Influence of Geological Structures in Aiding Landslide Initiation in Chimanimani, Zimbabwe

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Abstract:- In March 2019, the Southeastern part of the Zimbabwe craton, Chimanimani, experienced a landslide that resulted in at least 350 deaths. There is considerable work currently ongoing in Chimanimani by researchers and experts to understand the landslides and prevent or minimise future damage. The objective of this study was to meticulously examine the role of geological structures in precipitating landslides using the Chimanimani district as a case study area. Comprehensive fieldwork encompassing site inspections, detailed structural mapping, petrographic analysis, and geotechnical assessments of outcrops was undertaken. The findings revealed that the region had experienced multiple deformation episodes, leading to its classification into three principal strain zones. These zones showed a positive correlation with historical and current landslide occurrences. It was noted that micro-faults were emerging progressively across various rock types. Both macroscopic and microscopic faults, along with joint systems, were identified as pivotal factors in both the onset and advancement of landslides. The majority of landslides were found on slopes with a concave upward geometry where fault planes inclined towards the slope's base. The orientation, continuity, and type of minerals filling the joints were also found to significantly influence landslide activity in Chimanimani. The presence of clay within micro-faults or joints was hypothesized to exacerbate fracture expansion due to its swelling properties upon moisture absorption. The study concluded that areas exhibiting a fault density exceeding 0.8km/km² were highly susceptible to landslide events.

Keywords:- *Landslides**,** Geological Structures, Deformation, Strain Zones, Micro-Faults**.***

I. INTRODUCTION

Landslides are an unprecedented geo-hazard which oftentimes results in fatalities as in the case of Cyclone Idai which was a contributing trigger to the 2019 Chimanimani landslide event that left at least 350 residents dead (Munsaka *et al.*, 2021). They often occur as a combination of several factors such as weak bedding, intense rainfall, low-shear strength soils, rock joints and faults (Wen *et al.*, 2004; Stead and Eberhardt, 2013; Zhang and Wang, 2023). Chimanimani is located south-west of the Zimbabwean craton within the Umkondo sedimentary basin (Watson, 1969) with an average of 1,470m above sea level. This study will help in understanding major landslide causes in this district which will further help as an input to landslide early warning systems design for the district which could be a huge cost-cutting measure if compared to that of mechanical solutions to landslides over a large region in future events.

- *Statements and Declaration*

This is to certify that all the research, laboratory work and designs are the original work of the researcher, and that reference to other research papers was made for all the work that required expertise in some areas. The authors declare no competing interests.

II. METHODOLOGY

Three types of basemaps were used as a field guide. Another one had aerial photographs from QGIS's Google Earth plugin which were overlaid with contours extracted from the Digital Elevation Model downloaded from USGS Earth Explorer (USGS EarthExplorer, 2023). Narrow gravel roads and main roads were downloaded from Wolfram Schneider, (2024). The second one, instead of having a Google Earth background, it had a 1969 geological mapping background. The third one had contour lines overlaid with the planned traverse lines at 200m line spacing.

Field mapping traverse lines were planned at 200m line spacing in ArcGIS using base maps previously created in part (a), to create a third basemap with contour lines overlaid with the planned traverse lines at 200m line spacing.

Lithological and structural mapping was conducted simultaneously. Although this area had previously been mapped by Watson (1969), this mapping focused on specific intensely affected target sites like Ngangu and appraise the local geology. Hence, before the fieldwork, the 1969

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mapwork findings were digitised. Further field structural measurements were done on faults along outcrop exposures within landslide-affected regions as well as joint measurements on the general surface. This boots-on-the-ground technique was also aided by the use of PCI Geomatica, a software used in structural mapping. Final mapped structures in this research were then overlaid onto the previously mapped structures to make one structural database shapefile. By doing this, A few of the new mapped structures coincided with the already mapped faults, hence structures like these were removed from the database whilst retaining the old ones that had been mapped by Watson (1969).

