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Fault zones associated with the Matjhabeng earthquake, 1999, South Africa

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We mapped portions of the Dagbreek fault in Matjhabeng mine (Eland shaft, Welkom) that slipped during the 1999 Matjhabeng earthquake. The fault-zone that was active during this event is up to 30 m wide (and probably more) and it contains tens of gouge zones that are characterized by the well-known 'rock flour' and quartzite fragments. The slip on an individual gouge zone ranges from a few millimetres to 21 cm, and the largest measured total displacement along the Dagbreek fault is 44 cm. This displacement is of the same order as the maximum displacements measured after similar earthquakes in the Welkom gold field over the past 27 years.

Introduction

Active faults are generally inaccessible at the focal depth of large earthquakes. Thus it is practically impossible to directly relate measured seismic parameters of an earthquake to the structure of the associated subsurface rupture[1]. To overcome this difficulty, we initiated a study of faults associated with large earthquakes in deep gold mines of South Africa, following previous research of McGarr *et al.*[2] and van Aswegen[3]. The study has two main objectives: (1) to gain a better understanding of earthquake processes by direct observations at focal depth (2) to establish a better characterization of active faults in deep mines. The study includes detailed 3D mapping of active faults with emphasis on the internal structure of the subsurface rupture (fault-zone width, sense, amount and distribution of slip along secondary faults, and micro-structural features). Here we report on one particular case.

Earthquake history in the Welkom Gold Field

Major fault zones define the macro-structure of the Welkom Gold Field. These fault zones have extended tectonic histories including reverse, normal and lateral slip, during Archaean and Proterozoic times, displacing the gold-bearing quartzites of the Witwatersrand formation. The major faults now all appear as west-dipping, normal faults parallel to the western rim of the Witwatersrand Basin. They show dip displacements up to 1000 m, although their full tectonic histories include larger lateral displacements. The exact finite displacements are traced through the chemical characterization of marker rocks (e.g. Rompl[4]).

The major fault zones have been the sources of several earthquakes during the past three decades (Figure 1). The Welkom earthquake of 1976 made history because a multi-story building near its epicentre was destroyed. After the earthquakes, displacements of tens of centimetres were measured along several of the fault zones indicated in Figure 1. The opportunity to make accurate observations of the co-seismic slip were, generally, limited, either by severe underground damage or by the lack of tunnels intersecting the faults specifically in the source regions. The measured displacements were always found to be normal slip (Table I).

The last seismic event of earthquake size occurred in April 1999 along the Dagbreek fault in the area of Eland Shaft, Matjhabeng Mine[5]. The tremor, recorded as a magnitude 5.1 event by the South African Council for Geoscience and generally referred to as the Matjhabeng earthquake, caused extensive damage underground, including the displacement of a sub-shaft by > 20 cm where it cuts through one of the major components of the Dagbreek fault zone.

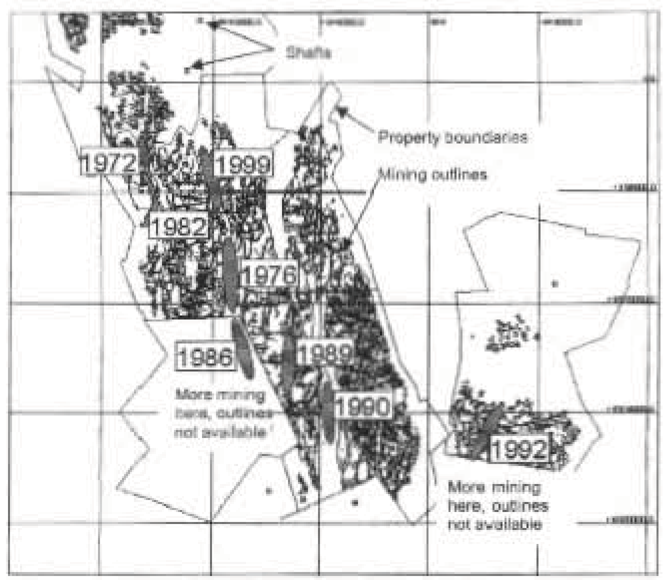

Figure 1. The distribution of tremors > magnitude 4.6 in the Welkom gold field. The outlines of mining faces shown are those along Basal reef, that dips at an average of 20 to the east and is mined at an average depth of 2000 m below surface. All these tremors had a normal slip mechanism. The ellipses indicate the approximate sizes and shapes of the areas of significant co-seismic displacement (van Aswegen[3]). The co-ordinate grid spacing is 5 km

