# STRESS CONDITIONS IN THE KILOMBERO RIFT, CENTRAL TANZANIA

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## Abstract

The ancient and current stress conditions at the northwestern flank of the Kilombero Rift are assessed in this paper. Neoproterozoic stresses in the area were associated with $320^0/20^0$ trending principal axis of straining ($\lambda_1$) in the rocks. This deformation imparted Precambrian ductile gneissic and concordant mineral foliation with attitude of $020^0/35^0$ WNW, $320^0/20^0$ trending b-mineral lineation and isoclinal folds with axes trending parallel to the mineral lineation.Phanerozoic deformations are mainly of Permo-Triasic and Cenozoic periods. Both of the two episodes of deformation had constant orientation of principal axes of stresses with $\sigma_1$ trending $060^0/02^0$, $\sigma_2$ trending $160^0/80^0$ and $\sigma_3$ trending $335^0/10^0$. Stress conditions that are prevailing at present in the Kilombero Rift as determined by hydraulic fracturing tests are characterized by $260^0/70^0$ trending $\sigma_1$, $145^0/05^0$ trending $\sigma_2$ and $045^0/10^0$ trending $\sigma_3$. These trends are totally different from those of the Precambrian and Permo–Triassic and Cenozoic stresses. This difference implies that at present there are no residual stresses at the northwestern flank of the Kilombero Rift. The present stresses in this area are attributed to the confining stresses induced by the load of the overlying rock-masses combined with the effect of gravity stresses that are controlled by the topography of the area.

## 1. INTRODUCTION

This paper makes an assessment of stress conditions that prevails at the northwestern flank of the NE-trending Kilombero rift in central Tanzania. The assessment is based on detailed geological and structural investigations in the area coupled with several stress measurements in the rocks at various depths in more than 3km long underground tunnels excavated for construction of an underground hydropower station at Kihansi. The stress measurements were done by hydraulic fracturing test techniques using water-pressurized parckers. Through structural studies, palaeo-stresses that account for the formation of the different structures of the area were established.

## 2. GEOLOGICAL SETTING

The NE-trending Kilombero Rift cuts the biotite and quartzo-feldspathic gneisses of the Precambrian (Pan-African) Mozambique belt (Brickmann, 1995).

The section of the Kilombero rift zone studied in this work is at Kihansi along the Udzungwa scarp (Fig. 1) that marks the NW fault scarp of the Kilombero rift. The northwestern flank of the Kilombero rift (the Udzungwa scarp) marks the southern boundary of the Udzungwa ranges rising 1,100 to 2,000m above sea level. The Udzunngwa scarp is formed by large-scale block faulting and tilting of the Kilombero rift system. The down-thrown block of the Kilombero rifting is the flat-lying alluvial marshlands of the Kilombero valley with an elevation of approximately 280 to 300m above sea level. These low lands are to the south of the fault scarp. The Udzungwa ranges (north of the fault scarp) composed of the Pan-African gneisses form the uplifted block.

