African Journal of Physics, Chemistry, and Medical Laboratory Science (AJPCMLS)

E-ISSN 2978-3348 (Online); ISSN 2978-333X (Print)

Indexed by SABINET and EBSCO

Volume 2, Number 1, June 2026

Pp 5-40

Integration of the Gravity Geophysical Technique and a Geospatial Approach in Delineating Geological Structures in Chimanimani and Chipinge Districts

DOI: https://doi.org/10.31920/2978-3348/2026/v2n1a1

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Abstract

The Chipinge and Chimanimani districts of Zimbabwe are regions of high tectonic significance and seismic risk, yet rugged terrain often limits comprehensive structural mapping. This study investigates the geological architecture of these districts to identify zones prone to earth movement using an integrated approach of geophysical gravity and geospatial techniques. Integrating gravity data with Landsat 8 OLI imagery allowed us to map lithological variations and tectonic lineaments across both accessible and remote terrains. The methodology utilised advanced gravity processing, including Simple Bouguer Anomaly, Horizontal and First Vertical Derivatives, and Automatic Gain Control (AGC), alongside geospatial techniques such as Principal Component Analysis (PCA), Optimum Index Factor (OIF), and directional filtering. Integration of these datasets revealed dominant fracture sets trending N-S and E-W, showing a high spatial correlation between deep-seated gravity anomalies and surface lineaments. These results validate the efficacy of data fusion for structural mapping in complex, high-relief terrains.

This study provides a vital framework for seismic hazard mitigation and geological characterisation in similar tectonic analogues globally.

Keywords: *Gravity, Geospatial, Lineaments, Lithology, Chimanimani and Chipinge, Tectonics, Earth Movement*

Introduction

Geological features, particularly tectonic lineaments, serve as fundamental indicators of the structural framework and evolutionary history of the Earth's crust. Lineament mapping is a critical tool for identifying fault structures that influence geological hazards, ore mineralisation, and hydrological systems. Although field mapping is the traditional method for identifying these features, direct ground-based observation is often heavily constrained by scale, perspective, and physical accessibility. Over the last two decades, the application of multi-platform remote sensing, including Landsat, ASTER, and Sentinel-1, has revolutionised structural geology by providing a synoptic view of tectonic features across diverse regional terrains. These surface manifestations, expressed as topographic reliefs or tonal variations, are the visible markers of complex 3D underground structures.

The integration of Geographic Information Systems (GIS), Remote Sensing (RS), and geophysical gravity surveys has transformed geological research from static 2D observations into dynamic, multidimensional analytical frameworks. Geospatial data is an indispensable component of modern tectonic mapping. Aiken et al. (1997) and Seber et al. (2000) demonstrated that GIS platforms possess a unique capacity to integrate extensive geophysical data such as gravity and magnetic anomalies to map structural and subsurface features across complex tectonic settings like Mexico and the Middle East. Specifically, Brew et al. (2000) utilised a GIS platform to synthesise hydrocarbon data with surface remote sensing imagery to generate new tectonic models for Syria. This research highlighted a key advantage of the geospatial approach: it enables rapid manipulation and visualisation of data that were previously "prohibitively time-consuming" to analyse. By merging existing datasets with new imagery, researchers can create high-quality structural maps essential for predicting how regional structures will respond during major seismic events.

The Chipinge and Chimanimani districts of South-Eastern Zimbabwe present a unique and urgent geological challenge. Situated at the southernmost extension of the East African Rift System (EARS) a region characterised by tectonic expansion and lithospheric thinning, this area is one of the most seismically active zones in Zimbabwe. The region suffers from a recorded history of seismic activity and tremors that threaten infrastructure and human life, notably the 2006 Mozambique earthquake detailed by Lloyd et al. (2019) . This seismicity is driven by a complex geological architecture of faults and folds; yet, despite this high-risk profile, comprehensive structural mapping remains incomplete. Research in this region is hindered by two primary constraints: scale and topographic complexity. The vast geographical extent of the districts makes exhaustive manual ground surveys logistically and financially prohibitive. Furthermore, the undulating mountainous formations and high-relief terrain of the Chimanimani range create "inaccessible zones" that prevent geologists from obtaining a continuous dataset through physical traversal alone.

To overcome these limitations, it is essential to look beneath the surface and beyond the reach of traditional fieldwork. Geophysical gravity surveys offer a powerful, non-invasive tool for this purpose. By measuring density contrasts within the crust, gravity techniques can identify and characterise deep-seated subsurface structures, such as basement faults and sutures, which may not be fully visible at the surface. While remote sensing provides a synoptic view of surface expressions, geophysical gravity surveys are essential for resolving the 3D geometry of the subsurface. Gravity anomalies arise from density contrasts between different rock units, making this technique a premier tool for delineating faults, sedimentary basins, and basement architecture.

Literature consistently supports using gravity data to resolve structural ambiguities. Both local and global studies document this efficacy; for instance, Okpolin and Akingboye (2019) used gravity data to characterise the lithostructural and depth properties of Nigeria's Igabi region, proving that density variations reveal concealed fault zones. Similarly, Satyakumar et al. (2022) employed improved gravity datasets to map structural and tectonic features in the Mahanadi Basin of India, proving that gravity derivatives can reveal structural grains obscured by surface sediments. Furthermore, Blaikie et al. (2014) emphasise that gravity gradiometry and vertical derivatives are critical for identifying steeply dipping faults and contacts that might not have a distinct topographic expression. In South-Eastern Zimbabwe, gravity surveys bridge the gap by directly connecting surface lineaments observed through satellite imagery to the deep-seated crustal structures of the East African Rift System.

Simultaneously, engineering geology and infrastructure planning within the region must contend with significant geo-environmental hurdles. Civil engineering projects in Zimbabwe, including the Risitu Mission road and the expansion of the Machongwe Growth Point, are situated in areas with karst features and variable bedrock, necessitating comprehensive suitability assessments to mitigate the risk of structural failure. Weighted GIS models are considered the "gold standard" for such suitability assessments. Following Aly et al. (2005), these models integrate multi-criteria layers, utilising lithological contacts and fracture densities to identify planes of weakness, slope and soil profiles to assess landslide susceptibility, and proximity to major faults and channels to evaluate tectonic and flood hazards. Establishing a 3D model that combines gravity-derived subsurface data with surface geospatial information ensures that settlement planning in the Chimanimani and Chipinge districts is informed by the underlying geological reality rather than surface observations alone.

The literature collectively confirms that the integration of satellite imagery (Landsat 8, SRTM), gravity surveys, and GIS tools is no longer optional but a requirement for modern geological surveys. For the Chipinge and Chimanimani region, where rugged terrain renders traditional mapping inadequate, this integrated approach bridges the gap between field-based observations and deep-seated structural interpretations. Consequently, there is an urgent need for an integrated approach that utilises Satellite Remote Sensing (SRS), Geographic Information Systems (GIS), and Geophysical Gravity surveys. This multidisciplinary methodology offers a practical, reliable alternative for extracting geological lineaments and subsurface structures in rugged terrains.

By correlating surface lineaments extracted from satellite imagery with deep-seated anomalies identified through gravity data, this study aims to build a robust 3D model of the regional fracture network. The core motivation of this work is to clarify the geological structures that promote seismicity and earth movement in South-Eastern Zimbabwe. By pinpointing these features, the research provides a foundational dataset for natural hazard mitigation in a region increasingly vulnerable to tectonic instability. Ultimately, these findings offer crucial data on the underlying structural framework of the region, illuminating its seismic potential to guide the development of robust hazard mitigation and risk management plans in Zimbabwe.

The Geology of the Study Area

Geological Outline

The rock formations within the area are of Precambrian age, and the Archean Basement schists of the Cronley schists are the oldest. These rock formations cover a tiny portion, approximately 14.5km long and 1.6km wide, extending from the Wengezi River East-Northeast into Mozambique. The northern end belongs to the Greenstone Series and is composed of basaltic lavas, which show a high level of metamorphism that results in massive, weakly schistose greenstones and epidiorites. These rock formations are made up of hornblende and clouded plagioclase feldspar.

The sedimentary series occupies the southern part and appears to be younger than the greenstone series. These sedimentary series are mainly composed of fine-grained quartz mica schists formed from argillaceous and silty sediments. On Cronley farm, the banded Iron formation extrudes between the two series. Small bodies of talc schist and serpentine are seen sporadically throughout the belt.

The Mutare batholith is a small, exposed granitic formation. These Basement Complex granites are later, intrusive units that exhibit contamination from the surrounding Basement Schists. This granitic formation is a white to pale grey, equigranular gigantic rock composed of sericitised sodic plagioclase, clear microcline, and quartz.

East of Chimanimani, in the Mozambique side, granitic gneiss underlies the rocks of the Frontier Series and away from the contact zone, it has a strong ENE foliation and contains parallel streaks and inclusions of chlorite and hornblende schists. Its composition is made up of sodic plagioclase and quartz, which is to a large extend altered to sericite and epidote. Chloritized biotite and hornblende are found in the area and are dark and are thought to be the Basement Complex granite that has been affected by the shearing and metamorphism of the Limpopo zone. In this area, no charnockitic or granulitic rocks were observed. Across a zone approximately 3 metres thick, the gneiss underlying the Frontier series has been transformed by tectonic movements and deformations into sheared, cataclastic, quartz-sericite schist or, more rarely, quartz-chlorite schists.

The geological record indicates that prior to the deposition of the Umkondo System sedimentary rocks, a prolonged erosional process occurred, affecting the older rocks and transforming their surface into a peneplain. A certain degree of brecciation and crushing is seen on the upper surface of the granite, and this could have been due to tectonic movement.

The Frontier series was deposited in a basin to the east of Zimbabwe, within the Mozambican territory. These frontier series represent the earliest formations of the Umkondo System, with only a small portion of the original sediments preserved today. They constitute a mountain range—most notably the Chimanimani mountains—that extends from Corner Farm to the north down to the Rusitu Valley in the south, forming a scenic 26km stretch with an approximate width of 8km. The northern sector exhibits a high level of folding and is cut against younger rocks, whereas in the south, the beds dip disconformably westwards beneath the younger Lower Argillaceous Series before terminating.

