larger than the influence of sensor orientations.

Spatial Variations in Completeness

We calculate the network detection-probability distribution, $P_E(M, \mathbf{x}, t)$, and the probability-based magnitude of completeness, $M_P(\mathbf{x}, t)$, as proposed by Schorlemmer and Woessner (2008) and described in the previous section. For the calculation of P_E and M_P, we use the sensor-detection probabilities $P_D(M, R)$ as defined by Schorlemmer and Woessner (2008). In order to resolve the details in the spatial completeness distribution, we use a finer binning with a magnitude interval of $\Delta M = 0.1$ and a distance interval of $\Delta R = 10$ m. We do not use the extended detection probabilities $P_D^*(M, R, \phi, z)$ of the previous section to calculate $P_E(M, \mathbf{x}, t)$, because the four-dimensional binning requires more data, and the available data are too sparse in large areas. A fine, four-dimensional binning would lead in many areas to less than 10 events per bin. Here, the limits of the catalog are reached. Furthermore, the extended detection probabilities $P_D^*(M, R, \phi, z)$ already reveal enough information to correctly calculate the spatial variations in completeness, as they allow us to define subvolumes in which the completeness is independent of the path direction. It is therefore preferential to avoid data reduction due to the four-dimensional binning in the second step and to calculate instead $P_E(M, \mathbf{x}, t)$ using $P_D(M, R)$ for subvolumes defined by the results of the first step.

First, the spatial distribution of catalog completeness is analyzed in the PG dike, where most of the Christmas-event aftershocks are located. The detection probabilities $P_D^*(M, R, \phi, z)$ do not show any heterogeneities within the dike, but there are some near the tunnel. We therefore define two subvolumes: the dike volume north of the tunnel and the dike volume south of the tunnel. In this way, we separate in the analysis ray paths that cross the vicinity of the tunnel from ray paths that do not cross. The results of the spatial completeness analysis for the PG dike are shown in Figure 5. The smallest probability-based magnitude of completeness $M_P = -4.8$ is found south of the tunnel at 3530 m depth in the focus of the