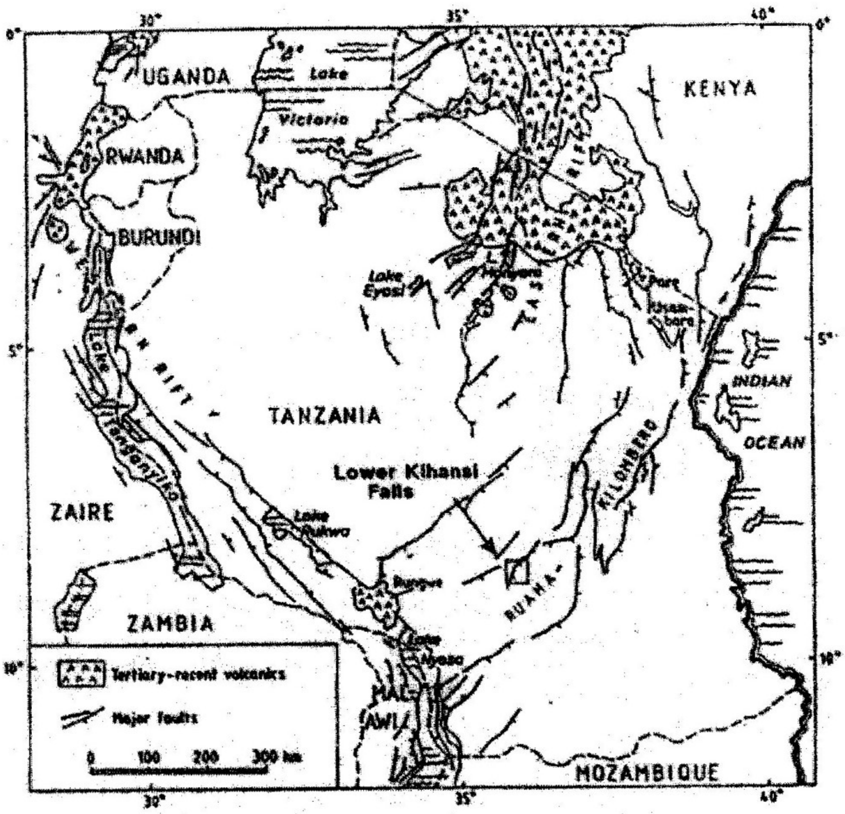

Figure 1. Geological setting of Kihansi in the northwest flanks of the Kilombero rift in Tanzania. After Iranga (1991).

## 3. STRUCTURES OF THE AREA

### (i) Ductile Precambrian Structures

The Precambrian (Pan African) gneisses of the study area were subjected to regional deformation and metamorphism at lower amphibolite facies conditions during the Neoproterozoic, leading to formation of pervasive ductile gneissic fabric, mineral foliation, mineral lineation and folds.

The gneissic fabric is defined by thin alternating white colored quartzo-feldspathic and dark-colored ferromagnesian rich layers. They normally form concordant layers in most outcrops (except in migmatitic portions) but frequently they also occur as low-angle cross-cutting layers (i.e. anastomosing bands) suggesting a high level of transposition during their formation. This fabric has a general strike of 020$^0$ and dip about 35° towards WNW (Fig. 2).

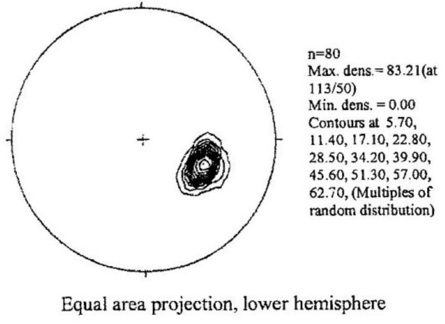

Fig. 2. Stereographic projection for gneissic fabric of the northwestern flank of the Kilombero rift.

In addition to the gneissic fabric, rocks of the area contain pervasive mineral foliation defined by preferred orientation of biotite, hornblende, chlorite, muscovite and flattened quartz. The mineral foliation is concordant to the gneissic fabric and it seems to be a result of shear straining that caused transposition to the gneissic fabric. In the amphibolitic biotite schist it seems that the mineral foliation defined by oriented coarse biotite flakes is so pervasive that the unit is very fissile and can easily split along the planes of schistosity.

Mineral lineation defined by preferred orientation of elongated minerals (e.g. elongated quartz and hornblende) is present in all the gneisses. It is a b-lineation with a general plunge of 20° towards 320°.

Isoclinal to tight folds deforming the gneissic layering are common but in general their limb zones are highly attenuated and transposed such that they appear as root-less intrafolial folds.

The fold axes are generally plunging 20° towards 320° i.e. parallel to the mineral lineation suggesting that they are sheath folds.

