Slip localization within a heterogeneous fault-zone

Earthquakes and reactivation along the Pretorius fault-zone, Tautona mine, South Africa (NELSAM)

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Problem

Many fault-zones display complex assemblies of fault-rocks (gouge, mylonite, or cataclasite) that bound blocks of damaged and intact host-rock. This structure of anatomizing, cross-cutting segments may develop into a mature fault-zone during repeated events of faulting.

The heterogeneous assembly of different rheologies that exists within fault-zones is likely to control the fault activation under tectonic stresses. We analyze here reactivation mechanisms in heterogeneous fault-zones. The analysis is presented in three steps:

1. Field observations of the structure of a heterogeneous fault-zone (the Pretorius fault) and the earthquake rupture along it.
2. Rock-mechanics experiments of the fault-rocks and the host rock.
3. Finite element analysis of shear localization in this fault-zone.

Field observation

The Pretorius fault (Figure 1)

The study is based on observations of reactivation of the Pretorius fault, which is one of the major faults in the Western Deep region, Witwatersrand basin, South Africa. We studied this fault in the Tautona mine at depth of 3.6 km as part of the NELSAM project (Natural Earthquake Laboratory in South African Mines).

The Pretorius fault is about 10 km long and 20 – 30 m wide, with a vertical throw up to 60 m, and it was not been active during the last 2.5 Ga. The fault-zone contains multiple segments with cataclasite that underwent low grade metamorphism. This cataclasite is similar in composition to the host rock, but of finer grain size. The fault segments form a complex anatomizing pattern of intersecting, quasi-planar surfaces; in between these surfaces the fault-zone consists of host quartzite (Figure 1).

Fault reactivation

The m2.2 of December 12, 2004, reactivated three to four quasi-planar segments of the Pretorius fault within the NELSAM area (Figure 1). We mapped the rupture for 25 m horizontally and 6 m vertically in a few cross-cutting tunnels. Displacement of man-made features (rock bolds) revealed normal-dextral slip up to 25 mm.

Rupture surfaces

The rupture is characterized by zones of fresh, white gouge (rock powder) that are typically located in 1-2 mm thick zones dominantly along the contacts between the quartzitic host rock and the ancient cataclasite (Figure 2).

The understanding of the mechanism that is responsible for the slip localization along the contacts within this fault-zone, will contribute to the understanding of fault reactivation processes in general.

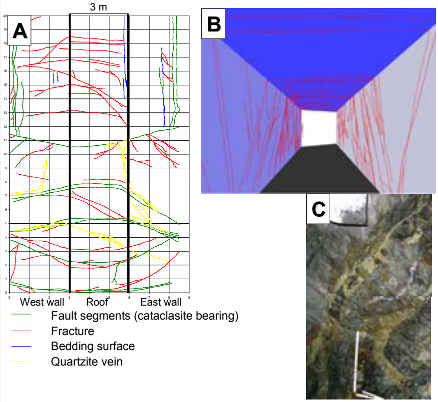

Figure 1: The complex structure of the Pretorius fault-zone.
A: Tunnel map of the fault-zone at depth of 3.6 km. The zone consists of multiple, anatomizing segments that contain cataclasite with fractured quartz in between.
B: 3D view of a tunnel that cross the fault-zone, showing the multiplicity of fault segments.
C: Cataclasite zones (green) within the quartzitic host rock of the Pretorius fault.

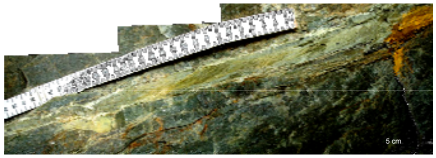

Figure 2: Rupture zone of the M2.2 earthquake, Tautona mine, South Africa.
The rupture reactivated the ancient cataclasite zone of the Pretorius fault with fresh gouge (white) formation along the contact (slip localization).