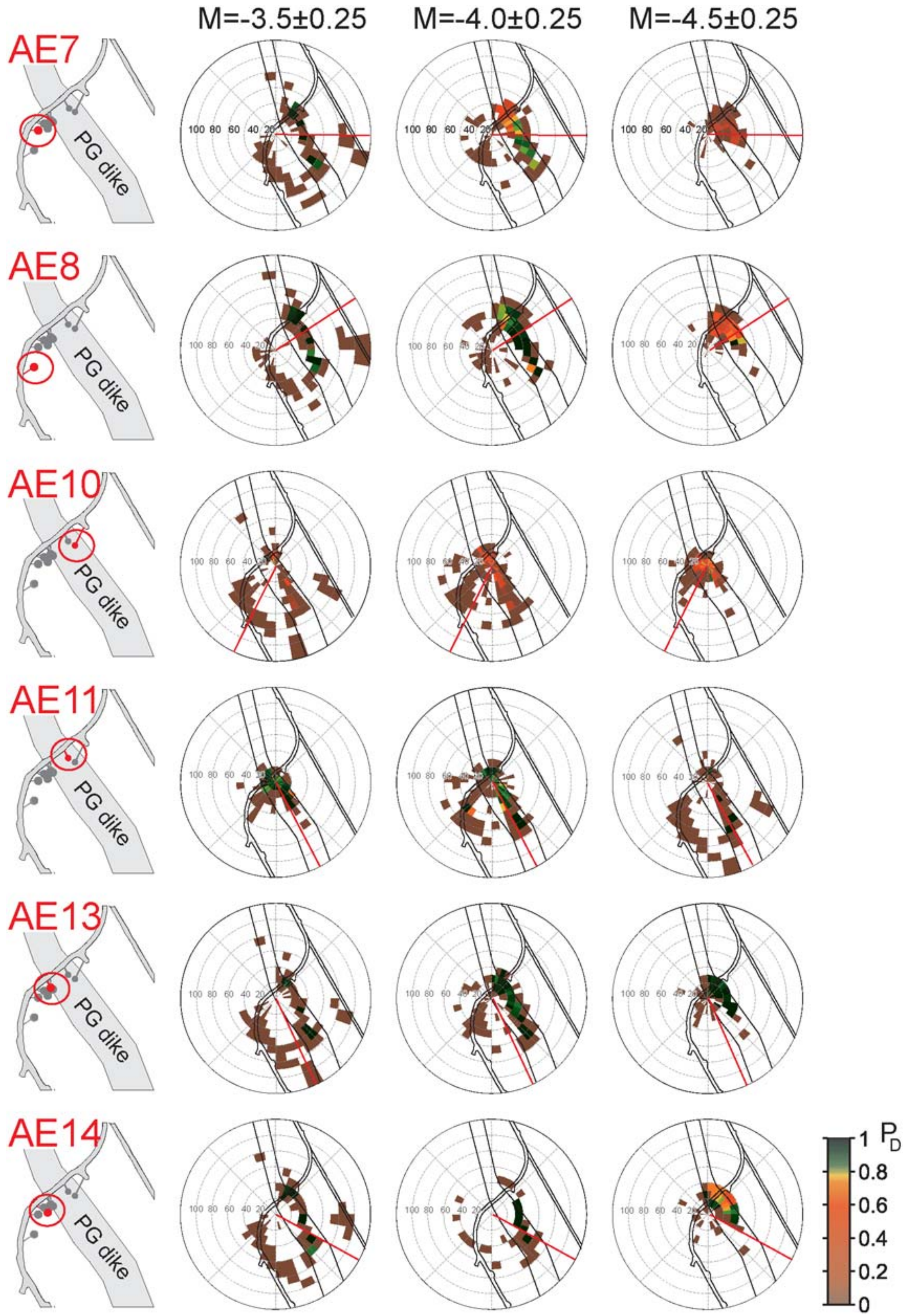

Figure 4. Detection probabilities, $P_D^*(M, R, \phi, \Delta z)$, taking into account the direction of the incoming wave for several sensors. The results for $\Delta M = -3.5 \pm 0.25$, $\Delta M = -4.0 \pm 0.25$, and $\Delta M = -4.5 \pm 0.25$ are presented. Depth interval Δz is 3520–3540 m. The centers of the rose plots are located at the analyzed sensor. For orientation, the tunnel positions and the location of the PG dike are shown. The orientation of each sensor is marked by a red line. Note: Data bins with fewer data points than required are automatically set to zero probability. The influence of local heterogeneities is clearly seen for sensors AE7, AE8, and AE14 for $M = -4 \pm 0.25$, where the detection probability depends on the direction. Differences in sensor performances are visible as discussed in the Sensor Detection-Probability Analysis section.

network. Figure 5 demonstrates that the differences in recording completeness are significant throughout space. The recording completeness varies by approximately one order of magnitude within the observational volume of about $100 \times 100 \times 100$ m. Furthermore, the results demonstrate that the extended PMC method is able to identify variations in completeness due to local heterogeneities. In approximately 50-m distance to the south, the sensitivity is reduced and results in $M_P = -4.6$; the same distance to the north, the sensitivity is reduced stronger due to the attenuation caused by the tunnel's fracture zone identified by the extended detection probabilities $P_D^*(M, R, \phi, z)$ and results in $M_P = -4.3$.

The third subvolume analyzed is the stope area, east of the dike and in a depth interval from $z = 3480$ m to $z = 3450$ m. At stope level, the extended detection probabilities $P_D^*(M, R, \phi, z)$ do not show any dependency on the direction. All events at the stope level have a similar ray path to the sensors, thereby crossing the rock volume adjacent to the stope face and the dike-host rock boundary. Nonetheless, we point out that rocks in the vicinity of the stope face are highly fractured, which might introduce more complexity locally into the completeness than estimated in this study. The results of the spatial completeness analysis of the stope area are presented in Figure 6. Compared to the catalog completeness inside the PG dike close to the network, the completeness is poorer at stope level. We estimate values between $M_P = -3.8$ and $M_P = -3.1$. The magnitude of completeness decreases with increasing distance to the network. In the western part of the stope, located approximately 70–80 m from the network focus, M_P was estimated lowest with −3.8. For comparison, at the same distance from the network focus, but within the dike, M_P values as small as −4.1 are achieved. It follows that waves propagating from the stope to the JAGUARS network are affected by stronger damping,