The Frontier Series has been divided into four categories, which are:

- The lower quartzites
- The lower Chlorite Schists
- The upper quartzites
- the upper chlorite schists

From Binga to the Corner farm, the lower quartzites lie on the granitic gneiss floor and are separated by a thrust plane. They are approximately 200m thick to the north, and at near Binga, the thickness increases to approximately 760m. They are well-sorted, fine-grained, white orthoquartzites with very little matrix in the basal areas. A red quartzite occurs with some bands of schistose, white to greenish, chloritic quartzite, where the chlorite appears as wisps and streaks across the rock in the upper section. Bedding is so distinct in the quartzite and not clear in the white quartzite, which sometimes gives a separate, very distinct foliation and cleavage.

The lower chlorite schists rest conformably above the lower quartzite and are approximately 180m thick on the north and increase in size to over 610m southwards. They exhibit argillaceous and silty sediments that have undergone a metamorphic process to form schists composed mainly of chlorite, sericite, and fine-grained quartz of varying sizes.

The upper quartzites can be best described as red beds-free, fine-grained and white. They are separated into two parts by the beginning of the upper chlorite schists on the north of Binga and the Bundi plateau.

The approximate thickness of the lower bed ranges from 90m to 458m, while the upper bed ranges from 152m to 305m, with a schist layer of up to 91m situated between the two. The thickness of the lower beds varies from 90m to 305m on the Southern end.

Upper Chlorite Schists are greenish grey, fine-grained, schistose rocks composed of sericite, chlorite and quartz structures. This formation contains significantly more silty beds than the lower chlorite schists, with some ottrelite observed close to the thrust planes. To the North of the Bundi River, they are roughly 90m to 152m and thicken abruptly to over 762m southwards in the Rusitu Valley.

Intense folding of the Frontier series generated a landmass east of the Haroni River; this positive topographic feature provided the source for the aeolian quartzite deposited within the sandy ironstone bed on the western flank of the Haroni Valley.

On both sides of the Save River a calcareous series is exposed along the western side of the Umkondo highlands (Swift ,1962); it thins eastwards and outcrop on top of the Frontier series in the western part of the Chimanimani Mountains. The Calcareous Series lies with a clear unconformity on the granitic floor on the west side. The rocks are lime-rich. The Calcareous series outcrop and extends SSW from the Himalaya plateau to the Tanganda Valley.

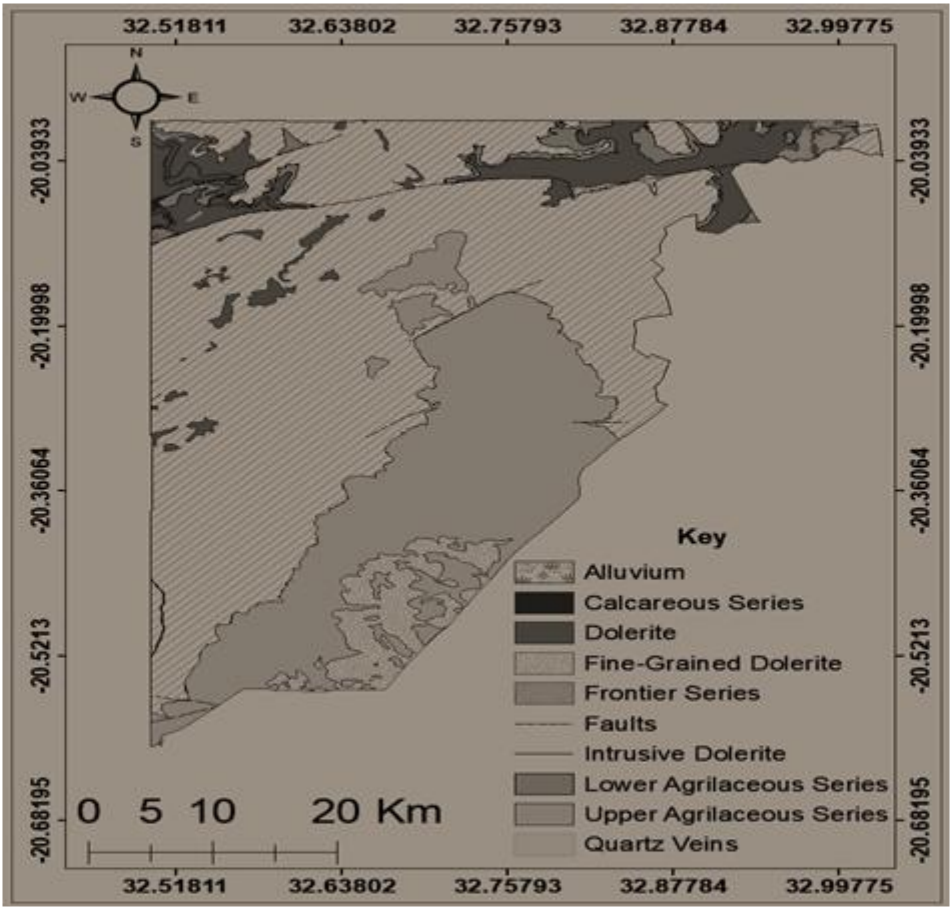


Figure 1: Geological map of the study area.

Methodology

To delineate geological structures in the rugged terrain of Chimanimani and Chipinge, a multi-phased approach using gravity data and geospatial techniques was utilised. This methodology integrates and correlates gravity data and spectral data to delineate lithology, topographic data for landform analysis, and spatial statistics to identify hazard zones.

Gravity Survey

Data Acquisition and Computational Methodology

Traversing the primary survey profiles, gravimetric observations were conducted employing a LaCoste and Romberg G-series geodetic gravimeter (G513), while precise vertical control and orthometric heights were established via Differential Global Positioning System (DGPS). The physiographic character of the study area exhibits significant variance, transitioning from the relatively accessible Odzi-Sabi graben/valley to the high-relief, topographically rugged terrain characterising the eastern sector, which poses substantial logistical constraints for terrestrial acquisition.

The Earth's gravitational field is a complex phenomenon influenced by the distribution of mass within the planet. By measuring the tiny variations in the gravitational field, gravity surveying can provide valuable information about the subsurface structure. The technique is particularly useful for exploring areas with limited or no access, such as remote or environmentally sensitive regions. Gravity surveying is a non-invasive geophysical technique that measures the variations in the Earth's gravitational field. These variations are caused by subsurface density contrasts, which can be related to different geological structures, mineral deposits, or hydrocarbon reservoirs. The technique has been widely used in various fields, including geology, geophysics, and environmental science, for mapping subsurface structures, identifying potential mineral or hydrocarbon resources, and monitoring groundwater movement. In this study, the technique was found to be useful in mapping potential seismically active geological structures by detecting variations in rock density.

Owing to the inaccessibility of certain portions of the study area, the gravity survey was restricted to main roads and accessible sectors. Conducting a ground gravity survey strictly along accessible roads in a mountainous region is a common compromise known as a Roadside Gravity Traverse. While it limits spatial coverage (producing 2D profiles rather than 3D grids), it is often the only cost-effective option in rugged terrain. However, roads in mountainous areas introduce specific sources of error (road cuts, traffic vibration, and poor GPS coverage) that must be managed.

The base stations were established at secure, accessible locations, such as schools; a LaCoste & Romberg G-series geodetic gravimeter and a high-precision Differential Global Positioning System (DGPS) were deployed in the study. The gravimeter was used to take gravity readings, and DGPS was used to record elevations and coordinates.

1. Survey design and plan

The purpose of the survey was to map faults (geological faults) within the study area. The greater part of the study area is inaccessible due to rugged mountains ranges.

Due to the structural inaccessibility of the region, the study design prioritised a regional gravity survey constrained to major road networks and accessible zones within the Chimanimani and Chipinge districts.

A Differential GPS was selected for this project, alongside a lacoste and Romberg gravimeter. The differential GPS was used to take elevations, and a High-Precision GPS (RTK) was considered, noting that in gravity, elevation control is the largest source of error. A 1-meter error in height results in a ~0.3086 mGal error (Free Air correction), yet vertical accuracy better than 5–10 cm was needed, and the Lacoste and Romberg gravimeter was used to take gravity readings.

A station Spacing of 1-5km was adopted depending on the accessibility of the area; however, in certain mountainous yet accessible terrains, a tighter spacing was preferred to capture rapid variations in terrain effects.

1. Base Stations were Llocated at stable, locally established, at a secure and stable locations (Schools and clinics were used).
2. Very High Traffic times were identified in certain areas to avoid carrying out surveys during such times, since Gravity meters are extremely sensitive to ground vibrations caused by passing trucks.

Readings were collected at all convenient points along major roads, where it was relatively straightforward to set up the gravimeter and establish a stable connection between the roving DGPS instrument and the DGPS base. Elevated grounds were primarily selected for the DGPS base stations to ensure an unobstructed line of sight and easy linkage between the base station and the roving DGPS unit.

2. Base Station Establishment

Several base stations were established across the entire area at schools and clinics, with permanent marks placed for reference purposes. The entire study area had 15 base stations for the gravity survey. Base stations for the DGPS were established progressively as the survey advanced, situated dynamically based on where an effective telemetry linkage could be maintained between the roving unit and the base receiver. As soon as the linkage between the two was lost, then the base was changed or migrated to a convenient point.

The base station is used as a reference point for repeated measurements to correct for instrument drift over time.

3. Field Data acquisition.

The "Looping" method was used to correct for instrument drift (spring fatigue) and tidal variations. Since gravity meters (gravimeters) are extremely sensitive, their readings change over time even if the instrument remains at the same location. Looping ensures these these temporal variations are successfully removed, leaving only spatial density differences within the data dataset.

Step 1: Base Station Reading (Start of Day)

1. The gravimeter was set up at a designated Base Station.
2. The instrument was levelled perfectly.
3. A minimum of 3 consistent readings were taken (standard deviation < 0.005 mGal).
4. The time, height of the instrument (HI) above the ground, and the readings were recorded.

