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Steady activity of microfractures on geological faults loaded by mining stress

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ABSTRACT

Acoustic Emissions (AE) down to $M_W \sim -4$ were recorded at a site 1 km beneath the surface in the Cooke 4 Mine, South Africa. Several planar AE clusters with lateral extent of 10–100 m were identified. Most of them were located several tens of meters away from the mining front, and exhibited steady activity during the analysis period of about two months. Some of the clusters coincided with mapped faults. The planar-cluster AEs were sharply aggregated within a thickness of several decimeters, likely delineating the fracture interface of the fault and its higher-order morphology such as branches, bends, and stepovers. The composite focal mechanism evaluated for each cluster was consistent with slip events on the fracture interface. These results imply that numerous shear microfractures occur steadily on a natural fault surface subjected to a mining-related stress increase. The planar clusters consist of very small AEs (99.7% were smaller than M_W −2), exhibiting high *b*-values much exceeding unity. This contrasts with the more usual *b*-values of the stope-cluster AEs, which were aggregated within 20 m of the mining front and exhibited a more scattered distribution. The size distribution of microfractures on a fracture interface may directly reflect fine-scale irregularities of the interface. On the other hand, many other mapped faults near the planar AE clusters were not accompanied by AE activities, despite the fact that these quiet faults were subjected to a similar stress history. The presence or absence of AE activities on a fault may reflect different states of the fault, including stress and strength.

1. Introduction

The acoustic emission (AE) activity preceding a macroscopic shear failure or an unstable slip event has been studied in laboratory experiments as a possible analogue of microseismicity preceding a large earthquake. For example, in rock fracture experiments using intact rock, the two-dimensional aggregation of AEs on the plane of the future through-going rupture is often observed prior to the macroscopic rupture (e.g., Lockner et al., 1991; Lei et al., 2000a-c, 2004). Lei and co-authors reported that such AE activities were more abundant in an experiment on a heterogeneous sample than that on a homogeneous sample (Lei et al., 2000a-c, 2004) and that their statistical parameters such as *b*-values and fractal dimensions showed characteristic time-dependent patterns precursory to the through-going rupture (e.g., Lei, 2006; Lei and Satoh, 2007). In stick-slip experiments with saw-cut samples, AEs were observed preceding a macroscopic slip event (Thompson et al., 2005). These AEs are often associated with nucleation of a macroscopic slip, which was well investigated by stick-slip experiments (Ohnaka and Shen, 1999). More recently, stick-slip experiments have

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been conducted on a non-planar fault created by the prior fracturing of an intact rock sample in order to imitate a slip event on a natural fault, giving a more complicated geometrical structure than saw-cut samples (Thompson et al., 2009; Goebel et al., 2012, 2013). In such experiments, AEs preceding the macroscopic event begin to occur at a lower stress level than is the case for saw-cut samples. However, similarly to the saw-cut sample experiments, their activity increases and their *b*-value decreases with loading.

The knowledge gained from laboratory experiments is expected to be applicable to microseismicity around natural active faults. However, except for aftershocks, microseismicity around faults is not very ubiquitous. Many active faults are not accompanied by steadily occurring microseismicity (Mogi, 1981). It seems surprising that a fault subjected to a stress close to its macroscopic strength is accompanied by little microseismicity. Considering the fractal geometry of natural faults (e.g., Sagy et al., 2007), high-stress spots are likely to be induced easily along a loaded fault, especially at short wavelengths. Numerical simulations by Dieterich and Smith (2009) demonstrated that high-stress spots are distributed ubiquitously along a fault. Hence, it may be natural to imagine that such high-stress spots induce many microfractures close to the central part of the fault, i.e., the "fault core" or "principal slip surface" (PSS), which accommodate most of the shear displacement across the fault zone (Chester and Chester, 1998; Chester et al., 2004).

Nonetheless, as mentioned above, many active faults lack significant microseismicity. Furthermore, recent studies based on accurate source locations report that microseismic events along a fault, even if they are observed, are actually spread over a broader "damage zone" (Chester et al., 2004) of several hundred meters width around the fault, and lack peaks of event density corresponding to the fault core or PSS (Hauksson, 2010; Powers and Jordan, 2010). Repeating earthquakes on plate boundaries (e.g., Nadeau and Johnson, 1998; Matsuzawa et al., 2002) may be the only example of steady activity of on-fault events that has been ever observed.

