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GEOLOGICAL LINEAMENT MAPPING THROUGH SEMI-AUTOMATIC EXTRACTION FROM SATELLITE IMAGES OF SIBI AND SURROUNDING AREAS (MALI)

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ABSTRACT

Geological lineament mapping represents an essential step in structural studies, mineral exploration, and natural resource management. However, its implementation remains challenging due to constraints related to field conditions, accessibility of outcrops, vegetation cover, and superficial formations that frequently obscure geological structures. In this context, remote sensing provides an effective alternative by enabling the identification and analysis of tectonic structures based on the spectral characteristics of satellite imagery. This study aims to develop a lineament map of the Sibi region and its surroundings using a semi-automatic extraction method applied to Landsat 7 ETM+ satellite images. The methodology is based on a sequence of digital processing techniques, including principal component analysis, band ratios, directional filtering, threshold-based binarization, mathematical morphology operations, and image algebra processing. These techniques enhanced structural contrasts and enabled the efficient extraction of linear features from satellite images. The results obtained allowed the identification and mapping of 10,058 geological lineaments, revealing a structural organization dominated by the NNE–SSW, NE–SW, and SE–NW directions, with a clear predominance of the NNE–SSW orientation. Validation based on field observations, existing geological data, and previous studies confirmed the reliability of the detected structures. The newly produced lineament map significantly improves the structural understanding of the region and highlights several previously unreported structures. These results demonstrate the relevance of the semi-automatic approach for updating geological maps and optimizing structural mapping activities in tropical environments.

Keywords: remote sensing, geological lineaments, semi-automatic extraction, structural mapping, Sibi.

INTRODUCTION

Geological lineament mapping represents an essential step in structural geology studies, mineral exploration, hydrogeological investigations, and land-use planning. Lineaments correspond to linear or curvilinear discontinuities observable at the Earth's surface, generally reflecting the presence of tectonic structures such as faults, fractures, shear zones, folds, or lithological contacts (Coulibaly, 1996; Scanvic, 1989; Kouamé, 2008). In cratonic domains, particularly within the West African Craton, these structures play a crucial role in controlling the circulation of mineralizing fluids and the localization of metallic deposits, especially gold deposits (Le Mignot, 2014; Lepretre, 2015). Traditionally, lineament identification relies on field observations, aerial photographs, and visual interpretation of geological maps. Although these methods have contributed significantly to improving the understanding of the structural architecture of geological terrains, they present several limitations related to their subjective nature, the time required for their implementation, and the difficulty of simultaneously analyzing large areas (Scanvic, 1989; Caloz and Collet, 2001; Jourda *et al.,* 2006). Furthermore, in highly weathered tropical regions, lateritic cover and the scarcity of rock outcrops further complicate the identification of geological structures using conventional approaches (Biemi, 1981; Kouamé, 2008).

The development of satellite remote sensing has considerably improved the capabilities for detecting and mapping geological structures at different spatial scales. Satellite imagery provides a synoptic view of the Earth's surface and enables the identification of morphological anomalies, topographic alignments, and discontinuities that may correspond to major tectonic structures (Ozer, 1989; Gomiez, 2004; Imessaoudene, 2012). Several studies have demonstrated the effectiveness of Landsat, ASTER, SPOT, and RADARSAT satellite data for fracture network identification and lineament mapping in complex geological environments (Youan Ta *et al.,* 2008; Hammad, 2016; Weerasekera *et al.,* 2014). Photo-interpretation remains one of the most widely used approaches for lineament extraction. However, this method strongly depends on the operator's experience and may produce variable results among different interpreters (Coulibaly, 1996; Kagamé, 2015). To reduce this subjectivity, numerous automatic and semi-automatic methods have been developed based on digital image processing techniques. These approaches rely mainly on directional filtering, morphological transformations, texture analysis, edge detection operators, and linear segment extraction algorithms (Caloz and Collet, 2001; Delahaye, 2016; Moslem Ouled Sghaier, 2017). They allow faster processing and improve the reproducibility of results. However, fully automatic methods often suffer from the drawback of extracting indiscriminately both geological structures and non-relevant anthropogenic or morphological features, such as roads, tracks, field boundaries, or drainage networks. Therefore, a validation and selection phase remains essential to distinguish true tectonic structures from linear features without geological significance (Kouamé, 2009; Hammad, 2016; Constans, 2022). The Sibi area and its surroundings, located in southwestern Mali, belong to the Birimian domain of the West African Craton, which is recognized for its high mineral potential and structural complexity. This region is characterized by intense surface weathering and extensive lateritic cover, which locally conceal bedrock formations. These conditions make conventional structural mapping difficult and justify the use of remote sensing techniques for geological lineament identification