Step 2: The Road Traverse (The Survey)

Although the survey stations were pre-planned, the actual survey was restricted to accessible roads and pathways. Readings were taken along the road at pre-planned stations. At each station:

1. Site Selection (The "Road Cut" Problem):
   - Avoid: Setting up a gravimeter immediately next to a steep cliff edge or inside a deep road cut (where rock is blasted away) was avoided. These create massive "Terrain Correction" errors.'
   - Preferred: Flat shoulders or culverts where the ground is relatively level for at least 5-10 meters around the sensor were preferred.
   - Surface: The meter was placed on the tripod or a baseplate on firm soil/tarmac. Never on asphalt that is soft/melting in the sun (the meter will sink, causing drift).
2. Vibration Management:
   - When taking a reading, heavy trucks were allowed to pass before taking the readings. If a car passes during the reading, that measurement was rejected, and a new reading was taken.
   - A "Wind Shield" was used to block the wind, if it is windy (common in mountain passes).
3. Measurement:
   - The meter was levelled.

- The station ID and Height of the Instrument were entered into the meter.
- Gravity reading was taken (typically 60-second averaging cycles).
- Simultaneously, when taking the GPS reading, meticulous care was taken to ensure that the GPS pole was positioned exactly adjacent to the gravimeter.

4. Near-Zone Terrain Notes (Critical):

On mountainous roads, the immediate topography was recorded. In gravity surveys, especially in mountainous regions like the Chimanimani or Chipinge districts, recording "near topography" is critical because of a process called Terrain Correction (or the Bullard C correction).

While standard corrections (like the Bouguer correction) assume the Earth is a flat, infinite slab of rock, the real world has hills and valleys that interfere with your readings.

The gravitational pull of any object follows the Inverse Square Law:

$$F = G\frac{m_1 m_2}{r^2} \qquad [1]$$

This means that a mass very close to your gravimeter has a much stronger influence than a massive mountain far away.

Hills (Mass Excess): A hill rising above your gravimeter station exerts an upward gravitational pull. This counteracts the Earth's downward pull, making the recorded gravity reading lower than it should be.

Valleys (Mass Deficit): A valley below the station means there is "missing" rock. In a perfect flat-earth model, that rock would be pulling your sensor downward. Since it is missing, the total downward pull is weaker, again making your recorded reading lower.

Both hills and valleys reduce the gravity measured. Therefore, the terrain correction was added to the observed data to "normalise" it as if the ground were perfectly flat.

A clinometer was used to estimate the slope of the ground in 4 directions (N, S, E, W) for the first 50 meters. (e.g., "North: Road flat; South: 45° cliff up; East: Road flat; West: 30° slope down") to handle the Inner Zone Terrain Correction.

Step 3: Base Station Loop (End of Day or Mid-Day)

1. At the end of the survey day (depending on the meter's stability), readings were taken or recorded at the same Base Station where the survey was started at.

2. This is called "closing the loop," and it allows one to calculate the linear drift of the instrument and mathematically remove it later.
3. Once the data was downloaded, baseline calculations were conducted using Excel, marking the initiation of data processing.

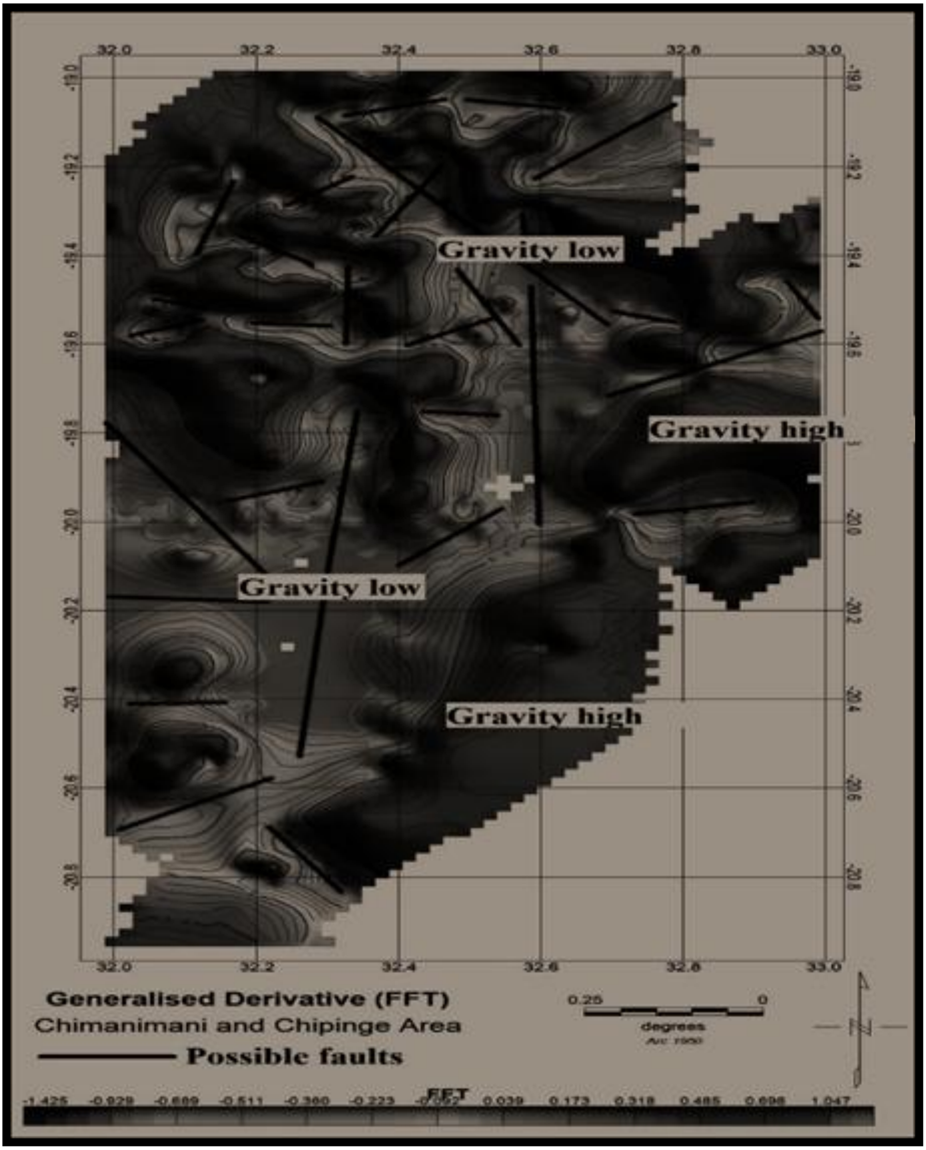
Geosoft Oasis Montaj was used to process data. Following the retrieval of the gravity and DGPS data and the subsequent execution of gravity survey correction calculations within Excel, the two datasets were integrated within Geosoft Oasis Montaj. A Nettleton density value of 2.75 g/cm3 was used. Data corrections was done manual in excel with special attention paid on instrument drift which account for changes in gravimeter readings using base station data, tidal effect which account for gravitational effects caused by the moon and sun, latitude correction which adjust for the Earth's shape and rotation and cause gravity to vary with latitude, free-Air correction which adjust for elevation difference between stations, terrain correction which correct for the gravitational effect of nearby topography (hills, valleys, etc.) and bouguer correction which account for the mass of material between the station and a reference elevation (usually sea level) and the Complete Bouguer Anomaly that Combines all corrections to produce the Bouguer anomaly, which reflects subsurface density variations.

The resulting stochastic dataset was archived, processed, and subjected to multidimensional analysis within the Seequent Geosoft Oasis Montaj (v.2025) computational environment. Subsurface lithostructural configurations were elucidated through a rigorous workflow of interpolation (gridding), frequency-domain filtering, and geophysical inversion modelling.

Signal Processing and Structural Enhancement

To establish a coherent structural-geological framework, a suite of digital signal processing (DSP) and potential field enhancement algorithms were deployed.

For Spectral Discretisation, Fast Fourier Transform (FFT) and Power Spectrum Analysis were executed to perform wavelength-based separation, effectively isolating deep-seated regional trends from high-frequency residual anomalies associated with shallow crustal sources.


Gravity low
Gravity high
Gravity low
Gravity high
Generalised Derivative (FFT)
Chimanimani and Chipinge Area
Possible faults
degrees
FFT