The reason why on-fault microseismic activity is so rarely observed may simply be that the events are too small to be detected by a conventional seismic network, although other possibilities, such as a large critical size on mature faults (e.g., Dieterich, 1986; Marone and Kilgore, 1993), are not excluded. Deep mines, where many earthquakes are induced by the stress concentration produced by excavation, provide a good opportunity to deploy an observation network that can detect very small earthquakes. However, even in observations in mines, there are no published examples of a preexisting fault that was clearly delineated by steady activity of microseismic events, though some studies reported that a larger earthquake (M > ~2) reactivated part of a geological fault (e.g., Heesakkers et al., 2011). For example, Snelling et al. (2013) investigated hypocenter distributions of $-2.3 \le M_W \le 0.8$ events and reported that there was no correlation between the hypocenters and geological faults near the microseismic network. Although some studies examined even smaller events in mines (e.g., Young and Collins, 2001; down to M_W −7), such observations can only detect events in a very limited region because small seismic events radiate high-frequency-dominated waves, which decay rapidly with distance. For instance, the network of Young and Collins (2001) targeted AEs occurring only within several meters from a tunnel, and hence it did not have capability to examine whether AEs occur on a large geological fault or not.

We deployed an AE network (hereinafter referred to as AEnet) 1 km beneath the surface in the Cooke 4 Mine (previously known as the Ezulwini Mine) in South Africa, which can detect events down to M_W −4 within ~100 m of the network (Naoi et al., 2014). From these observations, we identified several, thin, planar AE alignments that had a very high event density compared to the surrounding region. They consisted of very small AEs; almost all of them were smaller than M_W −2. Because the AEs aggregated sharply in two dimensions and had composite focal mechanisms that were consistent with slip events on the approximate plane of each AE alignment, these AEs are likely to be shear events on pre-existing discontinuities. Indeed, corresponding geological faults were found for some of the alignments. In the present paper, we will describe the features of these AEs.

2. Observations

2.1. Geology and mining around the observation site

Our observation network (AEnet) was deployed 1 km beneath the ground, within the 200-m radius circular shaft pillar of the Cooke 4 mine situated in the West Rand gold field near Johannesburg, South Africa. This mine exploits the topmost 10 m of the Upper Elsburg reef, which contains multiple gold-bearing strata of various thicknesses. The rock around our site, including the reef, is Archaean quartzite of the Witwatersrand Supergroup (2.98–2.84 Ga), which is overlain by the Ventersdorp Supergroup (2.72–2.63 Ga) mainly consisting of lava, and, in turn, the Transvaal Supergroup (2.58–2.20 Ga) that continues almost to the ground surface (Dankert and Hein, 2010).

Mining started in 1960. With the exception of the shaft pillar, the Upper Elsburg reef was mined out almost completely by tabular mining, up to 3-m high, by 2001, when the mine was closed. The extensive stopes surrounding the shaft pillar have not been back-filled (installation of bags of tailings to suppress the time-dependent stope closure), so the shaft pillar is subjected to vertical stress that is greater than the virgin stress. Ogasawara et al. (2014) measured in-situ stress in the shaft pillar by the overcoring technique (Sakaguchi et al., 1992; Sugawara and Obara, 1999), and obtained the near-vertical maximum principal stress σ_1 of 127 MPa, far greater than the overburden pressure (27 MPa for a depth of 1 km below the surface).

The mine reopened in 2010 to exploit the Upper Elsburg reef in the shaft pillar. Our study focuses on microseismic events induced by this mining. Fig. 1 shows the mined-out stope around the AEnet for the period July–November 2011, covering the period of the presently used AEnet catalogue. The main shaft is situated at $(x, y) = (-140$ m, -110 m). Tabular mining of 1–2 m height is advancing along the reef horizon that gently dips ~10° WSW in the study area. Although the stope in the study area is already quite large, backfill is diligently placed so that true voids are limited to a ~4 m-wide zone behind the mining face. The mining is done by blasting. The face generally advances outward from the center of the shaft pillar towards the rim (i.e., northward in the plotted area of Fig. 1) at a pace of ~10 m/month.

Many geological faults are known in the shaft pillar from drilling cores and exposures in the mining tunnels. Fault traces (as mapped by December 2013) are shown by brown lines in the plan view of Fig. 1. NNE-trending normal faults, which were formed before the deposition of Transvaal Supergroup, constitute the dominant fault system in this mine, including outside the shaft pillar. There are also some E-W striking faults, which were formed more recently. Most of the faults in both systems dip steeply at 60–90°. The latest major tectonic event affecting the Witwatersrand Basin was the formation of the Karoo Basin at ca. 190–180 Ma (Dankert and Hein, 2010). The geological faults have likely been inactive since then. Note that the fault traces shown in Fig. 1 are based only on the mapping at accessible exposures. There is little doubt that there are many unmapped faults in the area, as exemplified in Section 3.1. There are also many unmapped joints in the study area that can serve as mechanical discontinuities.

2.2. AE network and cataloguing procedure

Our AEnet consists of 6 triaxial accelerometers and 24 higher sensitivity AE sensors, all installed by grouting in boreholes drilled from the tunnel at 1 km depth (Figs. 1 and 2). Three of the six accelerometers have a flat frequency response up to 25 kHz, the three others up to 10 kHz. The AE sensors can record signals at workable S/N ratios up to about 50 kHz for the majority of events, though this depends on the intensity of the input signal.