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(Koné, 2022; Feybesse, 2004). In this context, the present study aims to produce a geological lineament map of the Sibi region using a semi-automatic extraction approach based on satellite imagery. The adopted methodology relies on a sequence of digital processing techniques, including directional filtering, threshold-based binarization, mathematical morphology operations, and analysis of derived spectral bands. This approach optimizes the detection of linear structures while reducing the influence of non-geological features. The obtained results will then be validated using existing geological data and field observations in order to assess the relevance of the extracted lineaments and their contribution to improving the understanding of the structural framework of the studied region (Kouamé, 2009; Koné, 2022; Youan Ta *et al.,* 2008).

MATERIALS AND METHODS

Study Area

The Sibi area and its surroundings are located approximately 50 km southwest of Bamako, within the Kati district, Koulikoro Region, Mali. It belongs to the southern margin of the Taoudéni Basin and represents a privileged area for geological structure studies due to its complex lithological and tectonic evolution. This region lies at the transition between the Precambrian basement of the West African Craton and the Neoproterozoic sedimentary formations of the Taoudéni Basin, giving it particular importance for structural and metallogenic investigations (Feybesse, 2004; Le Mignot, 2014; Leprêtre, 2015). From a structural perspective, field observations indicate that the main geological structures exhibit a dominant NNE–SSW orientation, reflecting the influence of several successive tectonic phases. According to Boudjema (1987), Haddoum *et al., (*2001), and Guiraud *et al.,* (2005), the tectonic evolution of the Taoudéni Basin is closely related to the geodynamic processes that affected the West African Craton during the Proterozoic. The collision between the West African Craton and the Pan-African domains located to the north resulted in the segmentation of the African plate by major tectonic structures that controlled the organization and evolution of the Taoudéni Basin. These tectonic structures mainly display submeridional orientations in the central and western parts of the basin, while NE–SW directions are locally observed. They played a major role in controlling sedimentation processes and the regional litho-tectonic evolution (Boudjema, 1987; Guiraud *et al.,* 2005). The geological history of the region reflects a polyphase evolution characterized by several tectono-sedimentary episodes. The first stage corresponds to the emplacement of the Proterozoic basement and associated granitic intrusions. This phase was followed by a major erosion period that resulted in partial stripping of the superficial formations. Subsequently, subsidence processes promoted the development of a large sedimentary depression, progressively invaded by marine waters and filled by detrital and carbonate deposits attributed to the Infracambrian period. These deposits currently represent the main sedimentary cover exposed in the Sibi region (Fabre, 2005; Leprêtre, 2015). From a lithological perspective, the area is characterized by the presence of several generations of granitoids. Field observations allow the distinction of three main facies: a grey granite with a coarse-grained texture, rich in feldspars and plagioclases; a pink granite containing a high proportion of orthoclase and showing significant thickness variations; and a microgranite that commonly occupies fractures, joints, and faults affecting the surrounding formations. This petrographic diversity reflects the complexity of the magmatic events that affected the region during the Proterozoic. The Precambrian formations generally exhibit a slight dip toward the north to northwest, indicating regional tilting of the southern compartments of the basin. This structural arrangement is locally expressed by gravitational movements and deformation affecting the sedimentary sequences. A progressive reduction in the thickness of the earliest Infracambrian formations is also observed in the Sibi area, with some units thinning and disappearing locally. This phenomenon may result from differential vertical movements related to the reactivation of inherited deep-seated structures (Leprêtre, 2015). Furthermore, small synsedimentary faults affecting Neoproterozoic sandstones are observed on the southern flank of the region. These structures indicate tectonic activity contemporaneous with sediment deposition and illustrate the dynamic evolution of the basin during its infilling. The Taoudéni Basin, considered one of the largest intracratonic sedimentary basins in West Africa, developed during the second half of the Proterozoic and experienced a long subsidence phase that continued until the end of the Neoproterozoic (Fabre, 2005; Leprêtre, 2015). Subsequent Pan-African tectonic events profoundly reshaped the region. Several authors, including Donzeau *et al.,* (1981), Haddoum *et al.,* (2001), Guiraud *et al.,* (2005), and Leprêtre (2015), emphasize that compressional deformation associated with the Pan-African orogeny generated numerous structures within the sedimentary cover of the Taoudéni Basin. These deformations are mainly concentrated along reactivated suture zones and are expressed by the development of folds, faults, and fractures affecting the entire basin. According to Leprêtre (2015), the regional geodynamic evolution occurred within a transtensional context followed by transgressive episodes. This dynamic favored the reactivation of inherited structures and the development of new tectonic discontinuities. Hercynian events, which affected North Africa, Western Europe, and the western margin of the West African Craton, also contributed to the final structural configuration of the basin. Several authors consider that it was during this period that the Man Ridge acquired its present-day anticlinal architecture, bounded by the synclinal basins of Taoudéni, Tindouf, and Reggane (Boudjema, 1987; Guiraud *et al.,* 2005; Leprêtre, 2015). Therefore, the Sibi region represents a particularly favorable geological setting for studying inherited and reactivated tectonic structures. The presence of fracture networks, faults, and lithological contacts resulting from multiple tectonic episodes fully justifies the use of remote sensing techniques and semi-automatic lineament extraction methods to improve the understanding of the structural organization of this part of the Taoudéni Basin and its geological potential.