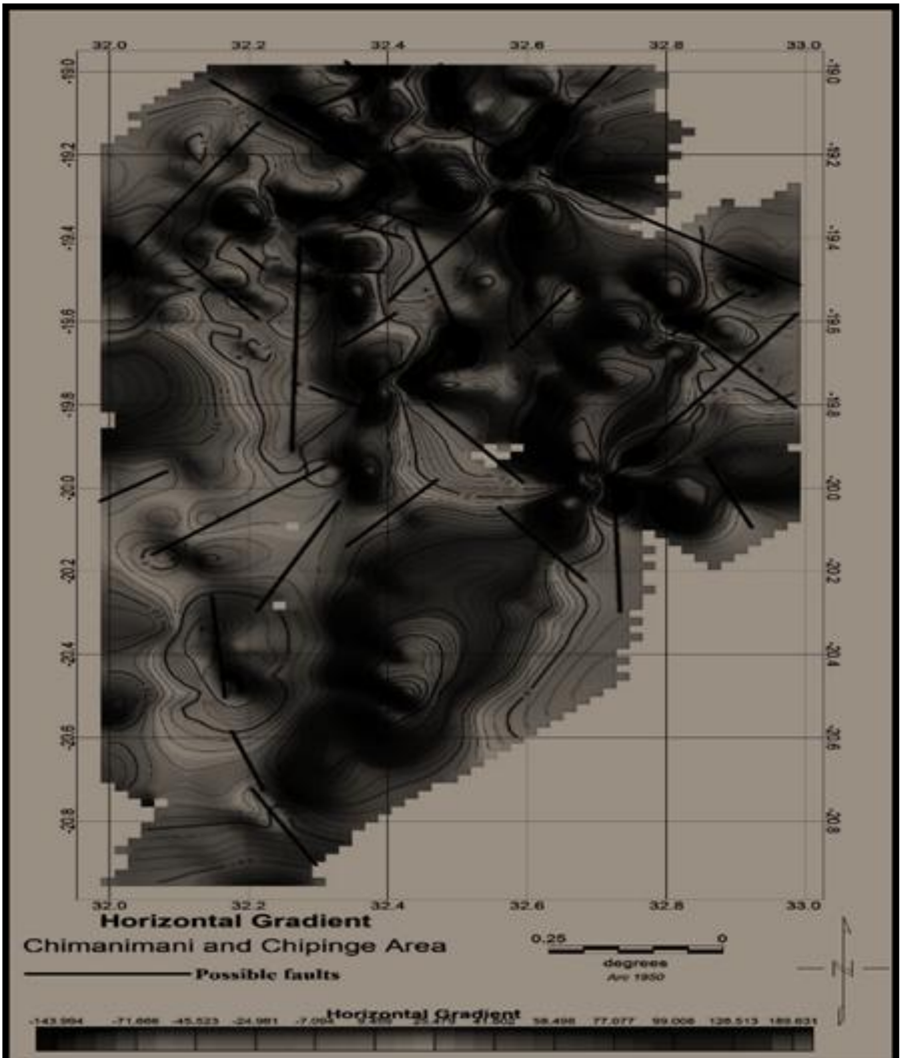
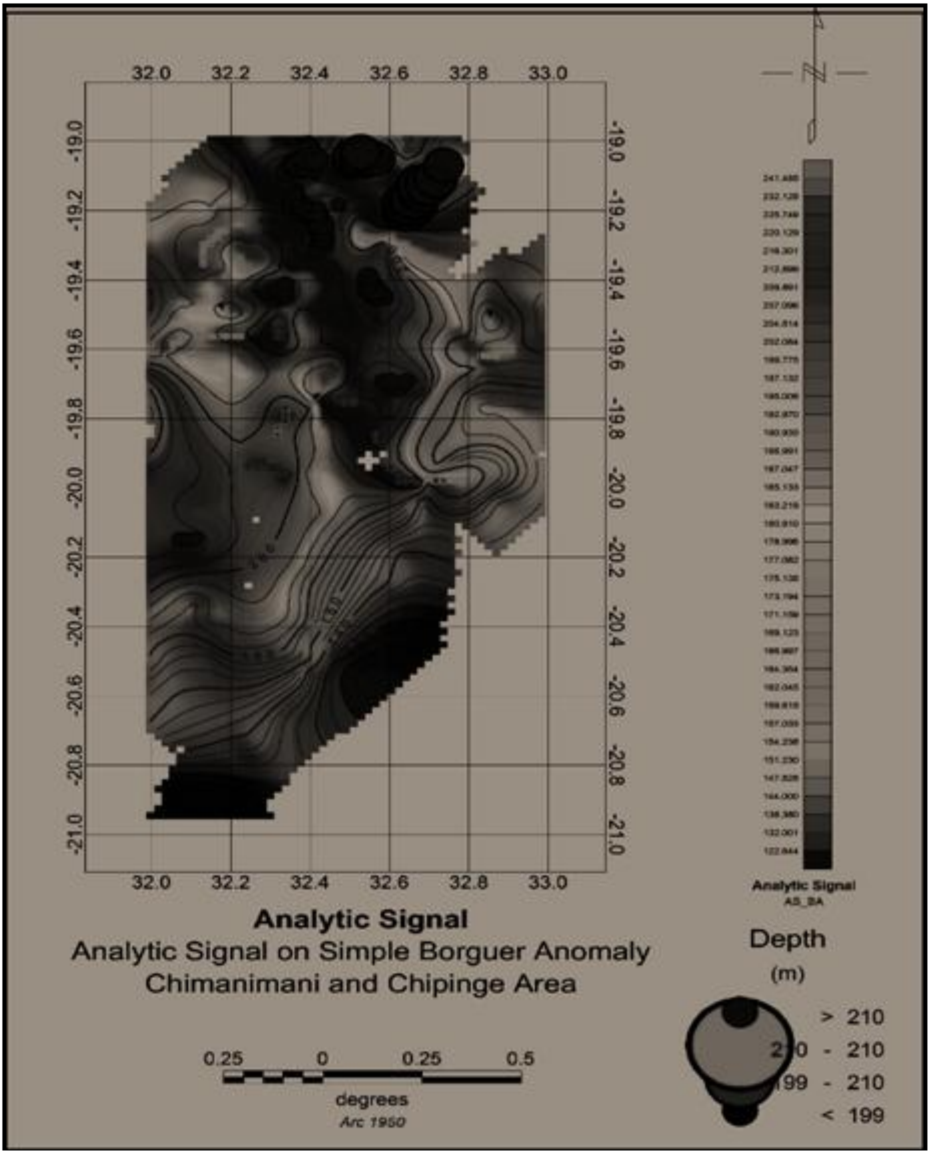


Figure 2: Generalised Derivative (Fast Fourier Transform) and Horizontal Gradient maps of the Chimanimani and Chipinge area.

Depth-to-Source Estimation using 3D Euler Deconvolution was implemented as a semi-automated inverse technique to constrain the spatial coordinates and structural indices (SI) of anomalous causative bodies. The following parameters were used to enhance structures: a gravity structural index (SI) of 0.0 was selected to target faults and contacts, while a 9 x 9 window size was applied to resolve deep regional basement morphology or deep-seated crustal structures.



32.0
32.2
32.4
32.6
32.8
33.0
-19.0
-19.2
-19.4
-19.6
-19.8
-20.0
-20.2
-20.4
-20.6
-20.8
-21.0
Analytic Signal
AS_BA
Analytic Signal
Analytic Signal on Simple Borguer Anomaly
Chimanimani and Chipinge Area
Depth
(m)
> 210
210 - 210
199 - 210
< 199
0.25
0
0.25
0.5
degrees
Arc 1950

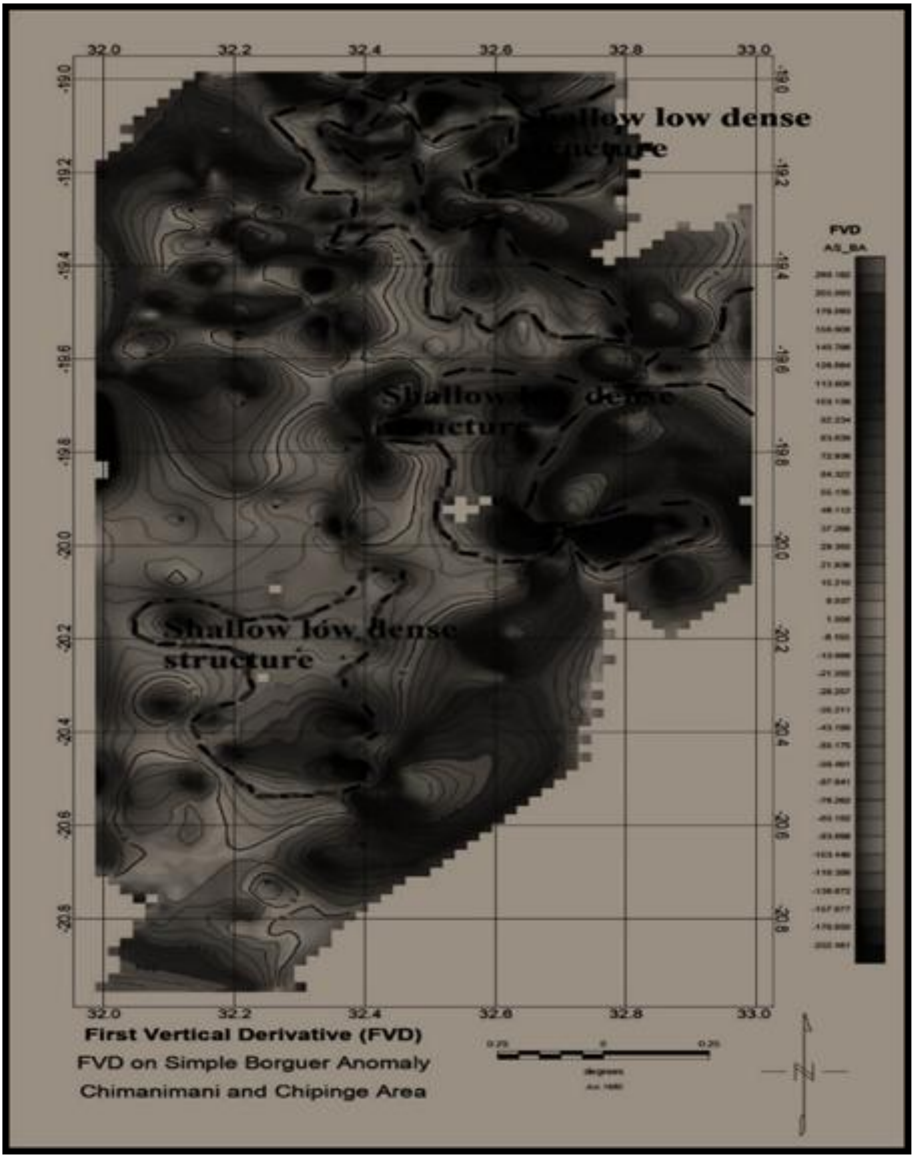


Figure 3: Euler deconvolution on the analytic signal and First Vertical Derivative (FVD) maps.

The First Vertical Derivative acts as a high-pass filter that enhances high-frequency anomalies, thereby accentuating shallow, near-surface geological structures. It is highly sensitive to shallow, low-density structures and is used to precisely delineate the horizontal boundaries of faults or lithological contacts while the Euler Deconvolution uses the spatial gradients of the gravity field (including the vertical derivative) to solve a homogeneity equation. By analysing these gradients, the technique estimates the 3D position (X, Y, and Z depth) of the causative bodies that have been highlighted by the FVD.

The application of FVD to the Simple Bouguer Anomaly to isolate "shallow low-density structures" provided the structural grain or "skeleton" of the area.