Table I
A list of earthquakes in the Welkom gold fields since 1972[5]

Year	Mag.	Fault	Minimum displacement measured (mm)	Comment
1972	4.5*	Erfdeel	?	Damage to Kudu shaft steelwork and concrete lining
1976	5.2*	Dagbreek	150	Extensive u/g and surface damage: the original 'Welkom earthquake'
1982	4.8*	Wesselia/ Erfdeel	410**	Extensive u/g and surface damage. Kudu and Sable shafts out of action for several days
1986	4.8*	Dagbreek	>200	Extensive u/g damage along fault zone at St. Helena Mine
1989	4.8	Brand	370	Widespread f.o.g. damage. ' 'burst' type damage confined to few highly stressed pillars and dykes
1990	4.8	Stuirmanspan	>200	High stress drop event, intense local u/g damage, noticeable pre-cursory seismicity
1992	4.7	Saaiplaas	150	Extensive damage to main haulage transecting fault
1999	5.1*	Dagbreek	440***	Extensive damage spatially associated with fault zone; Sub-shaft displaced by co-seismic fault slip ~200 mm

* Magnitude from national network—the 'local' magnitude recorded for the Brand, Stuirmanspan and Saaiplaas events would be minimum magnitudes since the seismic moment, on which the empirically derived 'local magnitude' relation is based, is under-estimated for large events—the regional mine seismic monitoring system relies on 4.5 Hz geophones, not sensitive to the lower frequency band

** Measured 36 months after the event

***Measured 18 months after the event

The tremor occurred along a part of the fault zone lacking in significant prior seismic deformation—a seismic gap was defined by contours of seismic Deborah number[5,6] (Figure 2). Temporal patterns of micro-seismicity in the area of Eland shaft prompted an 'Alert level 2' advisory issued by the local mine seismic centre several days before the earthquake. This advisory was confirmed a day before the earthquake[5].

Observations at Eland Shaft

We document parts of the Dagbreek fault that slipped during the Matjhabeng earthquake at Eland Shaft. The best exposures were found on 45 level. This is approximately 1660 metres below surface.

Observations at Site 1 (Location: Z3388 in 45II18)

The tunnel at this site was repaired after the earthquake and broken rock that littered the tunnel after the tremor had been removed. The local dip of the fault is 37°/253°, roughly normal to the local inclination of the quartzite layers. The local slip is normal dip-slip. We measured the vertical displacement of the rail tracks (H in Figure 3) as H = 44 cm across the fault. We examined the tunnel walls and could recognize slip-surfaces and displaced blocks to a distance of up to 45 m from the main fault, but only in the footwall of that part of the fault zone shown in Figure 3.

Observations at Site 2

Site 2 is located on the Dagbreek fault, about 1300 m south of Site 1. This area was severely damaged during the earthquake with no subsequent cleaning or repairs. The advantage is that the extent of damage is still clearly visible. The disadvantage is that access to the fault zone is limited to a few metres. We could, for example, identify here a fault-zone of only 9.5 m, compared to significantly greater fault zones widths observed elsewhere (see above