Study Implementation and Research Team Organization

This study was conducted over an eleven-month period, from November 2024 to September 2025. The research program was structured around two main phases: the processing and analysis of satellite imagery on the one hand, and the field validation of remote sensing results on the other hand. The geological structure mapping was carried out through an integrated approach combining remote sensing, field observations, and Geographic Information Systems (GIS). The first phase involved defining the study area, collecting available datasets, and processing satellite images for the semi-automatic extraction of geological lineaments. This step enabled the identification of major linear structures potentially corresponding to faults, fractures, or shear zones. The second phase focused on validating the remote sensing results through field surveys. These missions made it possible to verify the geological nature of the identified lineaments, perform detailed structural observations, measure structural orientations and dips, and collect representative samples of the different lithological formations. The field data were subsequently compared with the results obtained from digital image processing in order to improve the reliability of the structural interpretation. At the end of these investigations, all datasets were integrated into a GIS environment to produce the final structural map of the study area. This stage also allowed the overlay and crossanalysis of geological, geomorphological, and remote sensing information, leading to the preparation of the present scientific article. The study was conducted by a multidisciplinary research team bringing together specialists from several complementary fields. Field geologists were responsible for collecting geological data through direct observations of outcrops, description of tectonic structures, measurement of structural orientations, and sampling of representative rock units. Petrographic and structural analyses were carried out in the laboratory to characterize the rock formations and improve the understanding of their geological evolution. At the same time, remote sensing and Geographic Information System (GIS) specialists were responsible for satellite image processing, lineament extraction, integration of field data, and management of spatial databases. They also carried out cartographic modeling, production of thematic maps, and generation of the final geological map using specialized software. This multidisciplinary approach enabled the production of a coherent and reliable structural representation of the Sibi region and its surroundings.