Implementation of the 3D Euler Deconvolution was executed as a semi-automated inverse. By using the structural indices (SI) and the gradient data, it constrained the spatial coordinates of the anomalies previously identified in the FVD and Analytic Signal images.

The locations of 'Possible Faults' identified through Automatic Gain Control (AGC) and derivative imaging were mathematically constrained in 3D space using 3D Euler Deconvolution. These Euler depth-to-source solutions reveal the physical depth and subsurface orientation of the faults, directly linking surficial satellite lineaments to deep-seated crustal tectonic activity.

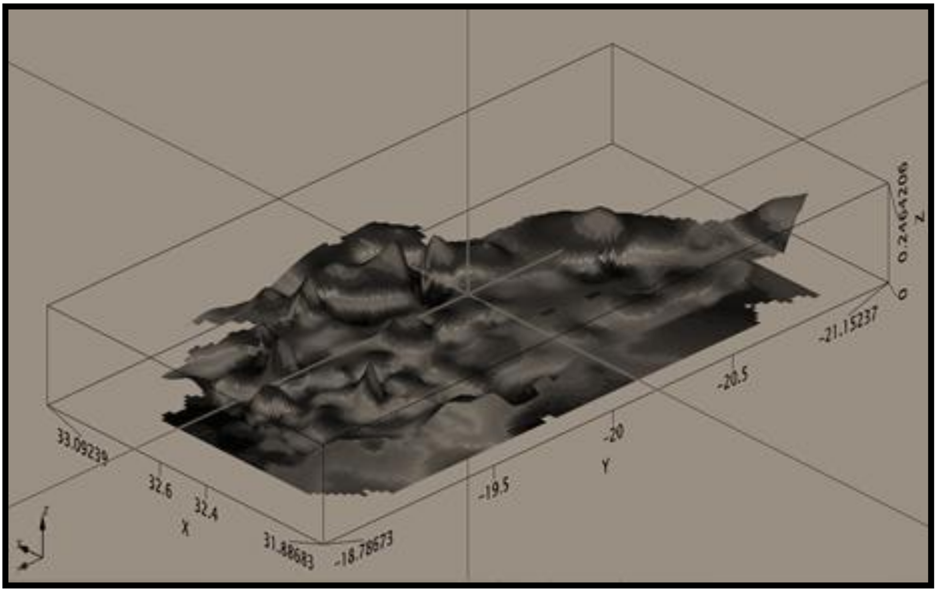


Figure 4: 3D surface plan of the Simple Bouguer Anomaly

Figure 4 image represents the Simple Bouguer Anomaly 3D surface plan for the Chimanimani and Chipinge area. This visualisation is a key output of the geophysical gravity survey used to elucidate subsurface lithostructural configurations.

Gravimetric Manipulation and Feature Extraction

The delineation of subtle lithospheric discontinuities and tectonic fabrics necessitated the application of advanced transformation operators such as Anomalous Field Derivatives. This workflow integrated the calculation of the Simple Bouguer Anomaly and the Analytic Signal (AS), the latter being particularly effective for centering anomalies over their respective sources regardless of remanent magnetisation or latitude.

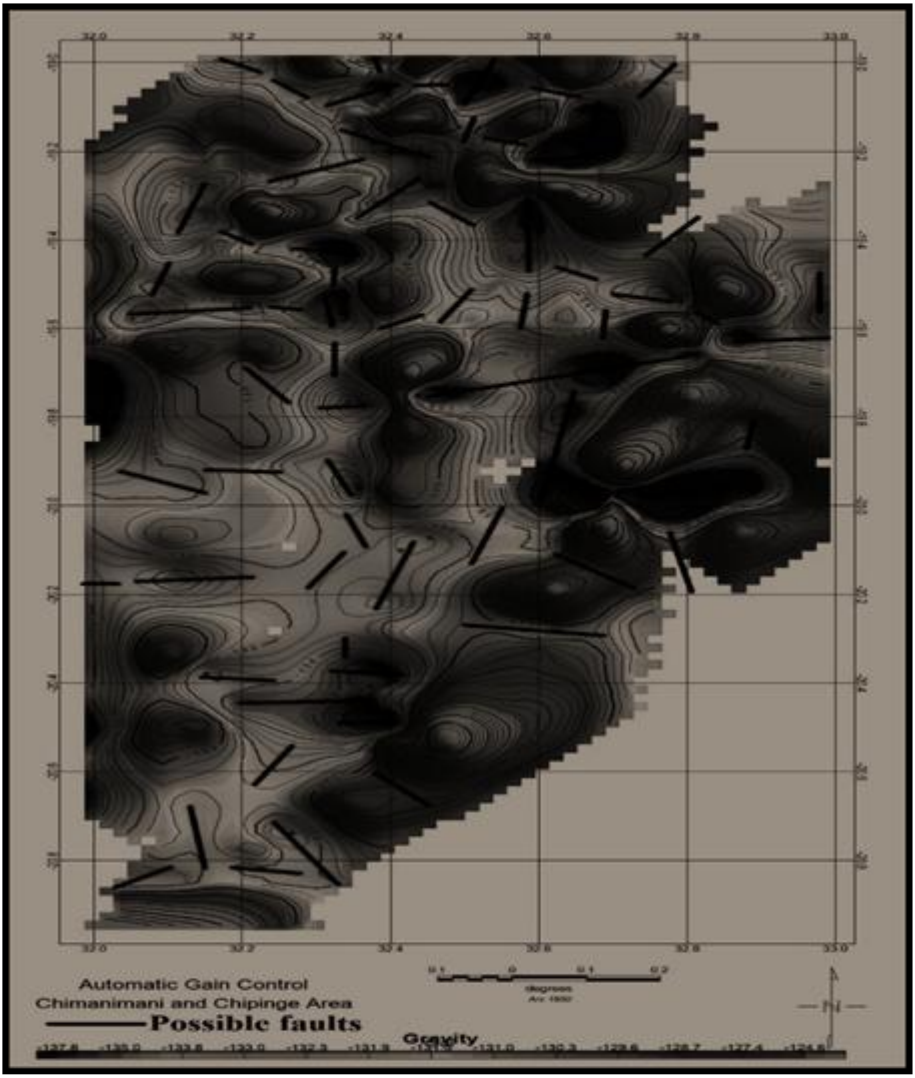


Figure 5: Automatic Gain Control (AGC) mapping with delineated structural lineaments and possible faults.

The application of an Automatic Gain Control (AGC) filter to the gravity data of the Chimanimani and Chipinge regions has successfully equalised signal amplitudes, facilitating the identification of subtle subsurface discontinuities that were previously masked by dominant regional trends. This processing stage plays a critical role in outlining the network of suspected faults, thereby defining the overarching architectural framework of the study area.

Geospatial Data

Data Acquisition and Pre-processing

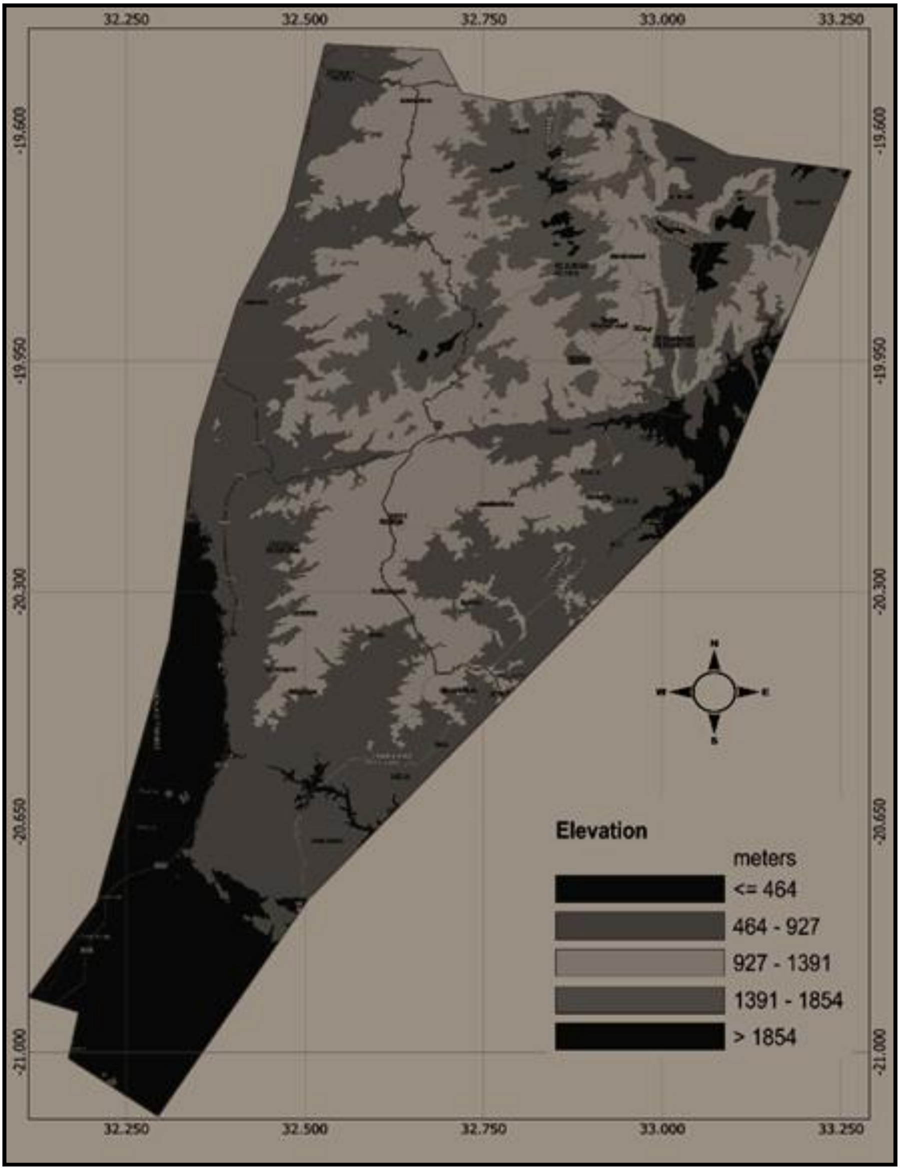
The study utilises Landsat 8 OLI imagery (U.S Geological Survey,2026)' for multispectral analysis and SRTM (Shuttle Radar Topography Mission) DEM for terrain modelling (Darwish & Smith, 2021). The Landsat 8 OLI scenes were selected from the dry season (May–September). This timeframe is critical for South-Eastern Zimbabwe to minimise cloud cover and ensure that the "inaccessible zones" are not obscured by dense seasonal vegetation. Pre-processing involves atmospheric correction (Top of Atmosphere) and topographic normalisation to remove shadows cast by the steep slopes of the Chimanimani mountains.