Rock mechanics experiments

Experimental conditions

Rock-mechanics experiments were conducted on 21 samples from within the fault-zone, collected in continuous coring drilling across the Pretorius fault. The samples consist of quartzite from within the fault-zone (damaged host rock) and samples of the cataclasite (Figure 3). All experiments were conducted under dry, room temperature conditions with 0-200 MPa confining pressures, and shortening rates of 1-3·10^{-5}/s.

Results: Brittle-plastic vs. Brittle-elastic rheology

The host quartzite and the cataclasite display distinct mechanical differences (Figure 4, 5 and Table 1):

a. The quartzite is twice as strong as the cataclasite.
b. The quartzite is severely damaged (Figure 5), showing significant plastic behavior and strain hardening. We refer to this behavior as brittle-plastic material.
c. The damage in the cataclasite is localized along the cross-cutting fault with no significant off fault damage. The cataclasite is a brittle-elastic material with no strain hardening.

The heterogeneity of the Pretorius fault-zone is reflected in these contrasts between the mechanical properties of both rheologies (Table 1).

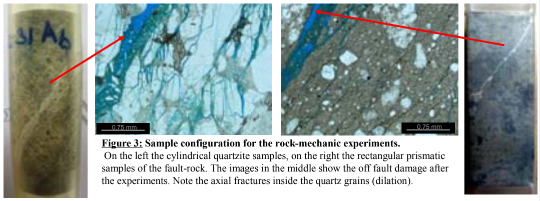

Figure 3: Sample configuration for the rock-mechanic experiments.
On the left the cylindrical quartzite samples, on the right the rectangular prismatic samples of the fault-rock. The images in the middle show the off fault damage after the experiments. Note the axial fractures inside the quartz grains (dilation).

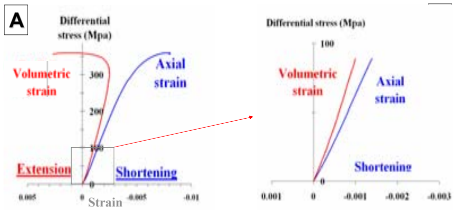

Figure 4: Stress vs. strain curves.
A: Quartzite sample that shows significant volumetric strain
B: Cataclasite sample with no significant volumetric strain

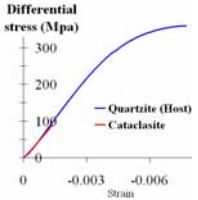

Figure 5: Stress vs. strain curve.
The quartzite shows inelastic deformation (strain hardening). The cataclasite shows linear elastic behavior

	Youngs modulus	Poisson’s ratio	Uniaxial strength	Strength	Damage	Brittleness
Host rock (Quartzite)	81 GPa	0.17	204 MPa	High $C_o = 45.7$ MPa $\mu_i = 0.82$	Intense, Wide spread, Inelastic	Brittle-plastic Inelastic > elastic
Cataclasite	71 GPa	0.15	97 MPa	Low $C_o = 28.1$ MPa $\mu_i = 0.58$	Minimal, Localized at fault	Brittle-elastic Inelastic < elastic

Table 1: Mechanical properties of both rock type within the Pretorius fault-zone

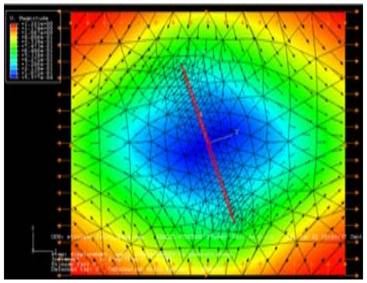

Figure 6: FEM setup
Colors indicate magnitudes of displacement; boundary displacement shown in orange arrows; node displacements shown in the black arrows.

Modeling the slip localization in the Pretorius fault

The segmental structure of the Pretorius fault-zone (Fig. 1), and the differences between the rheologies of the host quartzite and the cataclasite (Table 1), are modeled by an elliptical inclusion, composed of cataclasite-like rock, embedded in a medium composed of quartzite-like rock.

We calculated the stress and strain distribution within this heterogeneous fault-zone with the finite elements (ABAQUS/ Standard, student edition, v6.6).