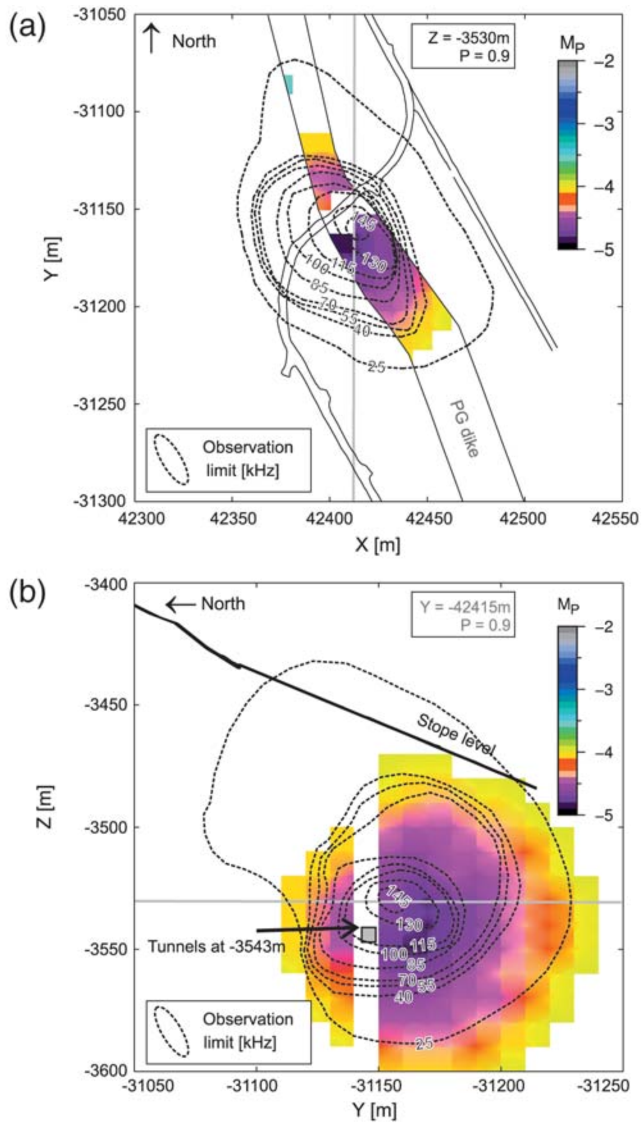

Figure 5. Spatial distribution of probability-based magnitude of completeness, M_P, within the PG dike in (a) mapview and (b) sideview. The volume north of the tunnel is analyzed separately from the volume south of the tunnel to take into account the influence of the fracture zone around the tunnel. Data near the tunnel are not analyzed, as a clear separation of ray paths is not possible due to location uncertainties. Dashed lines outline the maximum distances of high-frequency recording for frequencies $f \gg 25$ kHz (Plenkers *et al.*, 2010). The straight gray line marks the position of the sideview and mapview crosscut, respectively. The limitations in high-frequency recording correlate clearly with the decrease in catalog completeness. The completeness is influenced by local heterogeneities as discussed in the Spatial Variations in Completeness section. For orientation, the tunnels in the vicinity of the JAGUARS network are plotted.

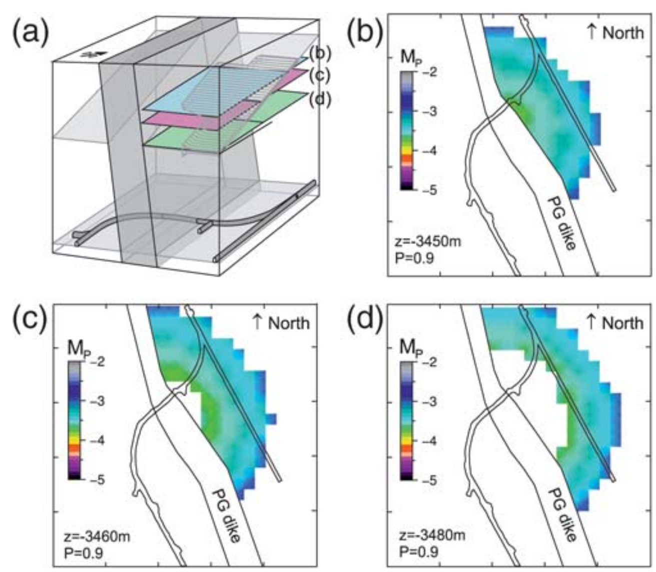

Figure 6. (a) Spatial distribution of probability-based magnitude of completeness, M_P, near the stope at depth (b) 3540 m, (c) 3460 m, and (d) 3480 m, as shown in the sketch. At stope level, only frequencies $f \ll 40$ kHz are recorded by the JAGUARS network (Plenkers *et al.*, 2010). M_P is clearly reduced compared to the same distance within the PG dike due to the presence of highly fractured rocks near the stope face. For orientation, the tunnels at 3540 m depth and the PG dike at stope level are plotted.

possibly due to the highly fractured zone of the stope face or due to traversing the dike-host rock boundary. The results emphasize that the JAGUARS network is not appropriate for recording very small events with $M < -3.8$ in the stope area.

To evaluate the results of this study, we have to consider the influence of location uncertainties. The influence of the isotropic velocity model on the location accuracy can be neglected because the velocities used in the localization algorithm differ only slightly (± 0.1 km/s) from the estimated velocity range. The resulting location uncertainties are much smaller than the bin sizes analyzed. The rather linear network geometry influences the location accuracy only of events located far from the network, as the JAGUARS network has an extension in the x direction of 32 m, in the y direction of 34 m, and in the z direction of 13 m. It follows that the spherical coverage of the network is good for events occurring close by the network. The location uncertainty of events that occurred within the dike ($R < 60$ m) is much smaller than the bin size of 10 m and therefore does not influence the results in this study. Events occurring at the stope level have longer source-receiver distances ($R > 80$ m) and therefore higher location uncertainties. The good correlation of the localization of seismic events with known structures, for example, the stope front where blasting occurrs (for details, see Plenkers *et al.*, 2010) demonstrates nonetheless that the location uncertainty is not crucial for this study. In general, the localization accuracy is crucial for the extended PMC study, and the bin size should not be chosen smaller than the localization uncertainty.