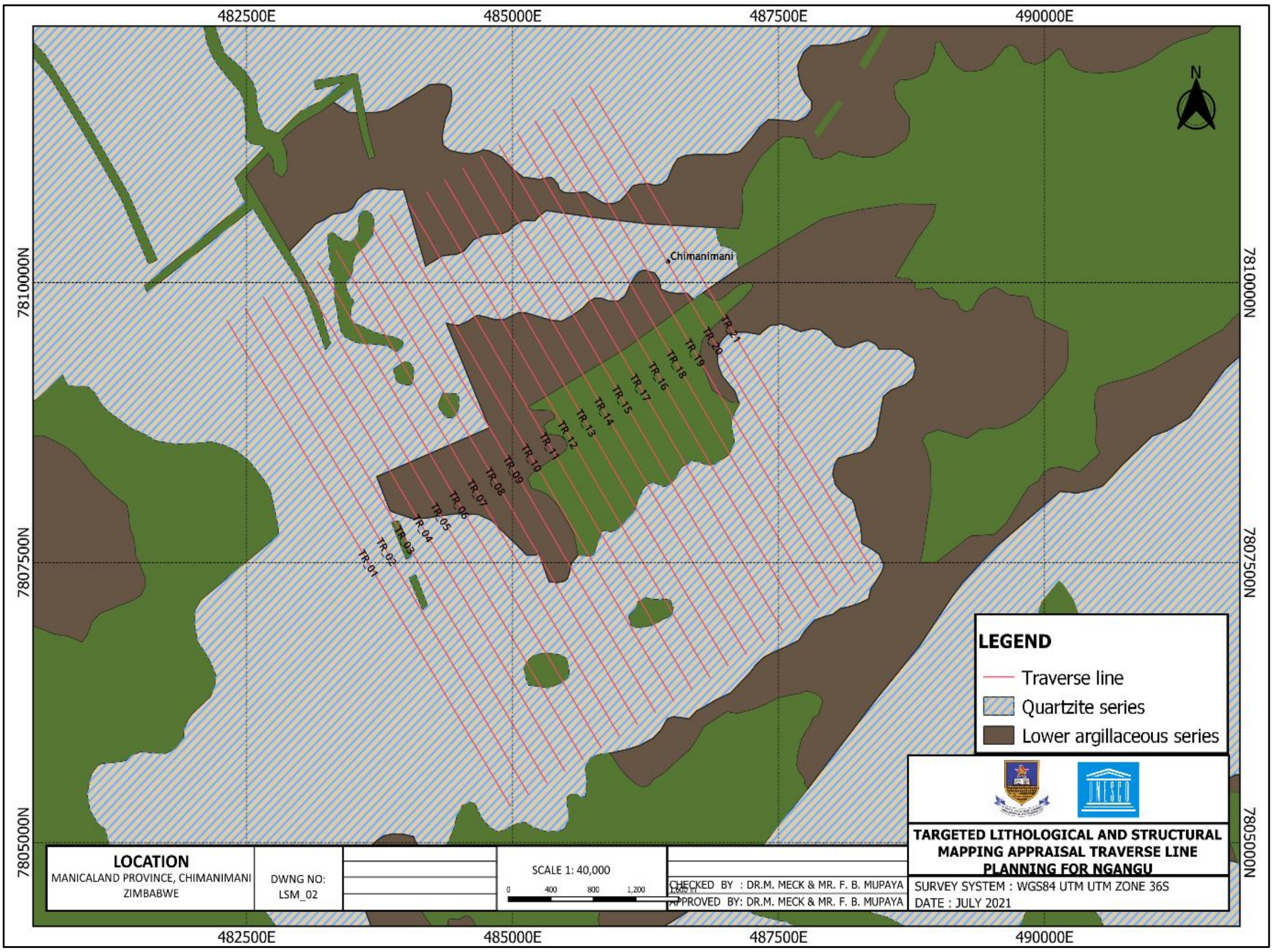

Fig 1 Traverse Line Planning.

➢ *Outcrop Geotechnical Logging.*

Joint descriptions focusing on orientation, aperture thickness, persistence, orientation, infill mineral, infill mineral hardness, rock hardness, and joint moisture condition were done whilst recording the data which was captured in Excel.

➢ *Thematic Map Outputs.*

From the mapping conducted above, fault density and fault trend thematic maps were produced using ArcGIS. To produce the fault density map, the line density tool located within the spatial analyst toolbox was used whilst, for the fault trend thematic map, the shapefiles produced were exported as is to create a thematic map. To produce a final thematic map for visualisation, all data produced from mapping in part "b," and thematic maps in part "c," were exported from ArcGIS to QGIS, since it produces map design outputs with a better visual impact.

➢ *Petrographic Analysis*

Petrographic analysis was performed on thin sections cut perpendicular to bedding or foliation and examined under a Zeiss microscope to understand the presence and nature of microfractures, infill minerals, and possible associated infill-wall rock alteration.

➢ *Microfracture Characteristics*

For petrography, oriented hand specimen collection was vital. The hand specimen was labelled with North arrow, which on preparing the sample, was kept consistent throughout the subsequent stages. Henceforth, direction referencing could be made easier. Microfracture characteristics such as orientation, propagation, infill mineralogy, and termination types were assessed by rotating the microscope's stage where the thin section was mounted on. During stage rotation, reference was made to the sample's bedding or foliation to assess the relative orientation of the

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micro-structures. To assess the type of termination, if the joint plane just ended abruptly, the type of termination would be classified as sharp but if the plane's end was gradational or fading, the type of termination would also be classified as gradational. For infill mineralogy, rotating the stage produces different interference colours under crossed polars, i.e., birefringence. Hence, clays typically produce low to intermediate interference colours whilst the magnetite and other organic matter will be typically dark or opaque. A better reference guide was made from the hand specimen cutting plane.

III. RESULTS

➢ *Targeted Field Surveys*

Most landslides were located within regions that had a thick regolith cover, i.e., >10m thick forming relatively north-east to south-west linear patterns along the mountain ranges. The soil types within most of these areas were sandy clay loams.

Fig 2 Deep Landslides within a Sandy Clay Loam Environment.

➢ *Lithological and Structural Mapping*

A hybrid structural map was produced from the 2019 landslide scarp faces, filed mapping, geological bulletin maps, and PCI Geomatica's advanced Canny algorithm structural mapping. The number of faults previously mapped by Watson (1969) was increased by about 30%. The district is dominated by northeast-southwest and northwest-southeast trending faults with some local fault planes having been crosscut by present-day landslide scarps (**Fig. 3**). Some faults were initially observed from a distance and thereafter followed up closer for verification (**Fig. 3** and **Fig. 4**).