Data and Materials Used

The main objective of this study is to develop a geological lineament map of the Sibi region and its surroundings through the analysis of Landsat satellite imagery. The choice of these data is based on their ability to provide spatial and spectral information suitable for regional geological mapping and the identification of linear structures. Several studies have demonstrated the effectiveness of Landsat imagery for highlighting lithological contrasts and fracture networks at medium and small scales (Kouamé, 2009; Weerasekera *et al.,* 2014). To ensure the spatial consistency of the datasets used, an image-to-map geometric correction was applied to the satellite images. This procedure ensured accurate registration of remote sensing data with existing cartographic documents and facilitated their integration into a GIS environment. The main geoscientific datasets used in this study include geological maps and technical documents produced at a scale of 1:200,000 covering the Bamako region and its surroundings (Feybesse, 2004). These reference datasets were used for the validation of extracted structures and for the geological interpretation of the obtained results. The analysis was based on Landsat satellite imagery acquired on March 10, 2024, combining multispectral and panchromatic data. The datasets used include a panchromatic band (TM8) with a spatial resolution of 15 m, six multispectral bands (TM1, TM2, TM3, TM4, TM5, and TM7) with a spatial resolution of 30 m, and a thermal band (TM6) with a resolution of 120 m. This combination of spectral bands improves the discrimination of lithological units and enhances the detection of geological linear structures. The adopted methodology is based on the extraction, interpretation, and analysis of information contained in satellite imagery. Digital image processing techniques were applied to highlight geological discontinuities, morphostructural alignments, and fracture networks potentially corresponding to tectonic lineaments. The obtained results were subsequently compared with existing geological data and field observations in order to assess their reliability. Several specialized software packages were used for the different processing and analysis steps. ENVI 5.3 was used for satellite image preprocessing and processing, including geometric corrections, false-color composite generation, and directional filtering. SPOT 2003 was used for specific data processing and visualization operations. Statistical analysis of structural orientations was performed using ROSE.NET, while ArcGIS was used for data integration, spatial database management, and the production of final thematic maps. The combination of these tools enabled reliable lineament extraction and the production of a coherent cartographic representation of the structural organization of the Sibi region.

Methods and Validation

Methods for Identification and Extraction of Geological Lineaments

The identification of geological lineaments was carried out using an approach combining satellite image preprocessing and semi-automatic extraction of linear structures. This methodology aims to improve the quality of geological information contained in Landsat imagery and facilitate the detection of structural discontinuities. Digital imagery provides greater processing capabilities compared with analog data, allowing significant improvement in the quality of extracted geological information (Caloz and Collet, 2001). Several enhancement techniques were applied to emphasize lithological and structural contrasts. The main processing methods included color composite generation, Principal Component Analysis (PCA), selective principal component analysis, and spectral band ratios (Cortes *et al.,* 2003; Ricchetti and Palombella, 2005; Sarup *et al.,* 2006; Kouamé, 2008; Constans, 2022). Principal Component Analysis (PCA) was applied to reduce redundancy in Landsat multispectral data by generating new synthetic images. The first three principal components contain more than 90% of the total variance and effectively highlight lithological and structural contrasts within the study area (Constans, 2022). The spectral ratios ETM+3/ETM+4, ETM+4/ETM+5, and ETM+2/ETM+7 were calculated to minimize topographic shading effects and enhance spectral differences between geological formations (Weerasekera *et al.,* 2014). Directional filtering was then applied to enhance linear structures oriented along different directions. These filters act as artificial illumination systems, emphasizing geological discontinuities and improving the visual perception of lineaments (Moore, 1986; Kouamé, 2009). The processing was performed according to the following directions: North–South, East–West, Northeast–Southwest, and Northwest–Southeast. The filter sizes were adapted to the dimensions of the targeted structures. A 7 × 7 matrix was used for the detection of major lineaments, whereas a 3 × 3 matrix was applied to highlight smaller structures. The filters were applied to the ETM+3, ETM+5, and ETM+7 bands, as well as to the derived channels ETM+4/ETM+3, ETM+7/ETM+4, and the first principal component (PCA1). The ETM+7 band proved particularly effective for identifying tectonic structures (Kouamé, 2009; Constans, 2022). Lineament extraction was performed through a sequence of digital processing operations, including binarization, mathematical morphology, image fusion, and removal of non-geological structures. Threshold-based binarization was applied to filtered images to transform detected contours into binary images. The optimal threshold value was determined through interactive analysis of frequency histograms in order to achieve a balance between structural continuity and noise reduction. The binary images were subsequently processed using several mathematical morphology operations. Erosion was used to refine contours, whereas dilation helped reconnect interrupted segments. Opening and closing operations were applied respectively to remove unwanted objects and fill discontinuities within the extracted contours. These processes resulted in images displaying sharper and more continuous linear structures. All lineaments detected from the different processed images were then merged using the Band Math function to generate an omnidirectional image integrating all identified structural orientations. Finally, non-geological structures were removed using a supervised classification approach based on the Support Vector Machine (SVM) algorithm (Kouamé, 2009). Altered superficial formations were identified, vectorized, and used to generate a mask allowing the automatic exclusion of undesirable linear features. This procedure improved extraction accuracy while reducing manual intervention.