The uncertainty in magnitude estimation is more crucial to this study than the location uncertainties. As estimated by Kwiatek *et al.* (2010), the magnitude uncertainty can reach values of $\sigma_M = \pm 0.46$. The magnitude uncertainty is higher than usual, due to the implementation of acoustic emission sensors as discussed in Kwiatek *et al.* (2010). For this reason, the uncertainty in magnitude estimation is larger than some of the variations discussed earlier in this section. The good correlation of variations in magnitude of completeness estimated in this study with known structures suggests that the observed variations are real. The extended PMC method will benefit nonetheless if magnitudes with smaller uncertainties can be used in future studies.

The results of this study demonstrate that details of the spatial distribution of recording completeness can be resolved in very heterogenous network settings using the extended PMC method. We estimated strong spatial variations in recording completeness for the JAGUARS network, for example, for the area of the fault plane of the M_w 1.9 mainshock in which the completeness magnitude varies by nearly one magnitude compared to the surrounding areas. The effect of fractures on traveling waves was studied in detail by Hildyard (2001). This study reveals their crucial effect on the magnitude of completeness. The spatial variations in magnitude of completeness due to local heterogeneities are significant and must be taken into account both when designing a seismic network underground as well as when analyzing induced seismicity with very small magnitudes.

This study demonstrates that the data amount necessary for a detailed analysis of the spatial distribution of recording completeness is significant. Although we used more than 9444 events as input data, we were not able to obtain results in large areas with sparse event distribution. We conclude that a high-resolution analysis will be reliable only in areas with a large amount of data. In general, the approach described in this study is useful not only for in-mine networks but for all seismic networks located in complex settings monitoring high seismic activity such as induced seismicity near exploration sites or seismicity in volcanic areas.

Finally, we compare the results on the detection completeness of this study with the results of previous studies. Plenkers *et al.* (2010) studied the network sensitivity of the JAGUARS seismic network by analyzing the frequency content of recorded waveforms. They found that higher frequencies ($f \gg 25$ kHz) can be recorded only at locations with limited distance to the events. Frequencies above 100 kHz were observed only at distances up to 40 m; frequencies above 25 kHz at distances up to 100 m. Furthermore, they demonstrated that local geological structures, cavities, and the directivity of the AE sensors influence the data recording significantly and decrease the realized observational distances. In general, small magnitudes of completeness highlight areas where the seismic network is sensitive. Higher magnitudes of completeness point out that the recording is limited. The magnitude of completeness is therefore directly linked to the network sensitivity.

In Figure 5, the spatial distribution of the magnitude of completeness from this study, M_P, is compared with the network sensitivity as computed by Plenkers *et al.* (2010). We find that small magnitudes of completeness ($M_P \ll -4$) require the recording of very high frequencies ($f \gg 25$ kHz). As seen in Figure 5, frequencies $f > 100$ kHz are necessary to reliably record magnitudes $M_w < -4.5$. Magnitudes $-4.5 < M_w < -4$ are reliably recorded only if recording frequencies $f > 25$ kHz is possible. Local heterogeneities, that interact with the high-frequency wave field and introduce local attenuation, such as geological boundaries and cavities, increase the magnitude of completeness significantly.

The correlation of both results is noticeable. The probability-based magnitude of completeness increases for most parts in the same manner as the maximum-observed frequency is decreasing. Only one significant deviation of the magnitude of completeness, M_P, from the network sensitivity is observed (Fig. 5b). For the observational space located below the tunnel (at a depth greater than 3540 m), the PMC analysis computes small magnitudes of completeness, although the network sensitivity to high frequencies is decreased. We attribute this effect to the use of detection probabilities, $P_D(M, R)$, which assume that the recording does not depend on the direction, as discussed previously in this section. For this reason, the directivity of the AE sensors (Manthei *et al.*, 2001), which all point upwards but one and have accordingly a poorer sensitivity downwards, is not taken into account in the PMC analysis. We suggest that this effect leads to slightly underestimated magnitudes of completeness for depth below the JAGUARS network.

We summarize that both analyses agree in detail, although they are based on very different approaches. Whereas the PMC analysis of this study is based on the locations and magnitudes estimated from corrected waveforms, the network sensitivity study of Plenkers *et al.* (2010) is based on the frequency content of raw waveforms. We conclude that the good correlation of the results of this study with the results of Plenkers *et al.* (2010) demonstrates that the analysis of spatial variations of completeness magnitudes was successful and that the PMC method can provide these results without the use of waveforms.