Most flat areas were vegetated with tree plantations mainly utilised for timber. Along the mountain ranges, there was moderate vegetation density and short grasses. Within the mountain ranges, the most observed faults were almost perpendicular to the strike of the mountain ranges. In this regard, most faults were also localised in the immediate vicinity of these faults.

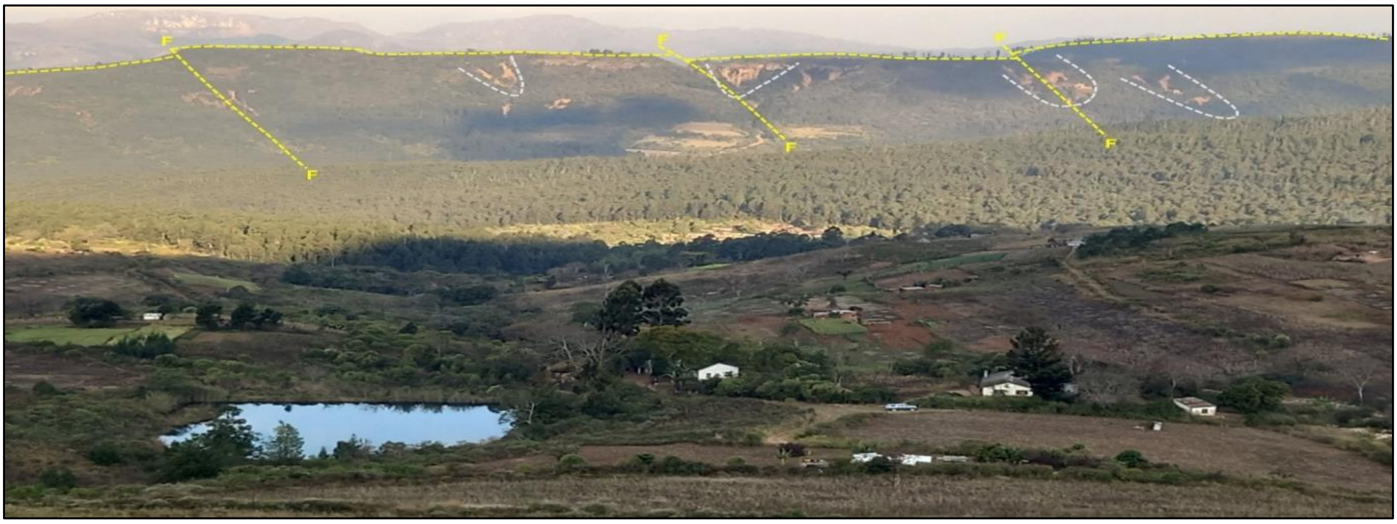

Fig 3 Distal Analysis and Preliminary Mapping of Faults before a Close-up view was Done.

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Fig 4 Fault Zone Outcrop Exposure also showing other Nearby Adjacent Joint Profile Orientations.

The local geology is dominated by shallow dipping sedimentary rocks which were truncated by occasional intrusions of gabbro. Faults with a northwest-southeast, and NE-SW trend appeared to crosscut the local lithologies which were also associated with their brittle deformation response of these lithologies.