Validation of Extracted Lineaments

Validation of the identified lineaments represents an essential step for assessing the reliability of the obtained results. Initially, the extracted lineaments were integrated into the ArcGIS GIS environment and superimposed with existing geoscientific datasets, particularly the reference geological maps produced by Feybesse (2004). This comparison allowed the evaluation of the spatial consistency between the detected structures and the major faults, fractures, and lithological contacts already mapped. Subsequently, a field survey was conducted in the Sibi region to directly verify the geological nature of the structures identified through remote sensing. Field observations, structural measurements, and outcrop examinations confirmed the presence of numerous lineaments corresponding to major tectonic features documented in existing geological references. The strong agreement observed between remote sensing results, available geological data, and field observations demonstrates the relevance and effectiveness of the adopted approach for the semi-automatic mapping of geological lineaments in the Sibi region and its surroundings.

RESULTS

Results of Semi-Automatic Lineament Extraction

The application of the semi-automatic extraction method enabled the rapid and objective identification of the main geological lineaments in the Sibi area and its surroundings. Compared with conventional photo-interpretation methods, this approach offers the advantage of reducing operator subjectivity while improving the efficiency of the structural mapping process. However, the processing phase required several correction and optimization steps to minimize the influence of constraints related to field conditions, superficial cover, and topographic effects. One of the most challenging steps involved determining the most appropriate binarization thresholds and designing masks capable of eliminating non-geological linear features that could be confused with tectonic structures. The originality of the adopted approach lies in the combination of different filtered and threshold images through numerical addition. This procedure made it possible to integrate, into a single image, the lineaments detected along all analyzed directions, thereby providing an omnidirectional structural representation of the study area. Furthermore, numerous segments associated with topographic ridges and the boundaries of sandstone formations were removed through the application of a specific mask developed from the mapping of altered sandstone units. This operation significantly improved the quality of the final image by reducing noise and eliminating false lineaments.

Validation of the Obtained Results

Validation of the extracted lineaments was carried out through comparison with existing geoscientific data, particularly reference geological maps, as well as through field observations conducted throughout the study area. The obtained results show strong consistency with tectonic structures previously recognized by earlier geological studies. The final structural map highlights almost all major tectonic features identified in the region, both at the surface and at depth. The dominant orientations observed, particularly the NW–SE and NNE–SSW trends, correspond to the main tectonic directions known in the Sibi area and its surroundings. In the southern part of the study area, several lineaments extracted from satellite imagery coincide with structures previously described in earlier studies conducted in Sibi (Koné, 2022). These correlations confirm the reliability of the applied method and the relevance of the processing techniques used. Furthermore, several newly identified lineaments extracted from satellite images were subjected to field verification. Field observations confirmed their existence and geological significance, demonstrating the ability of the semi-automatic approach to reveal structures that had not been clearly mapped previously.