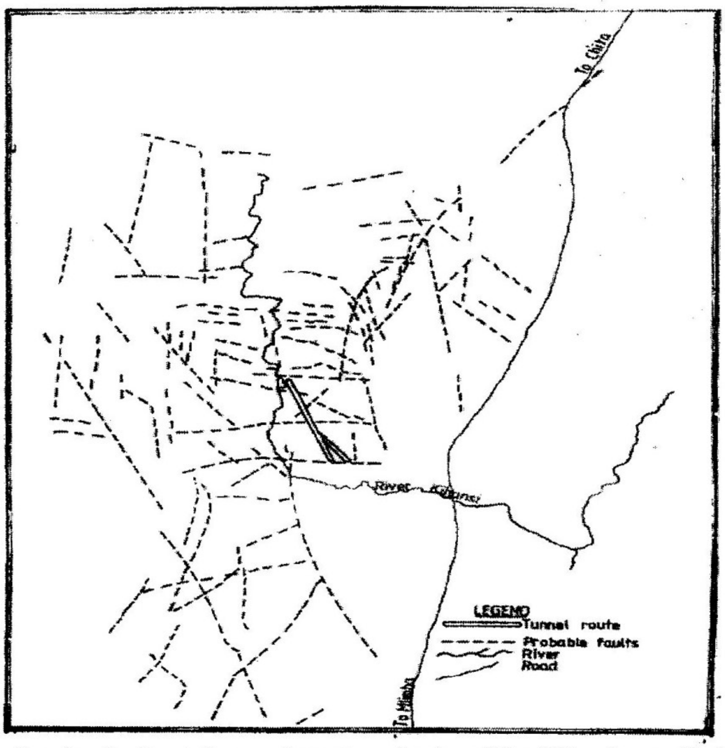

Figure 3. Trends of major faults at the northwestern flanks of the Kilombero rift deduced from interpretation of SPOT and Landsat images

### (ii) Brittle Phanerozoic Structures

### *(a) Faults*

Based on the geomorphology of the area, it is obvious that the study area has been affected by faulting which led to the formation of the Udzungwa scarp though the actual fault planes are rarely seen on the normal rock outcrops exposed along the slopes of the Udzungwa scarp.

Most of the faults were first inferred from the interpretation of SPOT and Landsat images, aerial photographs (Fig 3). However, detailed mapping and geomorphological studies have confirmed most of the initially inferred faults.

Some of these faults are trending WNW-ESE to E-W. These are referred in this report as FAULT-SET 1. The study area is also dominated by another set of faults (referred in this report as FAULT-SET 2) which have a general trend of NE-SW. Some very few NW-SE trending faults (referred in this report as FAULT-SET 3) which swing to almost N-S are also present. All these fault sets are sub-vertical with dip angle greater than $70^0$.

The senses of displacements, slicken-sides and infills in these discontinuities are described in detail in the next section.

### *(b) Joints*

Rocks of the whole study area are jointed but the intensity of jointing varies from place to place. There is no clear relationship between the intensity of jointing and the positions of the faults. In general, the intensity of jointing and fracturing is high at places where there are distinct faults. However, there are also several highly jointed sites with no faults.

Disregarding the intensely fractured zones close to the faults, in general the intensity of fracturing in the area decreases northwards as you move away from the Kilombero fault into the Udzungwa ranges. Areas close to the foot of the Udzungwa Scarp are somehow intensely fractured whereas those at Udzungwa plateau are relatively less fractured.

All the joints in the study area are steeply dipping, dip angle varying from 70° to 90°with average dip angle being 83°. They occur in conjugate form with two sets. SET-1 has a general E-W strike and it dips to the south but occasionally to the north also. SET-2 has a general NE-SW strike and it dips dips to the SE but occasionally to the NW. The general attitudes of these joints are presented in (Fig. 4). It should be noted here that these sets of joints are geometrically similar to the previously described SET-1 and SET-2 fault systems.

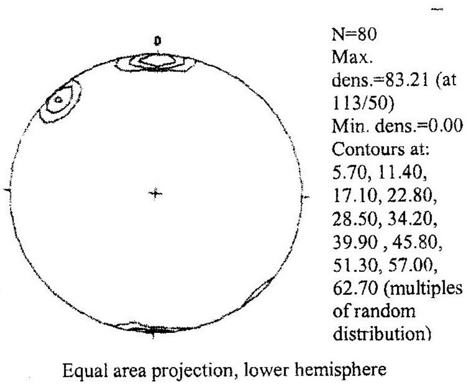

Figure 4. Stereographic projection for joints of the northwestern flank of the Kilombero rift.

Typical features and characteristics of these discontinuities and joints are described in detail by Mruma (in prep) as as follows:-

- In general they do not show significant amount of displacement but a good number of them show displacement.
- Surprisingly, most of them (even those which strike E-W and dip to the south) show reverse sense of block-movement. This sense of displacement do not match with the geomorphology of the southerly sloping Udzungwa scarp with its southern block (the Kilombero valley) being down-thrown relative to its northern block (the Udzungwa ranges). However, there are few of them with normal displacement.

Most of these discontinuities are regarded by Mruma (in prep) to be coeval though they have different strike-trends since the two conjugate discontinuity-sets are similar in many aspects like the magnitude of opening, sense and magnitude of displacements, in-fills, lack of slicken sides e.t.c. and also since there is no evidence of one set cutting and displacing the other.

Mruma (in prep) also regards these joints as to have been formed by tensional stresses due to the absence of confirming evidence of breccia zones formed by tectonic grinding and milling. Contrary to that, most of the breccias are formed by closely spaced joints without any significant rolling of the breccias pieces. Tensional stresses for the formation of these joints are further supported by the absence of sliken-side lineations on the surfaces of these joints.