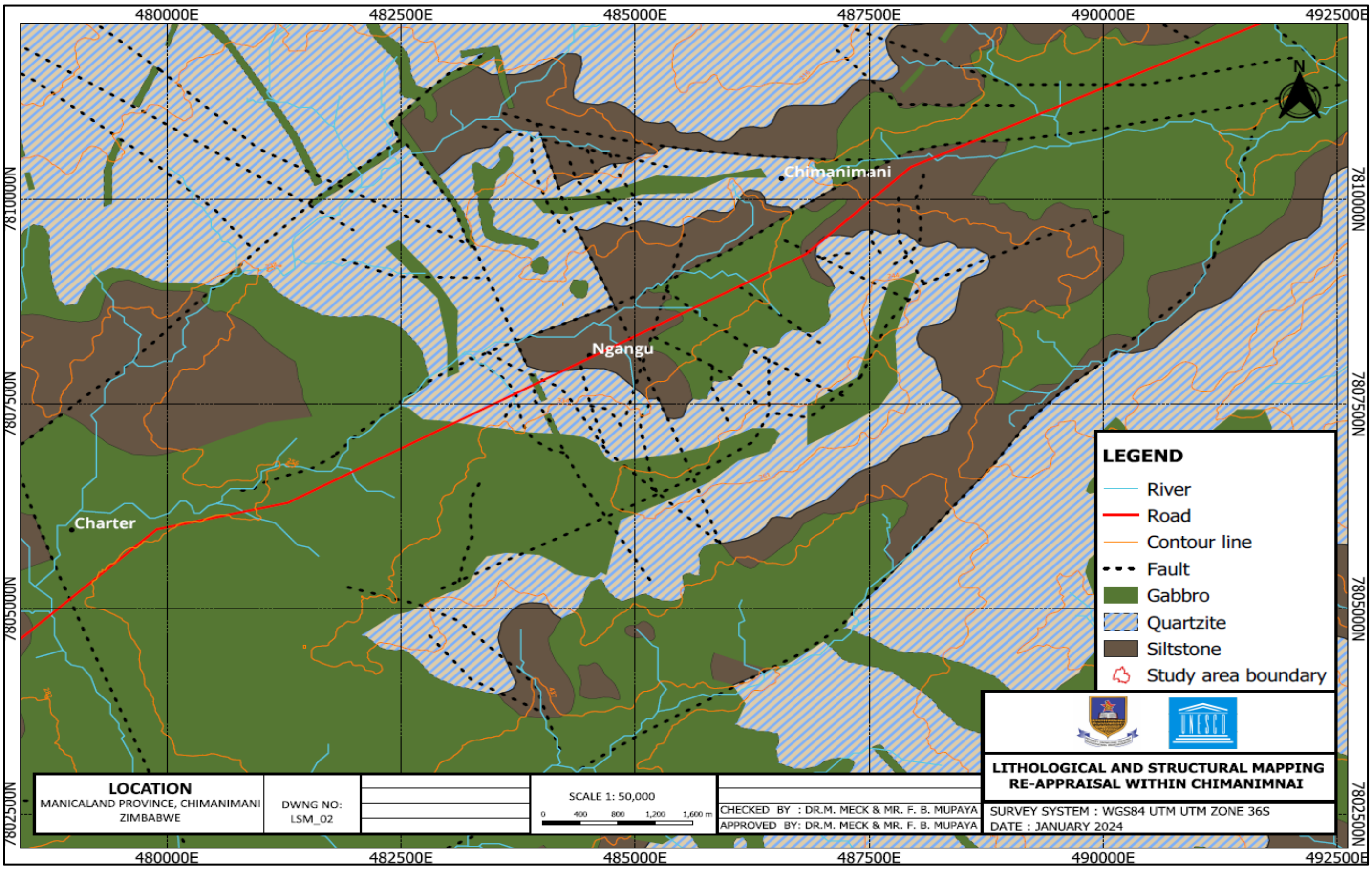

Fig 5 Appraised Lithological and Structural Mapping within Chimanimani.

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➤ *Thematic Maps*

Two thematic maps were deduced in this research. These include the structural map and the fault density map produced at the same scale.

➤ *Structural Map*

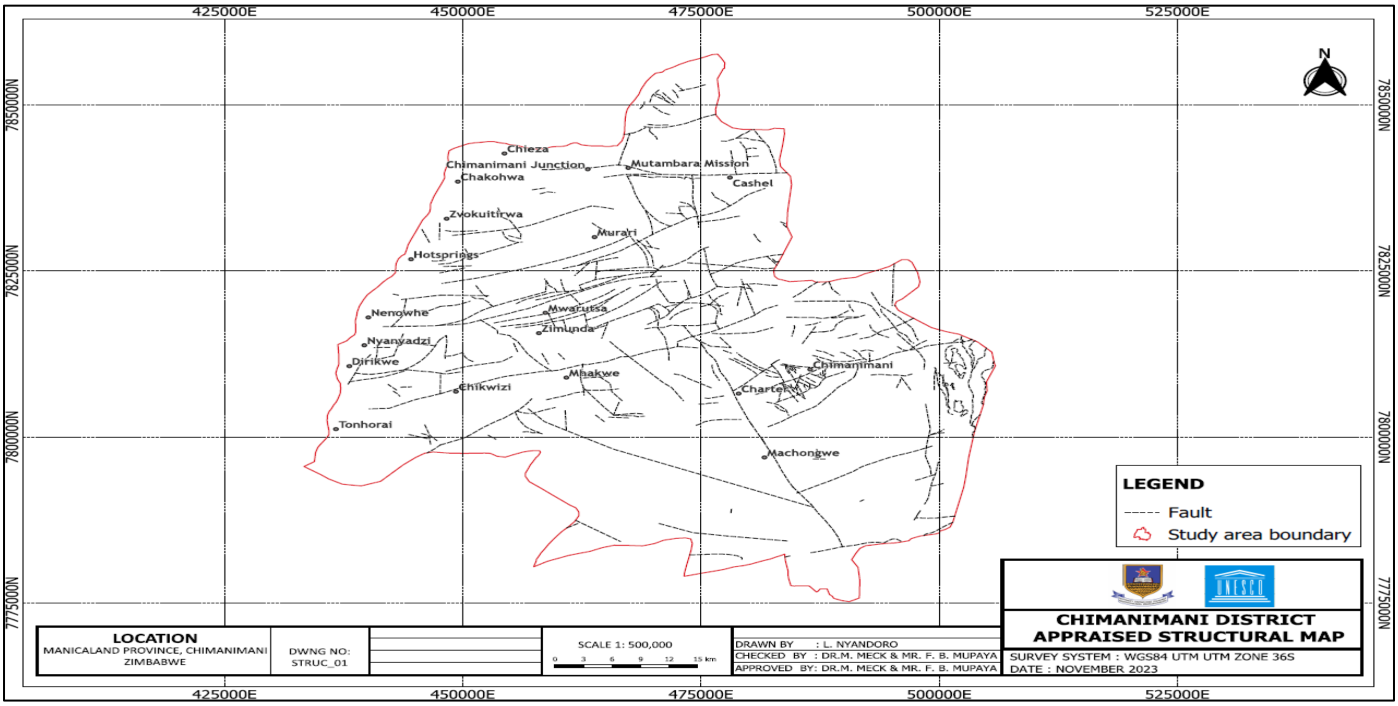

Fig 6 Appraised Structural Map for the Chimanimani District.

The district was predominated by northeast-southwest and northwest-southeast trending faults with the highest densities around Mwarutsa, Chimanimani and Outward Bound where there the frontier series thrust faults are found. Most of them are not laterally extensive. The fault concentrations decrease south and west of the district.