Overall, the results obtained demonstrate that the adopted methodology represents an effective tool for regional structural mapping. It not only allows accurate reproduction of already known geological structures but also enables the identification of new lineaments that may contribute to improving the understanding of the tectonic organization of the Sibi region.

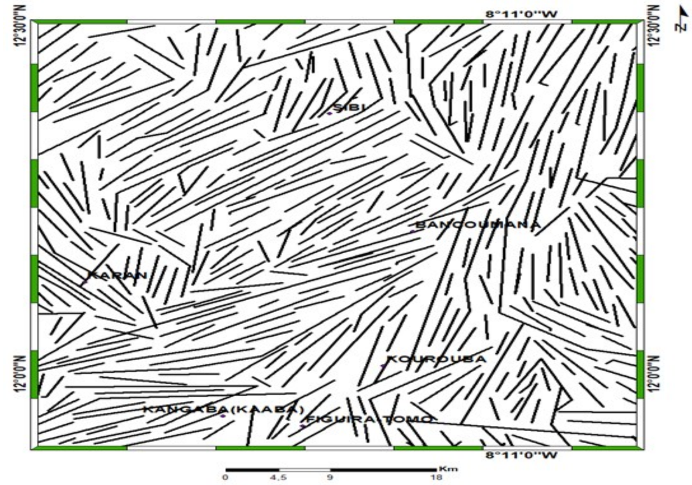

Figure 1: Lineaments Detected by Semi-Automatic Extraction in Sibi and Surrounding Areas

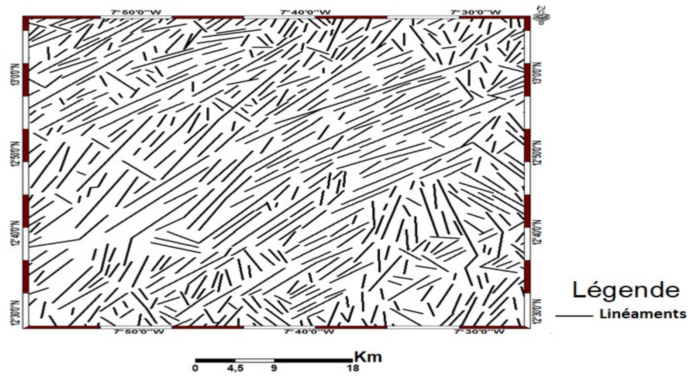

Figure 2: Semi-Automatic Extraction of Lineaments in Bamako and Surrounding Areas (Koné, 2022)

Statistical Analysis of the Extracted Lineament Networks

The application of the semi-automatic extraction method enabled the identification of a particularly dense network of linear structures in the Sibi region and its surroundings. A total of 10058 geological lineaments were mapped from satellite imagery. Their lengths range from 0.5 km to 130.5 km, with an estimated average length of 5.53 km. The cumulative length of all extracted lineaments reaches approximately 61,151 km, reflecting the significant degree of fracturing affecting the study area. The longest identified lineament reaches approximately 130.4 km in length. It crosses the study area diagonally following a NNE–SSW orientation, passing notably through the Karan sector. Except for this major structure, the majority of identified lineaments display lengths below 80 km. The superposition of the different maps generated from directional filtering processes allowed the production of a synthetic map integrating all detected structures. This synthesis map represents unique linear segments resulting from the merging of information extracted along all filtering directions. It therefore provides a global representation of the structural organization of the region and includes the entire set of 10058 mapped lineaments.

Directional Distribution of Lineaments

The statistical analysis of lineament orientations was performed using a rose diagram generated with the ROSE.NET software. The results show that lineaments are distributed across all directions between 0° and 180°, reflecting the complexity of the structural network within the study area. However, some directional families are clearly more represented than others. The dominant orientations correspond to the following directions:

- NNE–SSW (N20°–30° and N30°–40°),
- NE–SW (N40°–50° and N50°–60°),
- NW–SE (N120°–130° and N130°–140°),
- SSE–NNW (N140°–150° and N150°–160°).