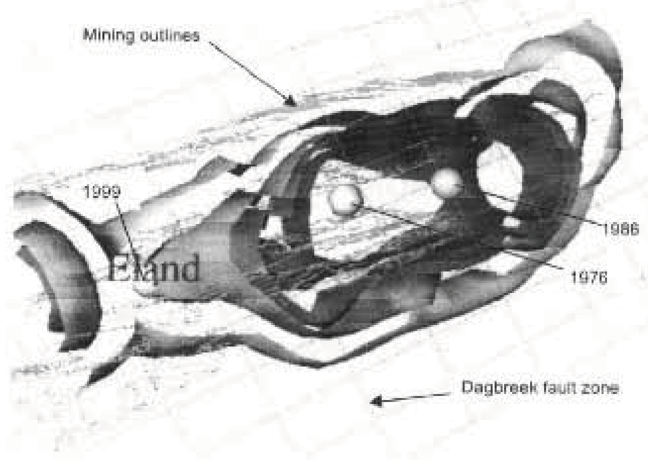

Figure 2. A perspective view of the Dagbreek fault zone and 3D contours of seismic Deborah number[2], indicated the existence of a seismic gap in the area of Eland shaft prior to the Matjhabeng earthquake[3]. The view is down towards the south-east. The length of the fault zone is estimated at 50 km. Here a 10 km portion is depicted by the coarse mesh. The contours are based on thousands of seismic events spatially associated with the Dagbreek fault zone for the period since recording started in 1988 till just before the Matjhabeng earthquake. The 1976 and 1986 events were added to the data set based on source parameters from the S.A. Council for Geoscience. The spheres indicate only the approximate hypocentres of the large events, not their sizes

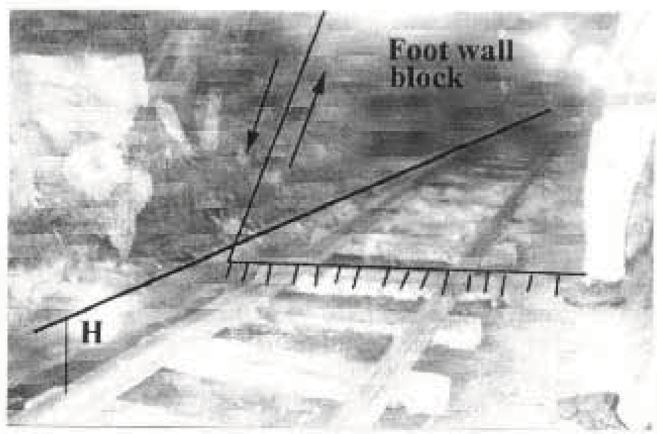

Figure 3. Displaced tracks at site 1, level 45, Eland shaft. H indicates the vertical displacement across the Dagbreek fault zone (line with short bars). Distributed damage (fractures and crushed zones) were found primarily in the uplifted footwall side of the fault zone

and below). We found several clayey, soft gouge zones with displacements of 0.5 cm and smaller. Slickenside striations in various directions and scales are distributed on most of the gouge zones; some of the striations could have formed during previous events. The largest localized slip measured is 21 cm of dip-slip as evident by the displacement of the reference line in Figure 4. The 21 cm slip is distributed within 3–5 cm thick, fine grained and fresh gouge zone.

Many broken rock bolts are observed at this site. Apparently, these rock bolts did not yield only in the event of April 1999; some of them apparently yielded previously by creep. Some rock bolts that penetrated into, but parallel to the gouge zone surprisingly do not display evidence of deformation or shear. The intense damage and complex deformation history referred to here, are possibly related to a site effect associated with the Y-shaped local tunnel configuration. It may also reflect the damage heterogeneity close to the tip of a propagating earthquake.

Observations at Site 3

Site 3 is located on the Dagbreek fault about 50 m north of Site 2 in a severely damaged, yet accessible tunnel. This site provided the best exposures of the subsurface rapture and we mapped in detail a 27 m segment of the E-W tunnel, normal to the fault zone. The mapped part is almost entirely in the footwall block of the fault zone. The hangingwall block is inaccessible due to damage.

The subsurface rupture includes about twenty gouge zones generally dipping westward and arranged in five clusters. Most of these slip-surfaces are coated with white 'rock flour' of comminuted quartzite of the host rock[6].