➤ *Fault Density*

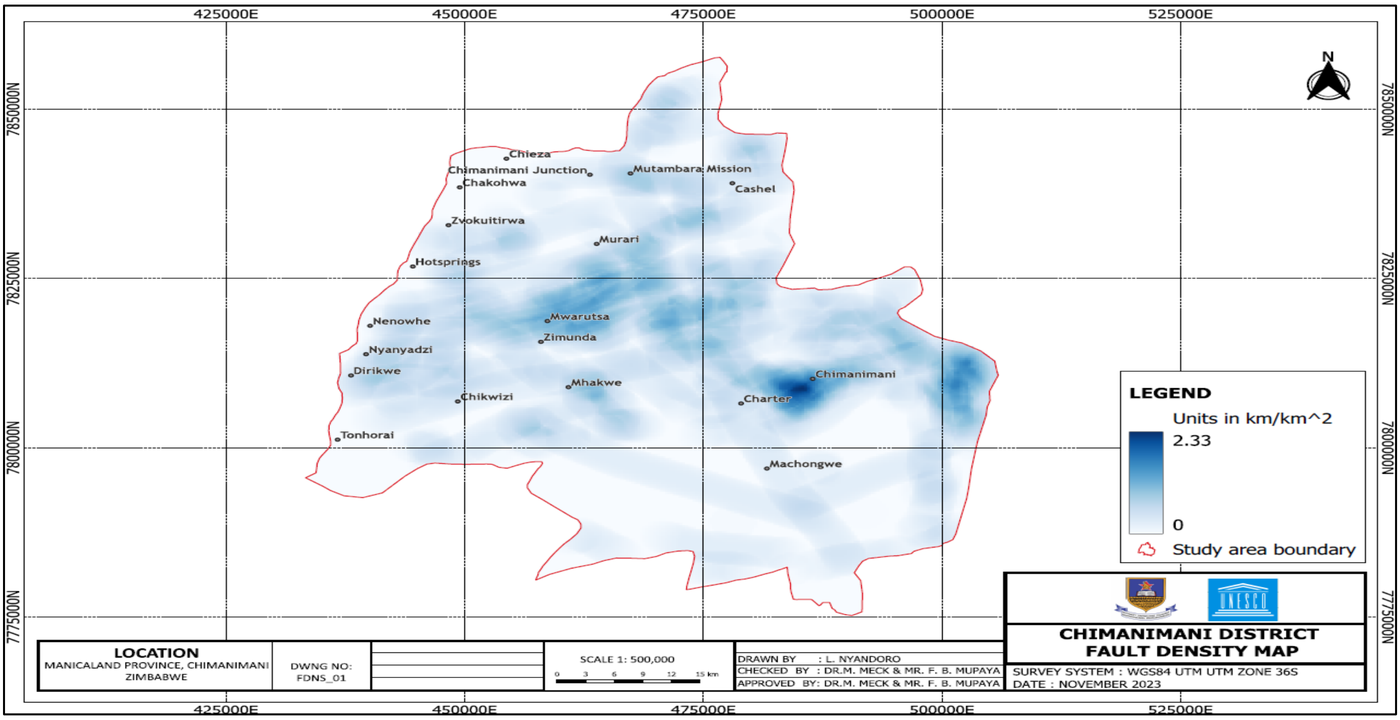

Fig 7 Fault Density Map Deduced from the Structural Map.

Regions around Mwarutsa, Chimanimani, and Outward have anomalous fault density values. When proceeding further south, north and west of Chimanimani and Mwarutsa, the fault density decreases.

IV. DISCUSSION

The eastern part of the Zimbabwe craton experienced at least two deformation events prior to the emplacement of the Umkondo (Mukwakwami, 2012, p87). Post emplacement, the northwest-southeast faults were associated with extension whilst the northeast-southwest faults were associated with compression and the Karoo as well as Post-karoo deformation (Mukwakwami, 2012, p.118). Further deformation can also be attributed to deformation events in the Limpopo Mobile Belt and the overthrusting of the Umkondo's Mozambique facies onto the Zimbabwe facies resulting in most thrust faults presently mapped. All this is alluded to by this research's findings in **Fig. 9**, where three major high fault density zones were observed i.e. zones A-C in areas such as Mwarutsa, Chimanimani, and Outward bound. These NE-SW faults strike is further spatially concordant with the deep landslide generation zones which also had a linear spatial trend along the mountain chains which is also identical to findings by Sendir and Yilmaz (2002) in Turkey. This is largely attributed to the inherent brittle faults, shear zones, joints, type of soil, and underlying lithology which is also alluded to by (Bamisaiye, 2019; Sun *et al.*, 2022). Deep-seated blind faults could have perturbated further upwards into the soil at shallow levels, forming shear planes by reducing the shear surface's friction coeficient (Li *et al.*, 2022) , hence these could have been presently followed by the landslide scarp faces(Bray *et al.*, 1994; Saiyar, Take and Moore, 2015). These perturbations cannot be easily identified with the naked eye unless aided by seismic geophysical surveys. In Chimanimani, E-N-W dykes cut the NE dykes at closer spacing causing more possible wedge breaks or failures (Stead and Eberhardt, 2013). At a local scale, this pattern is likely repeated. Furthermore, the 500Ma Pan African thrust faults in the frontier series covering the Chimanimani mountains reduced these cross dykes mesh.