Boundary Conditions
We used plane-strain, 6-node modified quadratic, triangle elements with reduced mesh size towards the inclusion. The boundary applied displacement are with 2.5% shortening in the global axis2, and 2% extension in the global axis1 (Figure 6).

Materials properties
The medium (quartzitic host rock) is isotropic elastic-plastic, with the elastic properties as measures in our rock-mechanics experiments, and plasticity following the yield stresses and amounts of plastic strains as derived from the experiments (Figure 5; Table 2).he inclusion is isotropic elastic, with elastic properties measured for the cataclasite in the experiments.

Yield strength (MPa)	Plastic strain (%)
2.00E+02	0
3.00E+02	1
3.50E+02	2.2

Table 2: Input for the plastic material properties of the quartzite

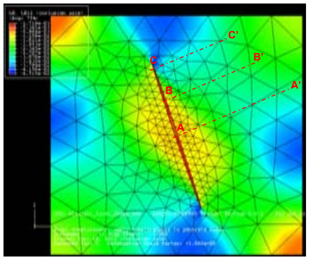

Figure 7A: Shear strain for idealized fault (elliptical inclusion at 20°)
Colors indicate shear strain parallel to the inclusion.

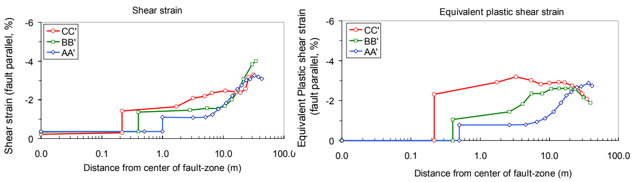

Figure 7B: Shear strain along profiles normal to the idealized fault (elliptical inclusion at 20°)
The shear strain and equivalent plastic shear strain along three profiles perpendicular to the inclusion.
Note the steep in the magnitude of the strain at the edge of the ellipse.

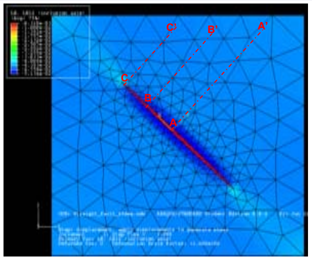

Figure 8A: Shear strain for idealized fault (elliptical inclusion at 45°)
Colors indicate shear strain parallel to the inclusion.

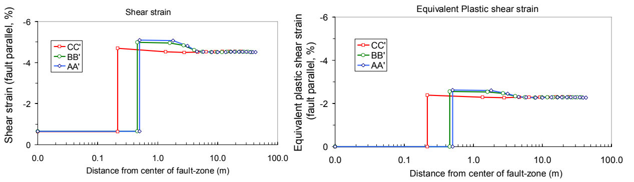

Figure 8B: Shear strain along profiles normal to the idealized fault (elliptical inclusion at 20°)
The shear strain and equivalent plastic shear strain along three profiles perpendicular to the inclusion.
Note the steep in the magnitude of the strain at the edge of the ellipse.

FEM result summary

The FEM models show:

1. The **shear strain** inside the inclusion is significantly lower than the shear strain in the surrounding medium (Fig. 6A, 7A).
2. The profiles (Fig. 6B, 7B) show an **abrupt increase** of the shear stress at the contact between the inclusion and the medium.
3. The high intensity of the **equivalent plastic shear strain** in the medium indicates that the host rock is in a stage of failure.

Discussion:

Strain gradient, slip localization, and reactivation mechanism

The steep gradient of the shear stress at the contact of the inclusion reflects the contrasts of mechanical properties between the fault-rock and the host rock. This steep gradient forms a likely site for slip localization (e.g., Fleck and Hutchinson, 1993. A Phenomenological Theory for Strain Gradient Effects in Plasticity). The plastic shear strain shows similar trends to the shear stress, suggesting that the gradient in shear stress is a result of the plastic behavior of the medium. Thus, the model suggest that the plastic behavior of a damaged host rock in a heterogeneous fault-zone may result in high gradients of shear strain parallel to the contact of the elastic, brittle fault-rock, forming the seed for strain and slip localization along the contact.

DAFSAM & NELSAM sponsors

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