## 4. STRESS CONDITIONS

### (i) Precambrian Stresses

Direction of mineral lineation in the Precambrian gneisses (plunge of 20° towards 320°) described in section 3 above is taken to be the $\lambda_{1}$- shear direction of the Precambrian straining that accounts for the formation of the Neoproterozoic ductile fabrics in the gneisses.

### (ii) Phanerozoic Stresses

The geometrical relationship of the two sets of the conjugate joints (and those of the conjugate faults described in the previous section indicates that the tectonic regime that accounts for the development of these discontinuities had NNW-SSE oriented sub-horizontal tensional stresses $\sigma_3$ producing NNW-SSE sub-horizontal extensional strains $\lambda_1$ ( see Fig. 5).

Mruma (in prep) and Le Gall *et al.* (in prep) confirms the occurrence of brittle deformations and formation of brittle discontinuities with the same geometrical configuration in the Kilombero area during the Permo-Triasic (Karoo) and Tertiary periods. It should be born in mind that the Kilombero rift is a northeastern continuation of the Ruhuhu basin that is underlain by Karoo sediments and that, further to the northeast, the Kilombero rift joins the Kidodi-Nyakatitu fault-controlled basin also of Karoo age. It is likely that the Cenozoic faults of the Udzungwa scarp are formed by reactivation of the pre-existing Permo-Triasic discontinuities that had the same geometrical patterns suggesting similarity of stress conditions during the two episodes of deformation.

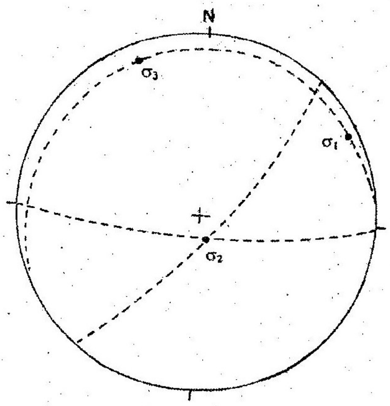

Figure 5. Orientation of principal axes of stress that accounts for the formation of conjugate joints in the northwestern flank of the Kilombero rift.

### (iii). Current Stress Conditions.

Average results for the 3-dimensional stress measurements from hydraulic fracturing tests done in the underground tunnels at a depth of about 400m (overburden) are shown in Table 1.

Table 1. Current tress conditions at the Udzungwa scarp (NW-flank of the Kilombero rift.

| Stress Axes | Trend | Plunge | Magnitude (in Mpa). |
|---|---|---|---|
| $\sigma_1$ | 261$^0$ | 66$^0$ | 20.5 |
| $\sigma_2$ | 150$^0$ | 9$^0$ | 13.7 |
| $\sigma_3$ | 56$^0$ | 22$^0$ | 7.8 |

The orientation of these stress axes that are currently at the north western flank of the Kilombero rift are different from those that account for the formation of the conjugate joints of the area (Fig. 5). They are also not comparable to the Precambrian straining episode that accounts for the formation of the gneissic fabric and the associated b–mineral lineation described in section 3 above.

## 5. DISCUSSION

### (i) Components of Total Stress

State of stress in a given rock mass is a combination of:-

(a) Confining stress due to loading by the overburden (in situ stress).
(b) Gravity stress which is mostly controlled by the topography.
(c) Tectonic stress.
(d) Residual stress.

***Confining Stress***

The confining (in situ) stress on a specific place is having two components of stresses (vertical and horizontal stresses) that can easily be computed by calculating total compressive stress due to overlying rock mass as per the following equation. According to Hoek *et al.* (1995) these computations are done using the following formula.

$$\textit{Vertical stress} = \rho \times h \qquad (1)$$

Where
$\rho$ = density of the overlying rock mass
$h$ = depth below surface

$$\textit{Horizontal stress} = k \times \textit{vertical stress} \qquad (2)$$

Where $k$ is a constant expressed as
$k = 0.25 + 7Eh \{0.001 + (1/z)$
$z$ = depth (in meters) and
Eh (Gpa) is the average deformational modulus of upper part of the earth's crust measured in horizontal direction.

Rations of horizontal to vertical stress can also be computed easily from graphs of Sheorey (1994) (see Fig 6).