One type of evidence for slip are the displaced boreholes of rock bolts in which both dip-slip and strike-slip components of the displacement could be evaluated (Figure 5). We found displaced boreholes at 10 places and they revealed slip from 0.5 cm to 6 cm. The dominant gouge zone of the Dagbreek subsurface rupture in this tunnel is 50 cm thick, pyrophyllite-rich with quartzite fragments. It dips 26°/280°. We used the present disposition of pieces of a drill-rod that had penetrated this zone and served as an excellent displacement marker, to measure 11 cm of dip-slip and 5 cm of right-lateral slip within this gouge-zone.

Discussion

The 'freshness' of the gouge along the many gouge zones mapped and the spatial association with severe rockburst damage indicate that they were all part of the fault slip process of the Matjhabeng earthquake. Such distributed slip has been observed, by the third author, at some of the other instances referred to in Figure 1, but the phenomenon was nowhere mapped or recorded in the same detail as was done at Eland Shaft. It is thus likely that such distributed, co-seismic displacement is a common feature of the Welkom earthquakes.

The total displacement of 44 cm most likely includes some post-seismic creep. Detail analysis of three sets of survey data (prior to, soon after, and long after the event) should indicate the relative importance of this. In the case of the Brand event of 1989, 37 cm displacement was measured within hours after the event, so the 44 cm displacement along the Dagbreek fault may not be too far off the true co-seismic displacement during the Matjhabeng earthquake.

Conclusions

Initial results of a detail mapping programme in the source region of the magnitude 5.1 Matjhabeng earthquake shows

- the importance of such work to gain insight into the details of the earthquake process
- the common feature of maximum co-seismic displacements around 40 cm for earthquakes in the Welkom gold field
- co-seismic displacement and massive increase in surface area is distributed over many gouge zones over a 30 m wide zone.

Acknowledgements

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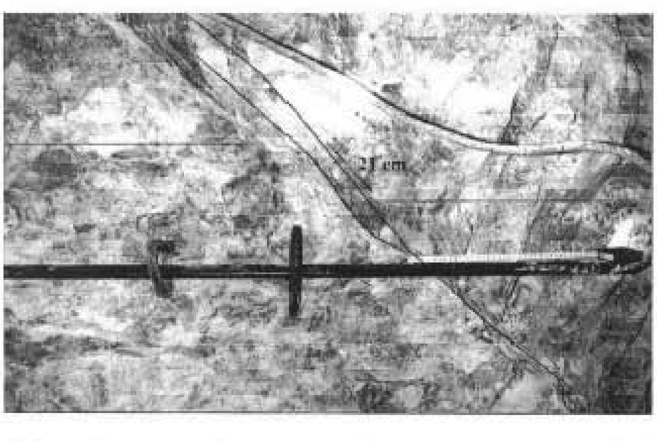

Figure 4. The main slip-surface (thick line inclined to the right) dipping to the west in site #2. The horizontal reference line is displace by 21 cm of dip-slip along the thick gouge zone

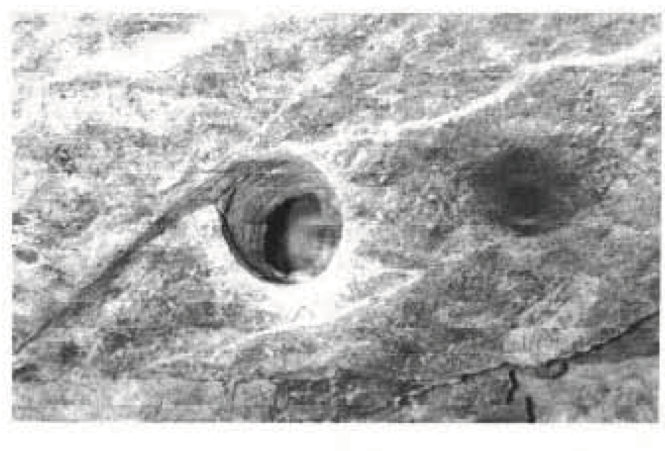

Figure 5. Displaced borehole at site #3. Upward view on the roof; the slip-surface is sub-parallel to the roof; displacement about 15 mm

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