We also compare the results on the detection completeness of this study with the results obtained from the magnitude-frequency analysis (Gutenberg–Richter) by Kwiatek *et al.* (2010). They analyzed the magnitude-frequency distribution of the data used in this study and estimated the magnitude of completeness following the approach of Wiemer and Wyss (2000). Both magnitudes of completeness, M_P calculated by PMC and M_c calculated by Gutenberg–Richter, describe the completeness of the seismic catalog and differ only in the estimation approach. Kwiatek *et al.* (2010) chose three different areas of the observational volume of the JAGUARS network in their analysis to account for spatial variations as discussed in detail in the Introduction. They found significantly varying magnitudes of completeness, M_c. The in-depth analysis of the spatial distribution of completeness using the extended PMC method to calculate M_P in this study confirms the differences in M_c found by Kwiatek *et al.* (2010). Both studies estimate that the catalog completeness is best in the network's focus and significantly lower at the stope level (Table 1).

For the network center, the Gutenberg–Richter computations result in $M_c = 4.45$, and the PMC method estimates values between $M_P = -4.8$ and $M_P = -4.4$. For the whole dike, the Gutenberg–Richter method estimates $M_c = 4.3$, and the PMC method obtains spatial variations with $-4.8 < M_P < -4.1$. At stope level, the Gutenberg–Richter results are $M_c = -3.0$ for the aftershock sequence and $M_c = -3.3$ to -3.4 for postblasting sequences. The PMC method, based on the aftershock sequence, estimates a completeness distribution at stope level with $-3.7 < M_P < -3.0$.

Table 1
Comparison of M_c Calculated Based on Frequency-Magnitude Analysis (GR) Following Wiemer and Wyss (2000) and M_P Calculated Using the Probability-Based Magnitude of Completeness (PMC) Method as Described in this Study

	M_c	M_P
HF	−4.5	−4.8 to −4.4
F	−4.3	−4.8 to −4.1
S	−3.0	−3.7 to −3.0

Because of the significantly better spatial resolution of M_P, a range of magnitudes is given. Areas HF, F, and Z are explained in Figure 2.

Completeness values obtained are in general in good agreement. The single value obtained by Kwiatek *et al.* (2010) using the Gutenberg–Richter method is the averaged value of results calculated in this study using the extended PMC method. The spatial resolution of the catalog completeness is significantly better when using the extended PMC approach of this study. Spatial variations cannot be easily detected using the Gutenberg–Richter analysis. Using the extended PMC analysis, we are able to demonstrate that the catalog completeness of the JAGUARS catalog varies significantly in space even over small distances.

In general, the values of M_P estimated with the PMC method are slightly lower than the estimates of M_c of the Gutenberg–Richter analysis. We point out that the PMC method developed in this study is based on the pick-distributions of events. It uses pick information as well as nonpick information. In the case of the JAGUARS network, we must take into account that nonpick information of events with small magnitudes is possibly missing. Small events containing very high frequencies are recorded from short distances only, as discussed earlier in this section. Accordingly, the events are recorded on fewer stations, for example, on four stations or less. If a single wave onset is not picked, even on one station, the missing pick can prevent a successful localization. Unlocated events are not considered in the PMC method and, as a consequence, the nonpick information is withheld from the analysis. In this case, the pick distribution overestimates the ratio of successfully picked events. This leads to an overestimation of detection probabilities and consequently to potentially smaller magnitudes of completeness, M_P, as discussed also by Schorlemmer and Woessner (2008). The effect of missing pick information was studied for regional networks (Schorlemmer *et al.*, 2010). No increase in probability-based magnitude of completeness was observed. Nonetheless, the effect must be taken into account for the JAGUARS network, as it consists of considerably fewer stations than regional networks. We suggest that the influence of missing nonpick information in the PMC analysis of the JAGUARS network is small because the results of PMC and Gutenberg–Richter are in good agreement. Taking into account the uncertainties in magnitude estimation, we suggest that the uncertainty of the magnitudes of completeness estimated is ±0.5 for both methods. The spatial distribution of the catalog completeness holds, even when taking into account the magnitude uncertainties.

Kwiatek *et al.* (2010) demonstrate that the frequency-magnitude distribution of the JAGUARS catalog follows the Gutenberg–Richter distribution. They conclude that, within the magnitude range studied, there is no evidence for a minimum magnitude as proposed by Dieterich (1979) and Aki (1987). The good correlation of completeness estimates of their magnitude-frequency study and the probability-based completeness study presented here demonstrate that the subvolumes chosen arbitrarily by Kwiatek *et al.* (2010) are justified and that their results are stable.