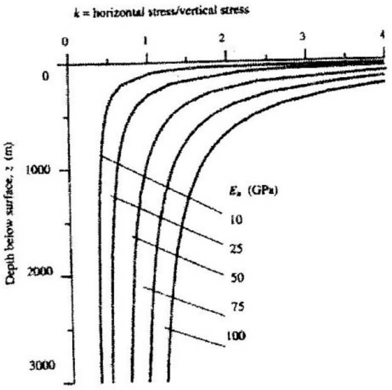

Figure 6. Ratio of horizontal to vertical stress for different moduli based upon Sheorey's equation. After Sheorey (1994).

***Gravity Stress***

Gravity stress is more effective near the surface in a mountainous terrain and it plays a major role in bringing anisotropism of stress regime in an area. It is a vectorial resolution of the confining stress parallel to the topography. Gravity stress on a point can easily be computed and it has a negative effect on the confining stress as expressed in Figure 7.

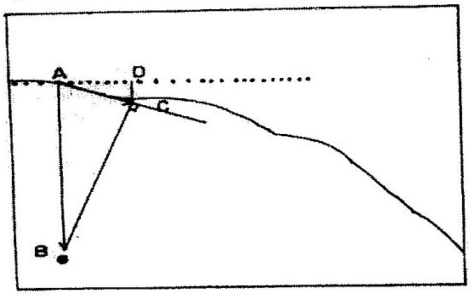

Figure 7. Component of gravity stress (AC vector) of the loading stress (AB vector) over a point located at a great depth. Note: Due to inclined topography, confining stress would be vector AB minus load equivalent to rock-mass in ACD triangle

Therefore mostly the tectonic and/or residual stresses together with the gravity stress are the one that may contribute much to the stress anisotropism of an underground opening that are in the near surface zones. At a relatively large depth, effect of topographical stress is negligible and therefore stress anisotropism is contributed by the tectonic and/or residual stresses.

### *Tectonic Stress*

Tectonic stresses are met at the tectonically active zones like along the crustal plate boundaries, close to the active fault zones or in upwelling zones, near active salt domes or plutonic intrusive. In these areas rocks are subjected to compressive or tensional stresses due to on-going tectonic processes. Such zones are normally seismically active.

### *Residual Stress*

Deformation (straining) is a volume change in rock masses in response to the newly imposed stress conditions. If equilibrium is to be met, the volume change will continue until the internal stresses in rocks become equal to the external (deforming) stresses. Shortly after cessation of tectonic stresses, rock masses retain some residual stresses in them and these decreases with time as the rock mass undergoes relaxation Residual stresses are encountered in a rock mass when the equilibrium (total relaxation) is not reached. In practice, rock masses that were in tectonically active provinces in the near past are therefore most likely retaining some residual stresses in them. Rocks that have been affected by compressive stresses retain much residual internal stresses whereas tensional stresses can easily be brought to the minimum levels (or even to zero) within segments of rock masses by simply developing brittle ruptures to the rock masses in the course of crustal extension.

## (ii) Contributors of Stresses at NW-Flanks of the Kilombero Rift

### *Tectonic Stress*

Seismological studies for the Lower Kihansi Hydropower Project in the NW-flanks of the Kilombero rift by NTNF/NORSAR, (1992) of Norway in 1992 reveal that, at present, the area is located in a low-activity zone. The seismic return time is found to be 100 years for a magnitude $m_b$ 5.0 earthquake and 36,000 years for a magnitude $m_b$ 6.0 earthquake similar to the conditions in the Tanzanian shield areas. Therefore it is very unlikely that at the moment the study area is having tectonic stresses.

Despite of these observations one can still argue that, in general, it takes some geological time for tectonic stresses to build up within an area up to the level of causing rock-deformation (seismicity). Therefore a possibility of having some amount of newly building up tectonic stresses in the area should not be ruled out completely.

Assumed stress slabbing has been reported in the mountain slopes both east and west of the project area and it has been attributed to existence of significant amount of sub-horizontal component of tectonic stress. Although this assumption can be very true, the possibility of forming this surface slabbing by exfoliation process should also not be underrated. Alternating rock expansion and contraction due to fluctuation of day and night temperatures has produced exfoliation to mostly granitic rocks in many parts of the world.

### *Residue Stress*

The last phase of deformation at the project area was associated with tensional stresses created by updoming that developed the brittle ruptures –"joints and faults" (Mruma, 1996). It is therefore most likely that much of these tensional stresses within the rocks were highly reduced after the jointing. It can even be argued further that even if there were some minor residual stresses which were left in the rocks after the jointing, much of it must have been reduced further during the subsequent extensional faulting episode which reactivated the joints.