Image Enhancement & Lineament Extraction

Directional Filtering was done through the application of Sobel or Laplacian filters to the DEM and Landsat Band 8 (Panchromatic) to enhance linear features in specific orientations (N-S, E-W, NE-SW). For Spectral Transformations, Principal Component Analysis (PCA) is used to decorrelate bands, highlighting lithological contacts where seismic activity often originates. Automated Extraction using algorithms (like the LINE module in PCI Geomatica) followed by rigorous manual editing to remove "man-made" lineaments (roads, power lines).

Terrain Analysis

The Terrain Index (TRI) and Slope are calculated from the DEM. High roughness and abrupt slope changes often coincide with active fault scarps or zones of brittle deformation (Hirt et al., 2010)


32.250
32.500
32.750
33.000
33.250
-19.600
-19.950
-20.300
-20.650
-21.000
N
S
W
E
Elevation
meters
<= 464
464 - 927
927 - 1391
1391 - 1854
> 1854

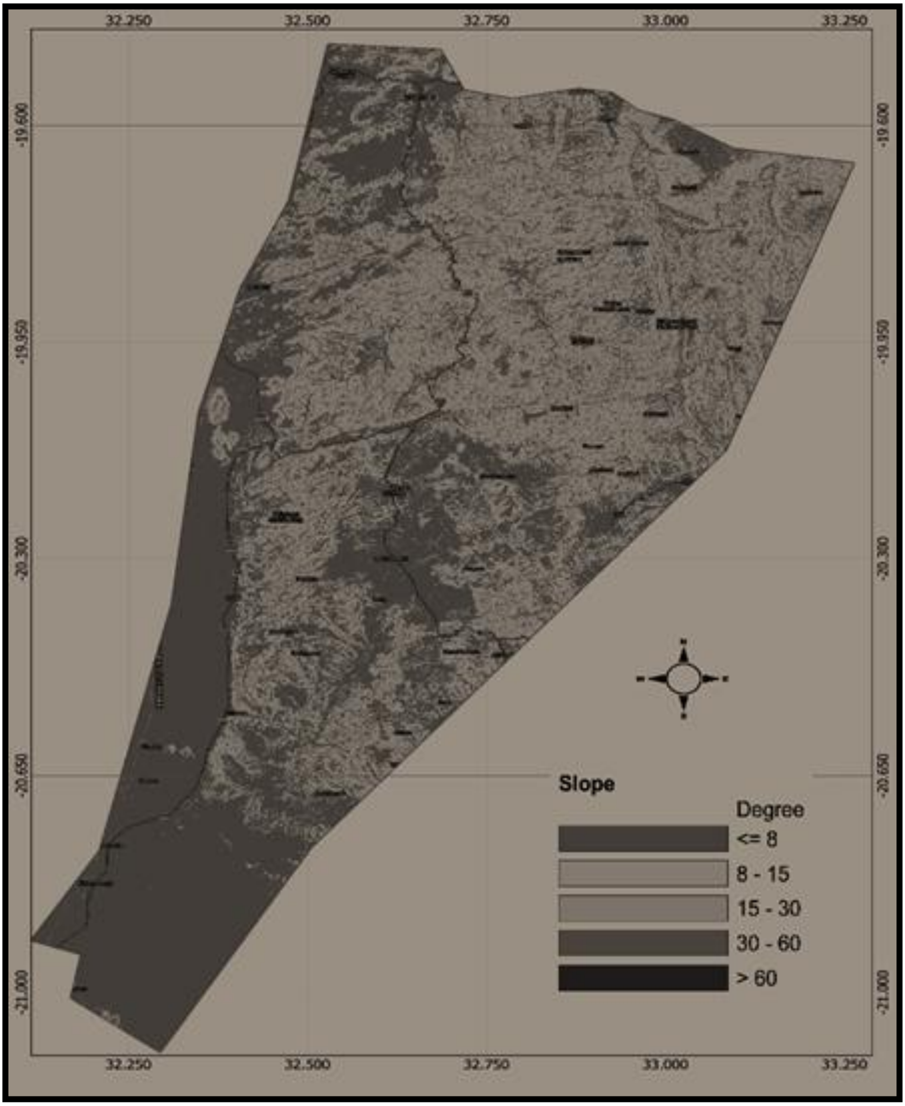


Figure 6: Elevation and slope classifications of the study area. Areas with a slope **> 30°** are classified as high-risk for earth movement, especially where they coincide with high fracture density.

Figure 7: Topographic Roughness Index (TRI)

A TRI value **> 2** is used as the indicator for abrupt topographic variations, which typically represent fault scarps or brittle deformation zones.

GIS Integration and Density Mapping

Extracted lineaments are converted into a Lineament Density Map. Areas of high density (intersections of multiple fracture sets) are interpreted as zones of crustal weakness.

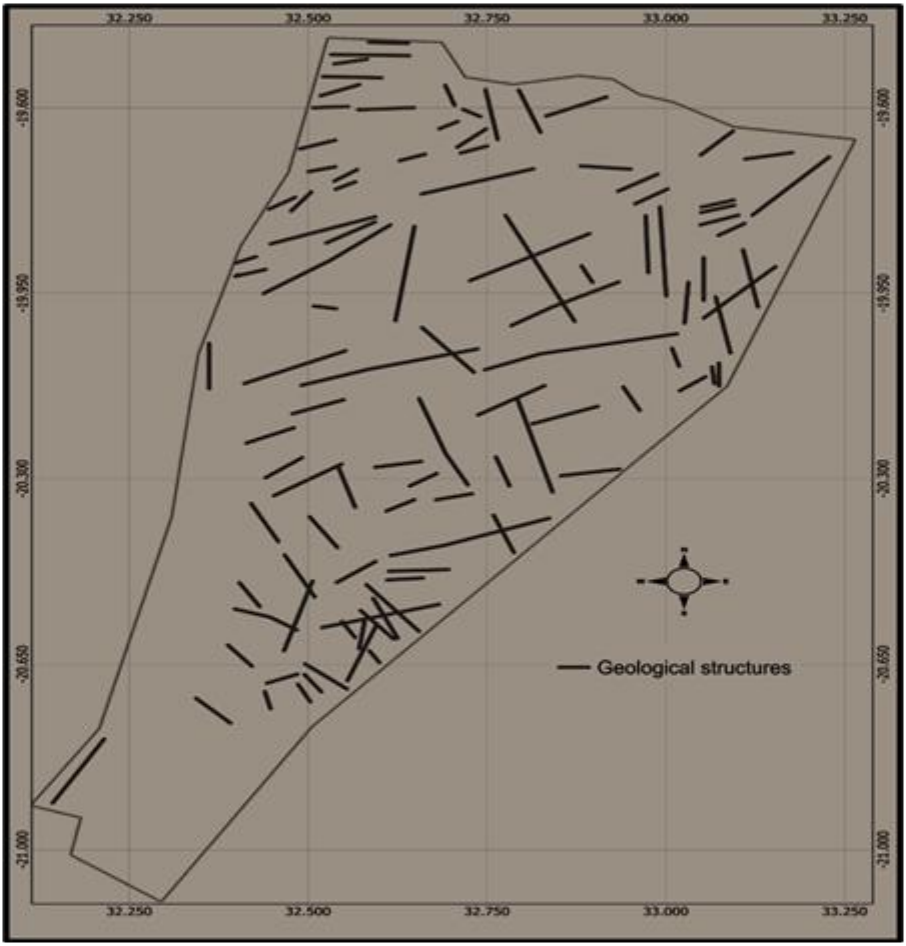


Figure 8: Delineated geological structures

Simplified Flowchart of Operations

The following flowchart outlines the logical progression from raw remote sensing data to the final hazard identification.

Table 1: Simplified Flowchart of Operations

Phase	Action	Output
I. Input	Landsat 8 OLI & SRTM DEM	Raw Geospatial Database
II. Processing	PCA, Band Ratios, & Directional Filtering	Enhanced Structural Images
III. Extraction	Manual & Automated Lineament Tracing	Preliminary Fracture Map
IV. Analysis	Density Calculation & Seismic Correlation	Structural Fabric Model
V. Validation	Fieldwork & In-situ Data Comparison	Final Seismic Structure Map

In the Chimanimani and Chipinge districts, the structural grain is complex due to the influence of the East African Rift System (EARS) and the Mozambique Belt. This geospatial methodology is the most efficient way to map large-scale tectonic features and other geological structures that are otherwise obscured by dense vegetation or inaccessible high-relief topography.

Results and Discussion

Based on the integrated gravity and geospatial analysis of the Chimanimani and Chipinge districts, the techniques revealed a complex network of geological structures and topographic risks that govern the region's stability.

The findings from the integration of gravity data and satellite-derived data are categorised below.

Structural Lineament Analysis

The study utilised Landsat 8 OLI processing, including Principal Component Analysis (PCA) and directional, filtering to identify tectonic features. The integration of Landsat 8 OLI processing and gravity data successfully identified a complex network of geological structures. The analysis identified primary fracture sets trending North-South (N-S) and East-West (E-W). These structures provide evidence of tectonic stress fields influenced by the East African Rift System (EARS) and the Mozambique Belt.

In satellite imagery, these lineaments manifest as distinctive topographic features or tonal variations, serving as the surface expression of underlying 3D underground structures.