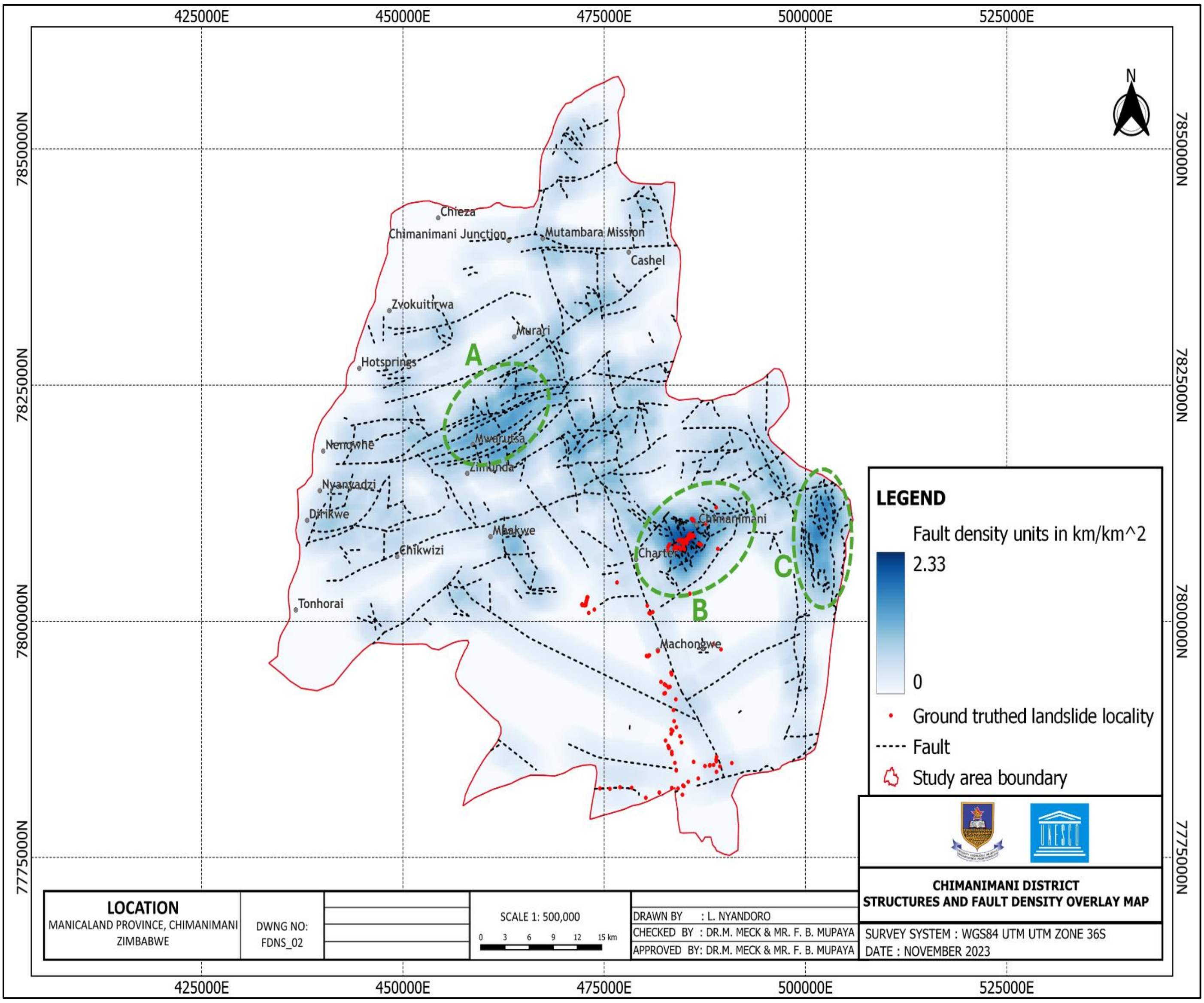

Fig 8 Structural Evolution Interpretation from the Appraised Structural Map and Fault Density Map.