Conclusion

Knowledge of the recording completeness of seismic networks is essential for almost every statistical study in seismological research. Analyzing the recording completeness of very sensitive underground networks is difficult because the high-frequency waves of small-scale seismicity are significantly influenced even by local heterogeneities. To analyze the local variations in recording completeness of the JAGUARS network that recorded picoseismicity (M_w −5 to −1) inside the Mponeng gold mine, we developed a detection completeness analysis that is able to take into account a complex and heterogeneous observational space. We extended the probability-based magnitude of completeness (PMC) method of Schorlemmer and Woessner (2008) to take into account the direction of observation. We introduce the extended detection probabilities $P^*_D(M, R, \phi, z)$ and suggest a two-step approach. First, we analyze the extended detection probabilities $P^*_D(M, R, \phi, z)$ of each station, taking into account the direction of observation. This analysis is used to gain insight into the detection probabilities of sensors and the location of significant heterogeneities in the observational volume. Local heterogeneities that interact with the seismic wave field are reflected in the detection analysis by decreased detection probabilities. We demonstrate that the fracture zone around a tunnel cavity has a crucial influence on the detection probability locally due to damping effects as well as damping effects of highly fractured rock near the stope face. Furthermore, the detection probabilities allow us to analyze the performance of individual sensors, identifying broken sensors or sensors with poor rock-sensor coupling. We define regions without local heterogeneities whose detection probabilities are accordingly direction-independent using the results of the first step and perform a probability-based magnitude of completeness analysis following Schorlemmer and Woessner (2008). We demonstrate that the new approach is able to resolve the strongly varying recording completeness of the JAGUARS network. We calculate magnitudes of completeness ranging from $M_P = -4.8$ in the center of the network to $M_P = -3.1$ at the stope level more than 100 m from the network. Also, within the area of the rupture plane of the M_w 1.9 event, the recording completeness varies by approximately one order of magnitude. These variations in recording completeness are significant and must be taken into account in further analyses.

Comparing the recording completeness of this study with the results of the network sensitivity study of Plenkers *et al.* (2010), we find that the recording completeness is directly correlated with the network capability of recording high frequencies. The best recording completeness is calculated where frequencies $f > 145$ kHz are recorded. In areas of reduced network sensitivity (frequencies recorded $f < 25$ kHz), the catalog completeness is reduced by more than one unit of magnitude.

We conclude that incorporating the direction of observation in the analysis allows us to resolve and to apply the PMC method to networks in complex underground settings. The detailed analysis of spatial variations in recording completeness of seismic networks inside mines becomes possible. Furthermore, we conclude that the PMC method is a reliable tool to insure proper sensor and network operation.

Data and Resources

The seismic catalog used in this article was collected using the JAGUARS seismic network in the Mponeng gold mine. JAGUARS is a joint project of the University of Tokyo, Tohoku University, Ritsumeikan University (Japan), Helmholtz Center Potsdam (GFZ) German Research Center for Geosciences, GMuG Gesellschaft für Materialprüfung und Geophysik (Germany), Seismogen CC, AngloGold Ashanti Ltd., Integrated Seismic Systems (ISS) International, and the Council for Scientific and Industrial Research (CSIR) Johannesburg (South Africa). Catalog data are currently not released to the public. All software codes used for this study are licensed under the General Public License Version 2 (http://www.gnu.org/licenses/gpl-2.0.html, last accessed July 2011) and are available from www.completenessweb.org (last accessed July 2011). The result data are licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License (http://creativecommons.org/licenses/by-nc-sa/3.0/, last accessed July 2011) and also available at www.completenessweb.org (last accessed July 2011).

Acknowledgments

We want to thank M. Nakatani, Y. Yabe, H. Ogasawara, and coworkers for their work in installing the JAGUARS network. We also thank J. Philipp and the Gesellschaft für Materialprüfung und Geophysik mbH (GMuG) for their work in developing and installing the network. We thank G. Dresen for valuable remarks and comments, A. Hendrich for help when preparing Figure 1, and M. Wieprich for helping us with the manual preparation of the dataset. The Rock Engineering and Geology departments (R. Carstens, C. Miller, M. Pienaar, and G. Flitton) at the Mponeng gold mine (Anglo Gold Ashanti Ltd.), Integrated Seismic Systems (ISS) Ltd. in Carletonville, and the Council for Scientific and Industrial Research (CSIR) in Johannesburg are acknowledged for providing us with useful information and many electronic materials. In particular, we want to thank the open-source community for the Linux operating system and the many programs used in this study. This research was supported by the NSF-EAR-0738785 grant and by the Southern California Earthquake Center (SCEC). SCEC is funded by NSF Cooperative Agreement EAR-0106924 and USGS Cooperative Agreement 02HQAG0008. The SCEC contribution number for this paper is 1463.

References

Abercrombie, R. (1995). Earthquake source scaling relationships from −1 to 5 M_L using seismograms recorded at 2.5-km depth, *J. Geophys. Res.* **100,** 24,015–24,036.

Abercrombie, R. E., and J. R. Rice (2005). Can observations of earthquake scaling constrain slip weakening?, *Geophys. J. Int.* **162,** no. 2, 406–424.