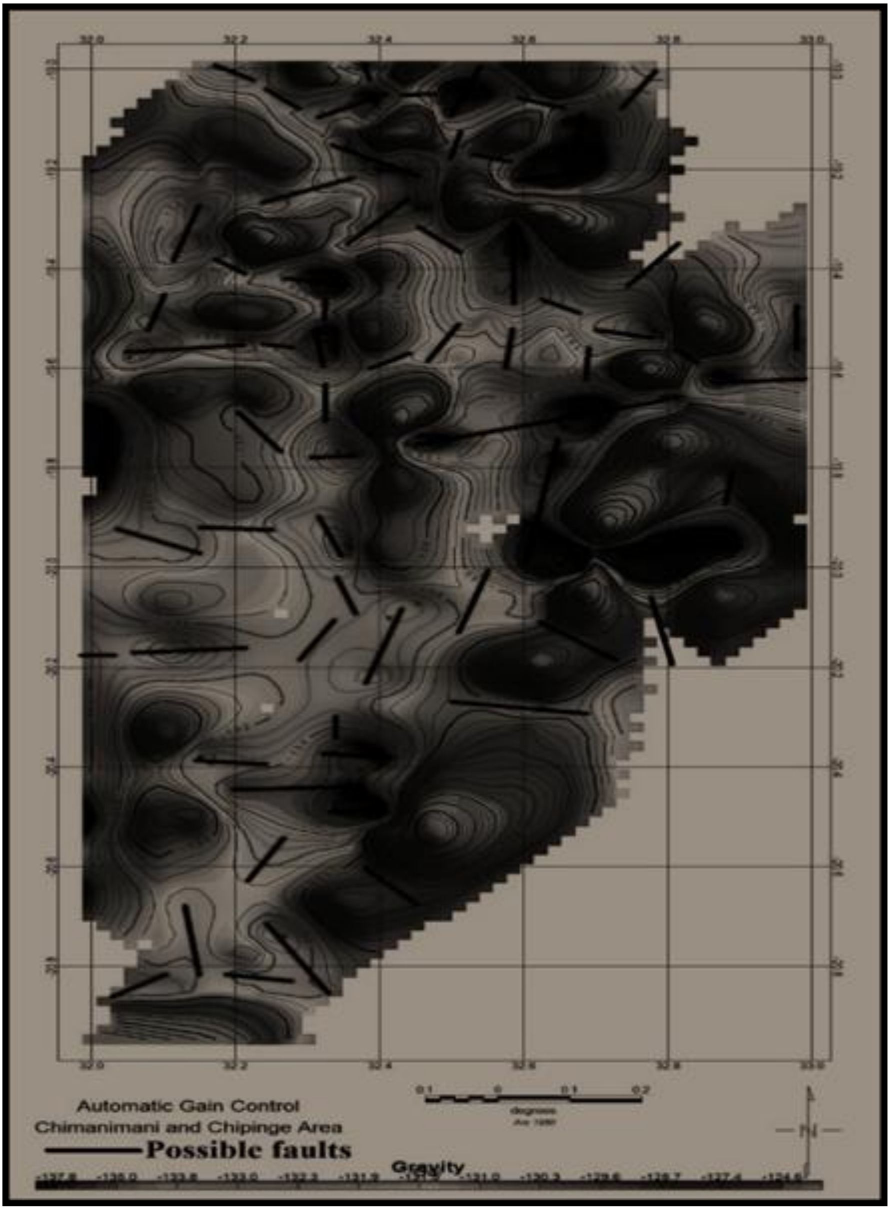

32.0
32.2
32.4
32.6
32.8
33.0
Automatic Gain Control
Chimanimani and Chipinge Area
Possible faults
Gravity
degrees

Figure 9: Automatic Gain Control and the remote sensing structural images

Table 2: Quantitative Structural Analysis and Cross-Validation Summary

Parameter Measure	**Quantitative Metric & Breakdown**	**Geological Implications**
Rose Diagram Structural Orientations	Primary Trend: N-S (340°- 020°) — 55% frequency Secondary Trend: E-W (080° — 100°)-30% frequency Minor Trend: NE-SW (040° -060°) — 15% frequency	Direct manifestation of regional tectonic stress fields governed by the East African Rift System (EARS) and the Mozambique Belt.
Lineament Extraction Statistics	Automated Extraction (LINE Module): 87 lineaments (Cumulative Length: 412.5 km)	Automated processing efficiently captured regional structural grains , while targeted manual editing

	Manual Field/Visual Editing: 55 lineaments (Cumulative Length: 284.3km) Total Unified Dataset: 142 lineaments (696.8km total length)	successfully eliminated anthropogenic errors like roads and power lines.
Lineament Density Mapping Scale	Low Density: < 0.2 lineaments/km^2 Moderate Density: 0.2-0.5 lineaments/km^2 High Density (Hotspots): > 0.5 lineaments/km^2	High-density fracture intersections delineate localised critical zones of crustal weakness prone to active earth movement and seismicity.
Gravity vs. RS Cross-Validation	Coincident Structures: 48 structures mapped simultaneously Spatial Alignment Tolerance: Within a 1-km lateral buffer zone Statistical Correlation Coefficient (R^2): 0.74	Mathematically validates that surface tonal alignments and radar-derived topographic reliefs are direct upward expressions of deep 3D basement faults.

The Automatic Gain Control (AGC) filter effectively equalised amplitudes, revealing an intricate network of "Possible Faults" previously masked by broader regional trends. The Analytic Signal (AS) was particularly effective at centering anomalies over their respective sources, bypassing issues related to remanent magnetisation. The dominant N-S and E-W fracture sets identified in the Chimanimani-Chipinge region provide evidence of the complex tectonic stress fields at the margin of the Zimbabwe Craton. These findings support current investigations into the Belingwe greenstone belt that leverage updated age constraints to clarify greenstone belt development and the regional structural framework of the Zimbabwean basement complex (Hofmann et al. 2024).

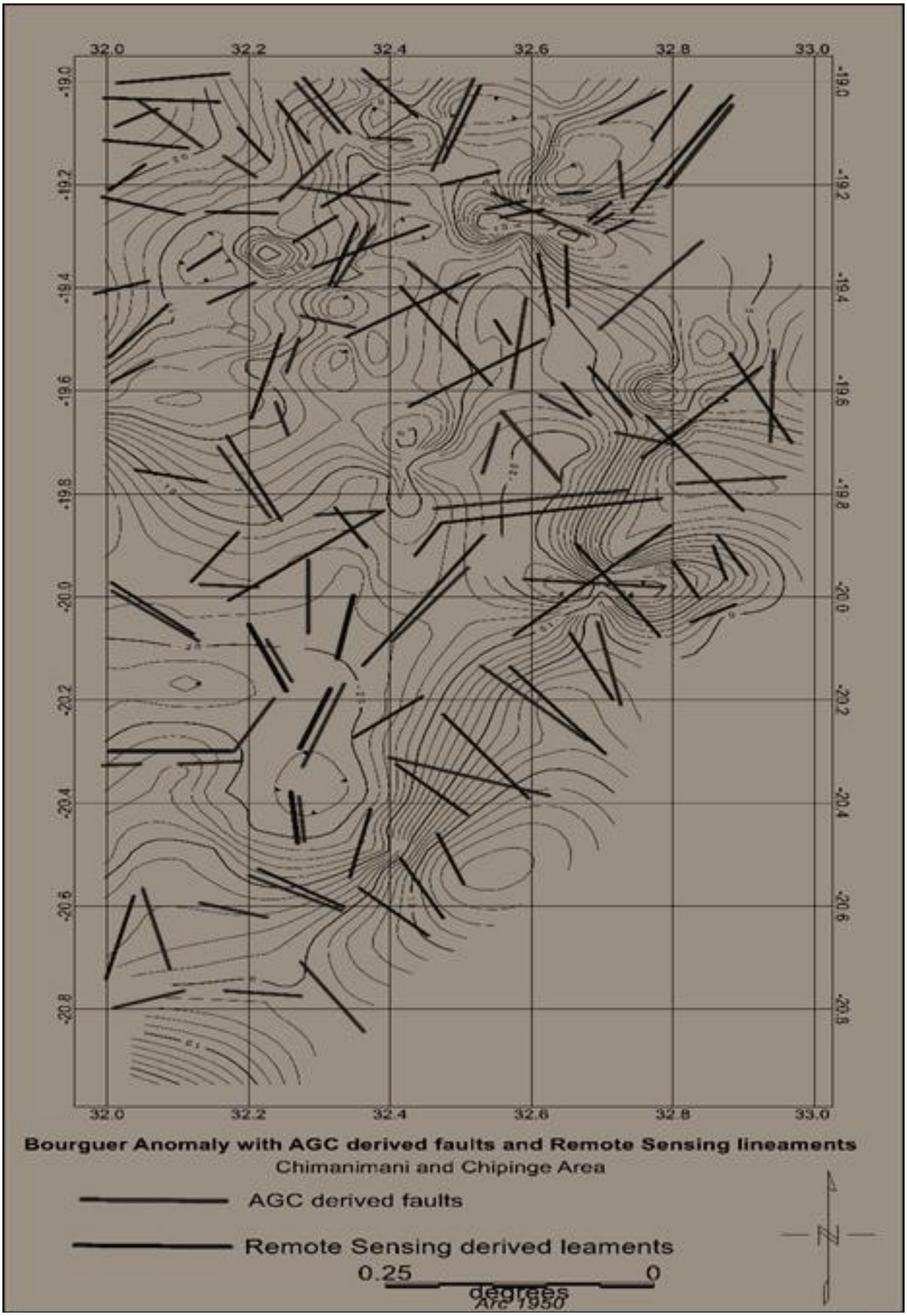


Figure 10: A GIS-integrated map overlaying gravity anomaly contours, AGC-derived possible fault traces, and remotely sensed lineaments

Terrain and Hazard Mapping

Using SRTM Digital Elevation Models (DEM), the research identified specific zones susceptible to earth movement based on topographic markers. Areas with a slope greater than 30° are classified as high-risk zones for earth movement. The identification of high-risk zones using SRTM Digital Elevation Models (DEM) aligns with recent morphometric studies, which demonstrate that DEM resolution and source data significantly impact the accuracy of extracted watershed and terrain parameters. Specifically, the use of 1 arc-second global data in this study ensures that the calculated slope and roughness indices are robust enough for seismic hazard characterisation in high-relief environments (Tesema, 2021).