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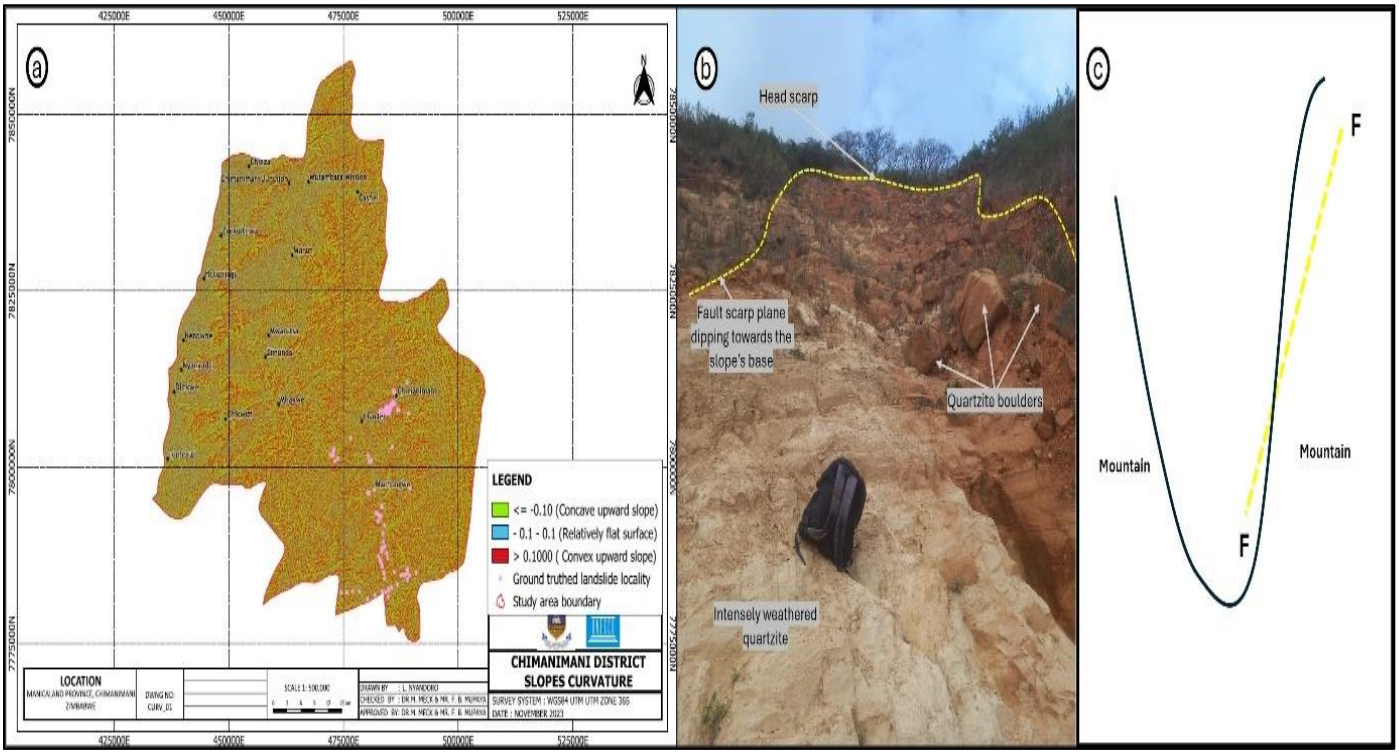

Fig 9 Slope curvature contribution to landslide initiation. In the images, "a" is the district slope curvature map overlaid with historical landslides coordinates, "b" is the field image supporting the concept of fault scarp orientation in relation to the slope whilst “c” is a typical cross-section which tries to explain the concept in graphical terms.

Brittle faults result in the formation of a lot of unconsolidated rock mass which when several parallel transverse sections of the soil profile are observed, there tends to be a thicker B to C horizon within the vicinity of brittle faults. Therefore, in the presence of triggers such as intense rainfall, there would be excess material to cause fatal mud and debris flows (**Fig. 2**).

These high-strain zones can be attributed to either the structural geology complexities, localised stress and tectonic setting, or strain accommodation. They were also positively correlated to the landslides ground truthing and survey done, hence landslide activity was therefore characterised by zones with fault density greater than 0.8km/km^2 (**Fig. 9)**. This concept is also explained by Hackl, Malservisi and Wdowinski (2009). Furthermore, the prominent orientation of structures in high strain zones possibly suggests the strain response as a result of different deformation events for example strain zone A has dominantly northeast-southwest trends, strain zone B has dominantly northwest-southeast trends whilst strain zone C has dominantly north-south trending faults. The linear array of these strain zones possibly suggests that Mozambique (i.e. the county immediately east of the study area) could be in the line of fire as well.

Microstructures (**Fig. 10**) also played a pivotal role in landslide propagation as alluded to by Andrea et al. (2011). These structural records were observed in most lithologies; hence they were not constrained to any lithologies i.e., they emerged progressively across various rock types. Most of the structures are either open or infilled with clay.

The characteristic regular cubic macro-jointing, i.e., consistent vertical and horizontal joints exposed from slope faces, but with differing joint frequency possibly increases the landslide susceptibility in the event of any triggering factor due to these favourable joint orientations with reference to **Fig. 4**. The current state of some macro-faults (**Fig. 10**) could allow for further microfracture nucleation forming one larger macroscopic fracture in the event of a propagation trigger.