The less brittle micaceous seams are rather slippery and they are easily reactivated by stresses. They therefore act as stress absorbers during deformation and they tend to release stored elastic energy (residual stresses) in rocks.

### *Confining Stress*

The tunnels where the 3-dimensional stress measurements were done are at a depth of about 300m. The column of the overburden rock-mass is sufficient to create a vertical stress estimated to about 8.0 Mpa.

It has been reported that some sounds of rock cracking were heard in the course of excavating the access tunnel from 400m level inwards. However, no cracking was encountered around the fault at 706-727m zone but it increased from 750m inwards. In the tailrace tunnel the cracking was encountered at the first 50m stretch and at 400m level inwards. Apparently these areas with spalling are slightly less jointed and significantly less faulted than those areas with no spalling. The lithotypes of the zones with spalling are also very massive, less foliated granitic migmatite with no or very few micaceous seams hence they are likely to cause much overloading stress.

### *Gravity Stress*

Gravity stress is anticipated to influence the anisotropism of stresses in the area where the underground tunnels are excavated since the topography of the area is dominated by very steep slopes and deep river gorges (Fig. 8).

The steep southerly inclined Udzungwa scarp and the presence of very steep and deep river gorges (Kihansi and Udagaji rivers) on both sides of the tunneled ridge will have an influence on the gravity stresses. These deep river gorges (Kihansi and Udagaji rivers) on both sides of the tunneled ridge may induce an east-northeasterly oriented sub-horizontal tensional stress ($\sigma_3$) perpendicular to the trend of the ridge. This proposed tensional stress direction may be due to side-ways bulging of the tunneled ridge (towards the river gorges) caused by heavy load of the overburden (confining stress) (see Fig. 8).

## 6. INTERPRETATION

Results of the 3-dimensional stresses determined by hydraulic fracturing tests shows that $\sigma_1$ – stress axis of the prevailing stresses at the NW-flanks of the Kilombero Fault is sub – vertical (Fig. 9). This is most likely due to the weight of the overburden. It has to be noted that the loci of the highest points of the tunneled ridge are to the NE above the position where the 3-dimensional stress tests were taken. Therefore the rock-load above this position is expected to induce a slightly southwesterly-inclined compressive stresses at the position of measurements. Indeed the obtained $\sigma_1$ – stress axis is slightly inclined to the southwest.

The $\sigma_2$ – stress axis in the area is sub-horizontal, trending towards SE (Fig. 9). This trend is interpreted to be due to the influence of the load of the rock-mass of the overburden combined with the influence of the gravity stress due to the SE-inclined slopes of NE-trending Udzungwa scarp (the Kilombero fault) to the southeast of the position where the stress measurements were taken.

The $\sigma_3$ – stress axis currently prevailing in the area is sub-horizontal trending to northeast (slightly plunging to NE) ( see Fig. 9). This trend is assumed to be contributed by the influence of the two steep and deep valleys of the Kihansi and Udagaji rivers on both sides of the tunneled ridge. The small plunge of this axis to the NE may be explained by the fact that overlying rock-mass towards Kihansi river (WSW-direction) is less than that towards the Udagaji river (ENE-direction). This mass imbalance is expected to create a minimum compressive direction (maximum extension)

Figure 8. Geomorphology of the position of the tunnels (red lines) where stress measurements were taken. Note: Blue = Kihasi (left) and Udagaji (right) rivers.

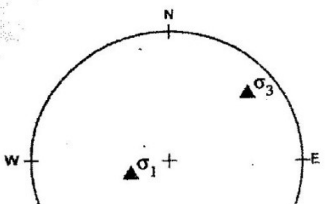

Figure 9. Orientation of mean principal axes of stress that are currently prevailing at the northwestern flank of the Kilombero Rift.

towards the direction with minimum load (in this case a direction slightly inclined upward towards the Kihansi river in the NW-direction). This axis will therefore have a low plunge angle to NE similar to the $\sigma_3$ – stress axis.

## 7. CONCLUSIONS

Based on the above observations and discussions it can be concluded that at present tectonic and residual stresses at the northwest flanks of the NE-trending Kilimbero rift seem to be negligible. The present stress situation is mostly attributed to the confining stresses due to the load of the overlying rock-masses combined with the effect of gravity stresses that are controlled by the topography of the area.

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