Aki, K. (1987). Magnitude-frequency relation for small earthquakes: A clue to the origin of f_{max} of large earthquakes, *J. Geophys. Res.* **92,** 1349–1355.

Amorèse, D. (2007). Applying a change-point detection method on frequency-magnitude distributions, *Bull. Seismol. Soc. Am.* **97,** 1742–1749, doi 10.1785/0120060181.

Boettcher, M., A. McGarr, and M. Johnston (2009). Extension of Gutenberg–Richter distribution to M_w–1.3, no lower limit in sight, *Geophys. Res. Lett.* **36,** L10307, doi 10.1029/2009GL038080.

Bohnhoff, M., G. Dresen, W. L. Ellsworth, and H. Ito (2009). Passive seismic monitoring of natural and induced earthquakes: Case studies, future directions and socio-economic relevance, in *New Frontiers in Integrated Solid Earth Sciences* (International Year of Planet Earth), S. Cloetingh and J. Negendank (Editors), Springer, New York, 414 pp.

Cao, A., and S. S. Gao (2002). Temporal variation of seismic *b*-values beneath northeastern Japan island arc, *Geophys. Res. Lett.* **29,** no. 9, 1334, doi 10.1029/2001GL013775.

Cichowicz, A., and R. Green (1989). Changes in the early part of the seismic coda due to localized scatterers: The estimation of Q in a stope environment, *Pure Appl. Geophys.* **129,** 497–511.

Cichowicz, A., R. Green, and A. v. Z. Brink (1988). Coda polarization properties of high-frequency microseismic events, *Bull. Seismol. Soc. Am.* **78,** 1297–1318.

Dieterich, J. H. (1979). Modeling of rock friction 1. Experimental results and constitutive equations, *J. Geophys. Res.* **84,** 2161–2168.

Ellsworth, W., S. H. Hickman, M. D. Zoback, K. Imanishi, C. H. Thurber, and S. Roecker (2007). Micro- nano- and picoearthquakes at SAFOD: Implications for earthquake rupture and fault mechanics, *Eos Trans. AGU* **88,** no. 52. Fall Meet. Suppl., Abstract S12B-05.

Gentili, S., M. Sugan, L. Peruzza, and D. Schorlemmer (2011). Probabilistic completeness assessment of the past 30 years of seismic monitoring in northeastern Italy, *Phys. Earth Planet. In.* **186,** 81–96, doi 10.1016/j.pepi.2011.03.005.

Gibowicz, S. J., and A. Kijko (1994). *An Introduction to Mining Seismology* Academic Press, San Diego, California, 399 pp.

Gutenberg, B., and C. F. Richter (1944). Frequency of earthquakes in California, *Bull. Seismol. Soc. Am.* **34,** 185–188.

Hildyard, M. (2001). Wave interaction with underground openings in fractured rock, *Ph.D. Thesis*, University of Liverpool, Liverpool, United Kingdom.

Imanishi, K., and W. Ellsworth (2006). Scaling relationships of microearthquakes at Parkfield, CA. determined using the SAFOD Pilot Hole seismic array, in *Earthquakes: Radiated Energy and the Physics of Faulting* R. Abercrombie, A. McGarr, G. DiToro, and H. Kanamori (Editors), Geophys. Monogr. Ser., **170,** 81–90, AGU, Washington, D.C.

Ishimoto, M., and K. Iida (1939). Observations of earthquakes registered with the microseismograph constructed recently, *Bull. Earthquake Res. Inst. Tokyo Univ.* **17,** 443–478.

Kwiatek, G., K. Plenkers, M. Nakatani, Y. Yabe, G. Dresen, and the JAGUARS Group (2010). Frequency-magnitude characteristics down to magnitude -4.4 for induced seismicity recorded at Mponeng Gold Mine, South Africa, *Bull. Seismol. Soc. Am.* **100,** 1165–1173, doi 10.1785/0120090277.

Manthei, G., J. Eisenblätter, and T. Spies (2001). Source parameter of acoustic emission events in salt rock, *J. Acoust. Emiss.* **19,** 100–108.

Marsan, D. (2003). Triggering of seismicity at short timescales following Californian earthquakes, *J. Geophys. Res.* **108,** no. B5, 2266, doi 10.1029/2002JB001946.

Maxwell, S., and R. P. Young (1998). Progpagation effects of an underground excavation, *Tectonophysics* **289,** 17–30.

McGarr, A. (1971). Stable deformation of rock near deep-level tabular excavations, *J. Geophys. Res.* **76,** 7088–7106.

Mendecki, A. (1997). Keynote lecture: Principles of monitoring seismic rockmass response to mining, in *Rockbursts and Seismicity in Mines*, Gibowicz, S. J., and S. Lasocki (Editors), Balkema, Rotterdam, The Netherlands, 16 pp.