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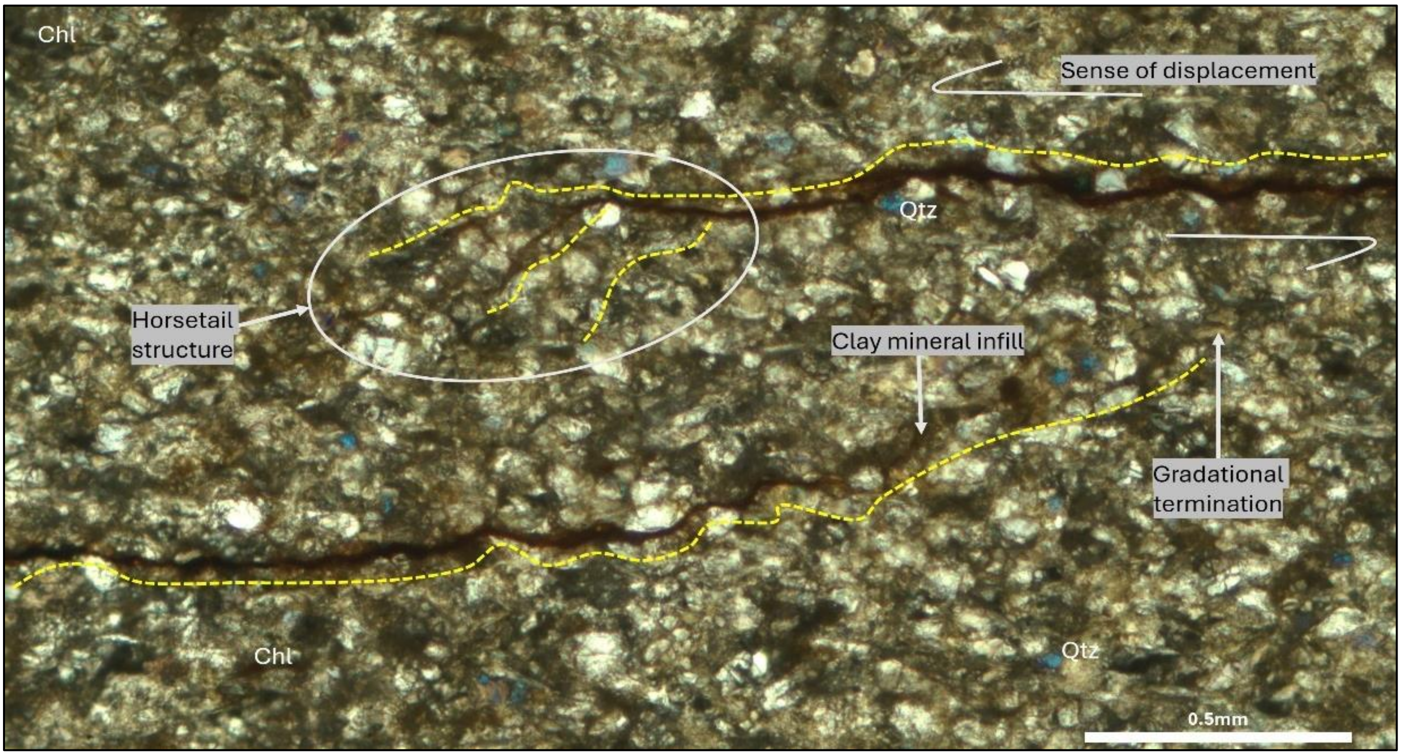

Fig 10 Photomicrograph of Thin Section CMCH001 showing Possible Micro-Fracture Development into Macro-Fractures. Field of view is 2.5mm.

The presence of clay within micro-structures or joints was hypothesized to exacerbate fracture expansion due to its swelling properties upon moisture absorption(Scherer and Gonzalez, 2005). Hence, clay as the dominant joint infill mineral in most of these microstructures might have had a further negative impact by creating conducive environments for slope failure. Due to the absence of fracture-healing minerals such as, quartz, the clays further reduce friction on the slip surfaces between two potentially unstable blocks (Brzovic and Villaescusa, 2007). Upon moisture absorption, the fracture would widen, thereby further increasing the fracture's persistnce, creating more accommodation space for further clay infill, hence precipitating landslides. As a cyclic event, this is how fracture propagation would occur in the absence of any active faulting or in the presence of slowly progressive active faults. This is also seconded by findings from Cai et al. (2019).

The application of mechanical landslide solutions over a large area within the district is very costly hence, this calls for an urgent need for affordable landslide mitigation measures as alluded by Popescu and Sasahara, (2009, p.610).

V. CONCLUSION

➢ *From the Work done and Results Obtained, the following can be Concluded:*

- Macro and micro faults and joints both play a crucial role in landslide initiation as well as propagation. Most landslides occurred on a concave upward slope with fault dip in the direction towards the toe of the slope.
- Joint orientation, persistence, and infill minerals significantly contributed to the Chimanimani landslides. The clay material infilling micro-faults/joints could be responsible for further propagation of fractures due to its expansivity when it gets moist.
- Landslides were more prominent in regions with a fault density greater than 0.8km/km^2.

From this research was a very essential pilot study which resulted in the targeting of prime targets and actual factors which led to landslides triggers to further avoid any diverse catastrophic impact of such events which often leave local communities socially damaged as alluded by (Cahyani, Warsini and Raymomdalexas, 2023)

VI. LIMITATIONS

Some targeted sites were not accessible due to thick, short, and dense vegetation. To counter this limitation, the use of remote-sensed Landsat images further aided in data collection and interpretations. This a also based on skills demonstrated by researchers such as (Roland *et al.*, 2020; Lan *et al.*, 2022).

RECOMMENDATIONS

➢ *From the Research Work Conducted, the Following Points are Recommended:*

- *Landslide Hazard Mapping and Monitoring:*
  Develop detailed landslide hazard maps that incorporate information about macro and micro faults, joint orientations, and infill minerals.

Implement a robust monitoring system to track changes in slope stability over time, especially in areas with high fault densities greater than 0.8km/km^2.

- *Land Use Planning and Zoning:*

Restrict construction and development in landslide-prone areas, especially those with concave upward slopes and fault dips toward the toe of the slope.

Collaborate with local authorities to enforce zoning regulations that minimize exposure to landslide hazards.

- *Community Awareness and Preparedness:*

Educate local communities about landslide risks and preventive measures.

Promote early warning systems and emergency response plans to mitigate the impact of landslides.

- *Research and Collaboration:*

Collaborate with Geologists, Engineers, and Environmental Scientists to enhance landslide prediction and prevention strategies.

ACKNOWLEDGMENTS

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➢ *Supplementary Information*

All associated data was included in this research paper.

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