Among these structural families, two major fracture directions are particularly significant: the N40°–50° direction (NE–SW) and the N130°–140° direction (NW–SE), which represent the dominant orientations of the regional lineament network. In addition to these main directions, several secondary orientations are observed, including N20°–30°, N30°–40°, N50°–60°, N120°–130°, N140°–150°, and N150°–160°. These orientations indicate the occurrence of multiple tectonic phases that contributed to the structural evolution of the region. Other directions, including N0°–10°, N10°–20°, N60°–70°, N70°–80°, N80°–90°, N90°–100°, N100°–110°, N110°–120°, N160°–170°, and N170°–180°, exhibit relatively low frequencies and represent secondary or accessory orientations within the regional structural network.

Relative Importance of Structural Families

Frequency analysis reveals a clear predominance of NNE–SSW-oriented structures, which account for approximately 70% of all mapped lineaments. This orientation corresponds to the dominant direction of regional foliation and reflects the influence of major tectonic events that affected the region. The NE–SW family represents approximately 25% of the observed frequencies. It is interpreted as the main regional fracturing direction and plays an important role in organizing the tectonic network. The NW–SE-oriented structures account for approximately 10% of the identified lineaments. This family is generally associated with major regional strike-slip faults and late tectonic reactivation processes.

The remaining orientations occur sporadically and are poorly represented within the overall structural network.

Spatial Distribution of Fracturing

The analysis of lineament density highlights a heterogeneous distribution of structures within the study area. The highest concentrations of lineaments are observed in the central and southern parts of the map, where the NNE–SSW orientation predominates. These areas correspond to zones that have been most strongly affected by regional tectonic events. In contrast, the northwestern and southeastern parts of the study area exhibit lower structural density, reflecting either a lower intensity of fracturing or partial masking of structures by superficial formations.

Geological Significance of Structural Directions

The main orientations identified in this study correspond to tectonic directions already recognized in southwestern Mali, particularly within the Birimian formations of the Bamako region (Koné, 2022). The NNE–SSW direction represents the dominant structural orientation and corresponds to the regional foliation observed within the metamorphic and volcano-sedimentary formations of the region. The NE–SW direction is associated with the main regional fracture and shear network. It largely controls the structural organization of the basement and plays a significant role in the circulation of hydrothermal fluids. The NW–SE direction is interpreted as a family of major strike-slip faults related to the different deformation phases that affected the West African Craton. These three structural families are also visible on satellite imagery and correspond to the main directions observed on geological maps of southwestern Mali. They reflect the influence of major tectonic events that shaped the geodynamic evolution of the region and highlight the structural complexity of the Birimian basement of Sibi and its surroundings.

DISCUSSION

Interpretation of Results and Comparison with Previous Studies

The lineament map of Sibi and its surroundings was produced from a series of processing techniques applied to Landsat satellite imagery, combined with semi-automatic extraction procedures and field validation. The obtained results highlight three main structural families oriented NNE–SSW, NE–SW, and NW–SE, representing approximately 70%, 25%, and 10% of the observed frequencies, respectively. These orientations are consistent with the known structural framework of southwestern Mali and confirm the results obtained by Koné (2022) in the Birimian formations of Bamako and its surroundings. The dominant directions identified in this study correspond particularly to the regional orientations ranging between N40°–80° and N130°–140°, recognized as the main tectonic directions affecting the Birimian terrains of the West African Craton. The comparison between the directional rose diagram of extracted lineaments and that established from field measurements of micro fractures shows a strong agreement. The NNE–SSW, NE–SW, NW–SE, and E–W orientations observed in outcrops are also identified in the remote sensing results. This correspondence confirms the reliability of the applied methodology and demonstrates that rose diagrams are relevant tools for validating lineament maps. Furthermore, the mapped lineaments reflect the organization of regional fracturing and provide important information on the tectonic architecture of the subsurface. These structures play a major role in fluid circulation, mineralization control, and the geodynamic evolution of the Sibi region.