Milev, A. M., and S. M. Spottiswoode (2002). Effect of the rock properties on mining-induced seismicity around the Ventersdorp Contact Reef, Witwatersrand Basin, South Africa, *Pure Appl. Geophys.* **159,** 165–177.

Nakatani, M., Y. Yabe, J. Philipp, G. Morema, S. Stanchits, G. Dresen, and the JAGUARS Group (2008). Acoustic emission measurements in a deep gold mine in South Africa: Project overview and some typical waveforms, *Seismol. Res. Lett.* **79,** 311.

Nanjo, K. Z., D. Schorlemmer, J. Woessner, S. Wiemer, and D. Giardini (2010). Earthquake detection capability of the Swiss Seismic Network, *Geophys. J. Int.* **181,** 1713–1724.

Naoi, M., M. Nakatani, Y. Yabe, J. Philipp, and the JAGUARS Group (2008). Very high frequency AE ($<$200 kHz) and micro seismicity observation in a deep South African gold mine-evaluation of the acoustic properties of the site by *in-situ* transmission test, *Seismol. Res. Lett.* **79,** 330.

Naoi, M., M. Nakatani, Y. Yabe, G. Kwiatek, T. Igarashi, and K. Plenkers (2011). Twenty thousand aftershocks of a very small (M 2) earthquake and their relations to the mainshock rupture and geological structures, *Bull. Seismol. Soc. Am.* **101-5,** 2399–2407.

Pettit, W., C. Baker, and R. P. Young (2002). Using acoustic emission for assessment of damage in rock around engineered structures at the Äspö hard rock laboratory, in *Proc. of the Fifth North American Rock Mechanics Symposium*, Toronto, Canada, University of Toronto Press, 1161–1170.

Plenkers, K., G. Kwiatek, M. Naoi, and the JAGUARS Group (2009). JAGUARS project: Attenuation, scattering and instrumental effects of events recorded by a high-frequency seismic network as seen from seismograms and their frequency content, in *Proc. of the First IASPEI General Assembly*, *Council for Geoscience*, Cape Town, Republic of South Africa, 10–16 January, 2009.

Plenkers, K., G. Kwiatek, M. Nakatani, G. Dresen, and the JAGUARS Group (2010). Observation of seismic events with frequencies $f > 25$ kHz at Mponeng Gold Mine, South Africa, *Seismol. Res. Lett.* **81,** 467–479.

Richardson, E., and T. Jordan (2002). Seismicity in deep gold mines of South Africa: Implications for tectonic eartquakes, *Bull. Seismol. Soc. Am.* **92,** 1766–1782.

Rydelek, P., and I. Sacks (1989). Testing the completeness of earthquake catalogues and the hypothesis of self-similarity, *Nature* **337,** 251–253.

Schorlemmer, D. (2009). Probabilistic seismic network completeness: Theory, application and results (abstract), *Seismol. Res. Lett.* **80,** 298.

Schorlemmer, D., and J. Woessner (2008). Probability of detecting an earthquake, *Bull. Seismol. Soc. Am.* **98,** 2103–2117.

Schorlemmer, D., F. Mele, and W. Marzocchi (2010). A completeness analysis of the National Seismic Network of Italy, *J. Geophys. Res.* **115,** B04308, doi: 10.1029/2008JB006097.

Schorlemmer, D., S. Wiemer, and M. Wyss (2005). Variations in earthquake-size distribution across different stress regimes, *Nature* **437,** 539–542.

Stanchits, S., G. Dresen, and the JAGUARS Ggroup (2010). Formation of faults in Diorite and Quartzite samples extracted from a deep gold mine (South Africa), *EGU General Assembly 2010*, 2–7 May, Vienna, Austria, Geophysical Research Abstracts, 12**,** 5605.

Wiemer, S., and M. Wyss (2000). Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the Western United States and Japan, *Bull. Seismol. Soc. Am.* **90,** 859–869.

Woessner, J., and S. Wiemer (2005). Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty, *Bull. Seismol. Soc. Am.* **95,** no. 2, 684–698, doi: 10.1785/0120040007.

Yabe, Y., J. Philipp, M. Nakatani, G. Morema, M. Naoi, H. Kawakata, T. Igarashi, G. Dresen, H. Ogasawara, and the JAGUARS Group (2009). Observation of numerous aftershocks of an M_w 1.9 earthquake with an AE network installed in a deep gold mine in South Africa, *Earth Planets Space* **10,** e49–e52.

Helmholtz Centre Potsdam—GFZ German Research Centre for Geosciences
Telegrafenberg, 14473
Potsdam, Germany
(K.P., G.K.)

Southern California Earthquake Center
University of Southern California
3651 Trousdale Parkway
MC-0740, Los Angeles
California 90089-0740, USA
(D.S.)

Manuscript received 13 January 2011