Topographic Roughness Index (TRI), a TRI value > 2 was used to pinpoint abrupt topographic changes, which represent fault scarps or zones of brittle deformation.

High-density fracture areas, where multiple fracture sets intersect, are interpreted as critical zones of crustal weakness.

Lithological and Geomorphological Findings

Shaded relief maps illustrate a sharp contrast between the flat terrain in the southeastern part of the study area and the undulating, high-relief terrain across the rest of the region. The remote sensing approach successfully mapped "inaccessible zones" where rugged formations previously prevented continuous ground-based data collection.

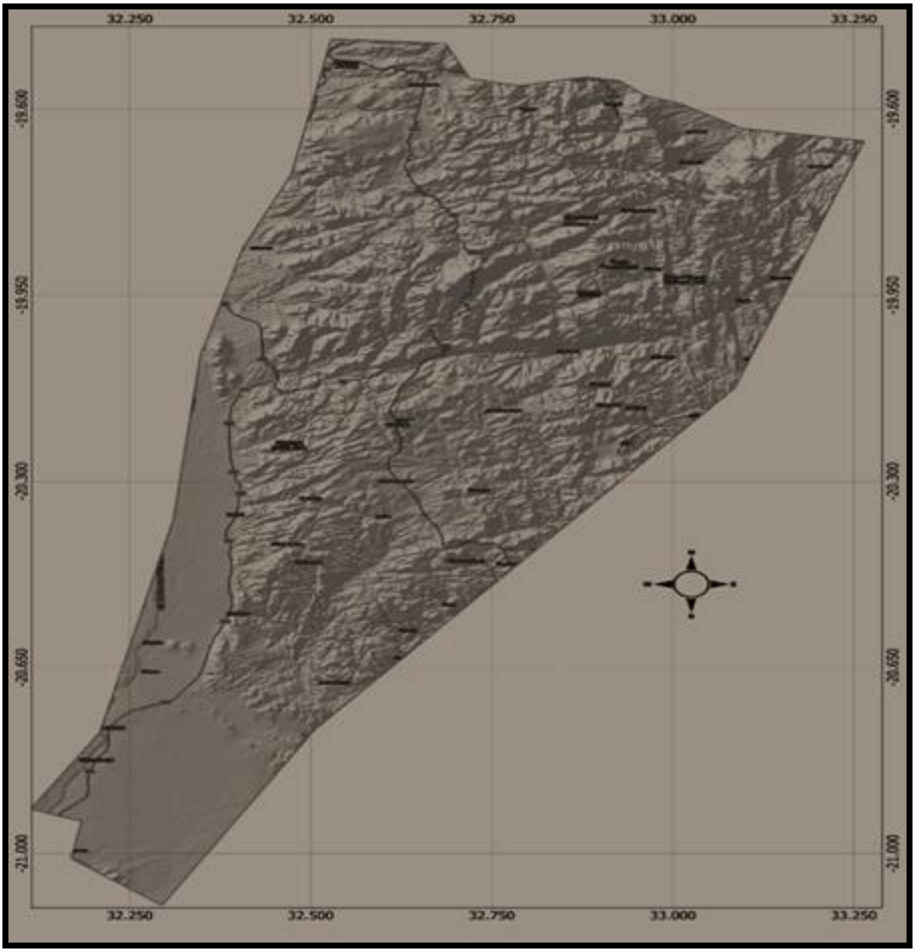


Figure 11: A shaded relief map illustrating the flat terrain in the southeastern part of the area, contrasted with the more undulating terrain across the rest of the region.

Limitations

Reduction in Density Sensitivities

The execution of the Complete Bouguer Anomaly (CBA) relies on a uniform Nettleton reduction density value of 2.75g/cm^3. In a highly heterogeneous Precambrian terrain characterised by dense basaltic lavas, greenstones, epidiorites, and lighter units such as quartz-mica schists or granitic batholiths, assuming a homogeneous density creates localised artificial anomalies and obscures genuine subsurface density gradients.

Spaceborne DEM Grid Constraints

The calculated terrain threshold specifically slopes exceeding 30°and Topographic Roughness Index (TRI) values greater than 2 are highly sensitive to the 1 arc-second (30-meter) resolution of the SRTM DEM. This cell resolution averages minor escarpments, micro-fault scarps, and localised brittle deformation planes, making small-scale landslide or seismic hazard indicators less reliable in high-relief environments.

Euler Resolution and Structural Index

Operating under specific structural constraints, the 3D Euler Deconvolution inversion model utilises a structural index (SI = 0.0) that is tailored to isolate steeply dipping faults and discrete lithological contacts. While resolving regional basement morphology, this setting limits the vertical resolution when encountering shallow, sub-horizontal overthrust sheets, and its accuracy remains bound to the horizontal derivative sampling grid spacing.

Border and Derivative Edge Artefacts

Digital signal processing algorithms, including the Fast Fourier Transform (FFT), Horizontal Gradients, and First Vertical Derivatives (FVD), are highly prone to edge mathematical distortions. Near the geographical boundaries of the survey area, where gravity station profiles terminate abruptly, filter window tapers generate false anomalies or mask genuine terminal lineament structures.

Automated Lineament Extraction Discriminating Limits

The automated LINE module utilised for spectral feature extraction operates strictly on pixel-level linear tonal variances and topographic shade edges. This processing stage fails to differentiate deep tectonic fabrics from superficial structural mimics, such as palaeo-drainage channels, linear weathering scars, or non-tectonic lithological contacts; consequently, extensive manual post-processing is essential to avoid inflating the mapped fracture density network.

Conclusion

The study successfully demonstrates that the combination of gravity surveys and multispectral remote sensing provides a comprehensive understanding of a region's tectonic health, especially in high-relief, inaccessible terrains.

The dominance of N-S and E-W trending fracture sets identified in this study aligns with regional tectonic frameworks, reflecting the structural interaction between the Archean basement complex of the Zimbabwe Craton, the polyphase deformation of the Mozambique Belt, and the propagation of the southernmost extension of the East African Rift System (EARS). While a strong correlation exists between subsurface gravity discontinuities and surface lineaments, localised areas of spatial discordance provide critical scientific insights; these mismatches likely represent blind, deeply buried basement faults that lack surficial topographic or tonal signatures, or conversely, shallow, inactive erosional lineaments without deep-seated crustal density variations. Depth-to-source estimations obtained via 3D Euler deconvolution resolve anomalies that correspond to brittle upper-crustal boundaries, which must be cross-referenced against established regional lithospheric models to distinguish localised basement faults from deep crustal transitions. By utilising empirical fault-length scaling relations on the mapped lineaments, the seismic hazard profile of southeastern Zimbabwe can be quantified; for instance, applying standard empirical equations to the longest continuous fault structures in high-density fracture hotspots (> 0.5 lineaments/km^2) yields a predictive capacity for a maximum expected earthquake magnitude, thereby establishing a formal mathematical foundation for natural hazard mitigation and engineering infrastructure safety protocols in the region.

By integrating density maps with terrain indices, the study showed zones of crustal weakness, specifically where multiple fracture sets intersect. These areas, combined with steep slopes (> 30°) and high topographic roughness (TRI > 2), represent the highest risk for earth movement and seismic activity.

Recommendations

To translate these scientific findings into practical safety and development protocols, the following actions are recommended:

Urban Planning and Infrastructure Development

Civil engineers and urban planners should use the generated seismic structure maps as technical guides. Critical infrastructure, specifically the Rusitu Mission road, Machongwe Growth Point, and the Jopa, area must be assessed for proximity to identified fracture intersections and high-TRI zones to ensure long-term suitability.

Before any major construction in the southeastern districts, site-specific gravity and terrain analysis should be mandatory to detect localised subsurface discontinuities.

Disaster Risk Reduction (DRR)

Government agencies should prioritise the installation of ground-based seismic monitoring stations in the areas identified as "high-density fracture zones".

Policymakers should use these findings to establish community-based disaster management plans, particularly for settlements located on slopes greater than 30°.

Future Scientific Research

The multi-phased geospatial approach (PCA, directional filtering, and terrain roughness) should be adopted as a national standard for mapping other complex Precambrian terrains in Zimbabwe.

Future studies should incorporate 3D gravity inversion modelling to provide even more precise depth-to-source estimates for the "Possible Faults" identified in the AGC filtered images (Hayward & Tschirhart 2023).

Practical and theoretical contributions

The integration and correlation of gravity data and geospatial technology in this study offer significant advancements for both applied hazard management and academic tectonic theory.

Practical Relevance for Policymakers

The findings of this research provide a robust data-driven foundation for regional development and safety protocols in the Chipinge and Chimanimani districts. Disaster risk reduction can be attained or achieved by pinpointing zones of crustal weakness and high lineament density. Policymakers can identify areas most susceptible to earth movements and seismic activity.
Infrastructure Suitability: The research acts as a technical guide for engineers and urban planners to avoid high-risk zones when developing critical infrastructure, such as the Risitu Mission road or Machongwe Growth Point and Jopa area in Chipinge, thereby ensuring infrastructure suitability. The study demonstrates that satellite-based mapping is a reliable, low-cost alternative to traditional field surveys, allowing government agencies to monitor vast, inaccessible terrains with limited financial resources.

Theoretical Contributions

This study enriches the broader scientific understanding of the geological evolution of Southern Africa, including the Southeastern part of Zimbabwe, which covers Chimanimani and Chipinge districts. The research contributes to the structural fabric model of the region by identifying dominant N-S and E-W fracture sets, providing evidence for the tectonic stress fields influenced by the East African Rift System (EARS) and the Mozambique Belt.

Theoretically, the paper validates a multi-phased geospatial approach combining PCA, directional filtering, and terrain roughness as a robust standard for mapping complex Precambrian terrains. By correlating surface lineaments with deep-seated tectonic activity, the study advances the theory of how 3D underground structures are manifested as surface tonal and topographic variations.

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