Contributions and Limitations of the Applied Approach

The approach based on semi-automatic lineament extraction presents several advantages compared with conventional photo-interpretation methods. It enables rapid, reproducible, and relatively objective processing of satellite data while providing extensive spatial coverage of the study area. The combination of directional filtering, mathematical morphology operations, and classification techniques significantly improved the detection of major geological structures. However, despite the good performance of this methodology, several limitations must be considered when interpreting the results. Indeed, lineaments extracted from satellite imagery do not always correspond to actual geological structures. Some linear features may be related to topographic, geomorphological, or anthropogenic factors and may be incorrectly interpreted as fractures or faults. The quality of the results also depends on the spatial and spectral resolution of the satellite images used. Some short-extension fractures or structures masked by vegetation, superficial formations, or weathering products may remain undetected. Conversely, certain lithological or morphological contrasts may be mistakenly interpreted as tectonic structures. Field validation also represents a challenging step. During field campaigns conducted in the study area, several fractures identified on satellite imagery were not directly observable in outcrops. This situation is mainly explained by the significant lateritic cover, locally dense vegetation, erosion processes, and recent deposits that conceal fresh bedrock exposures. Accessibility to certain areas also represents an important constraint. The condition of access tracks, local topography, and the advanced weathering of geological formations sometimes limit direct observations and the acquisition of detailed structural measurements. Furthermore, accurately determining the true length of fractures remains difficult when outcrops are discontinuous or partially covered. In tropical environments such as southwestern Mali, these difficulties are intensified by the considerable thickness of weathering mantles that frequently cover geological formations and reduce the visibility of tectonic structures.

Limitations of the Study and Future Perspectives

The present study involves several limitations that may influence the accuracy of the obtained results. The first limitation concerns the working scale and the spatial resolution of the satellite data used. Some small-scale structures or those with weak morphological expression may not be detected; leading to a local underestimation of fracture density. The second limitation is related to the lack of detailed and recent geological maps covering the entire study area. Validation efforts were mainly based on existing geological maps, field observations, and available bibliographic data. The third limitation concerns the significant superficial cover observed in several sectors of Sibi. Lateritic formations, alluvial deposits, and weathering products frequently conceal rock outcrops and complicate the direct verification of structures detected through remote sensing. Finally, lineament interpretation partly relies on extrapolation between available observation points. This approach may introduce a degree of uncertainty into the final representation of the structural network. Despite these constraints, the obtained results demonstrate that semi-automatic extraction applied to satellite imagery represents an effective tool for regional structural mapping. Further investigations integrating very high-resolution satellite imagery, geophysical data, high-precision digital elevation models, and detailed geological observations would allow a more comprehensive characterization of fracture networks and a better understanding of the tectonic evolution of the Sibi region.

CONCLUSION

This study enabled the mapping of geological lineaments in the Sibi region and its surroundings using a semi-automatic extraction approach applied to Landsat satellite imagery. The digital processing techniques performed facilitated the identification and characterization of the main tectonic structures within the study area. A total of more than 10,058 geological lineaments were extracted and analyzed. Statistical analysis revealed three main directional families: NNE–SSW, NE–SW, and NW–SE, with a clear predominance of the NNE–SSW orientation. These directions correspond to the major structural trends recognized within the Birimian formations of southwestern Mali. Validation based on existing geological maps and field observations confirmed the reliability of the obtained results. The identified lineaments reflect the organization of regional fracturing and contribute to a better understanding of the tectonic evolution of the Sibi region. Despite certain constraints related to image resolution, weathering processes, and field accessibility, the adopted methodology proved effective for regional structural mapping. This study therefore represents an important contribution to the geological understanding of the region and provides a valuable database for mineral exploration, hydrogeological investigations, and land-use planning. Future integration of geophysical data and very high-resolution satellite imagery will further improve the accuracy of geological structure mapping.

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