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ARTICLE

Contribution of Landsat 9 OLI-2/TIRS-2 Imagery to the Mapping of Dolerites in Aboutelfan (Central Chad Massif): Structural Implications

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ABSTRACT

This study focuses on the structural and lithological characterization of dolerite dykes in the Aboutelfan Massif, central Chad, using an integrated remote sensing and field-based approach. Landsat 9 OLI-2/TIRS-2 multispectral imagery was processed through radiometric calibration, spectral band combinations, and principal component analysis to discriminate doleritic bodies from surrounding lithologies. Field observations and petrographic analyses provided ground verification and detailed mineralogical descriptions. The dolerite dykes, generally post-tectonic, intrude the granitic basement with sharp contacts and exhibit variable thicknesses ranging from 3 to 25 m. Rose diagrams reveal dominant structural orientations

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along N 30° E, N 65° E, N 135°E, and N 153° E, reflecting the regional Pan-African tectonic control on dyke emplacement. The integration of satellite imagery and structural data led to the production of a high-resolution lithological and structural map of the Aboutelfan region. The results highlight the efficiency of Landsat 9 OLI-2/TIRS-2 imagery for identifying mafic intrusions and deciphering tectonic patterns in arid environments. This work provides new insights into the structural evolution of central Chad and establishes a methodological framework for future studies combining hyperspectral imagery and geochemical analyses to better constrain the petrogenesis and geochronology of doleritic intrusions.

Keywords: Mechanically Intelligent Infrastructure; Autonomous Design; Real-Time Environmental Control; Smart Cities; Sustainability

1. Introduction

The study of doleritic dykes provides crucial insights into the magmatic and tectonic evolution of continental crusts. In many regions of Central Africa, such intrusions are direct markers of lithospheric extension, rifting dynamics, and post-collisional magmatism associated with the Pan-African orogeny. In Chad, the Aboutelfan Massif represents one of the least documented geological domains, despite its strategic position at the interface between the Central African Shear Zone and the northern extent of the Pan-African Belt. Understanding the spatial distribution and structural orientation of dolerite dykes in this massif is therefore essential for reconstructing regional geodynamics and assessing the magmatic processes that shaped the basement during the Neoproterozoic to Phanerozoic transition.

Remote sensing and GIS techniques have become fundamental tools for lithostructural mapping and tectonic interpretation. Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery have been widely used to discriminate lithological units and delineate linear features indicative of fractures, faults, and dykes. However, earlier applications were limited by the spectral and radiometric resolution of sensors such as Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and ASTER, which constrained the precision of dolerite mapping. The advent of the Landsat 9 OLI-2/TIRS-2 system offers a significant improvement in data quality, enabling finer spectral discrimination and better radiometric stability across visible to infrared bands [1].

Previous studies across Central Africa have demonstrated the usefulness of remote sensing for lithostructural mapping and dyke analysis, but most have relied on earlier generations of satellite data such as Landsat 7 ETM+ or ASTER. For instance, Dourwe et al. [1] in 2019 and Nkouandou et al. [2] in 2017 successfully mapped dolerite dykes in the Adamaoua and Guéra massifs using Landsat 7 ETM+ and Shuttle Radar Topography Mission (SRTM) data, highlighting the role of structural discontinuities in dyke emplacement. Similarly, Karifene et al. [3] integrated ASTER and Landsat 9 imagery to identify hydrothermal alteration zones in the Guéra and Abtouyour regions of Chad, showing the growing potential of satellite-based mineralogical discrimination. However, these approaches have not yet been extended to a detailed structural characterization of doleritic intrusions using the most recent Landsat 9 OLI-2/TIRS-2 sensors, which provide superior spectral and radiometric resolution. Recent research on dolerite swarms in northern Cameroon [4] and southern Chad [2] has focused primarily on petrographic and geochemical aspects, often without integrating multispectral analysis or high-density structural data. As a result, the spatial organization and tectonic control of dolerite dykes within the central Chadian Massif remain poorly constrained. The present study therefore introduces a novel methodological framework by combining Landsat 9 OLI-2/TIRS-2 multispectral analysis with detailed field structural measurements and rose-diagram synthesis to achieve high-resolution mapping of dolerite dykes in the Aboutelfan Massif. This integration enables precise spectral discrimination between dolerites, granites, and basalts, while also revealing major tectonic trends that can be correlated with Pan-African deformation phases. The originality of this research thus lies not only in the first application of Landsat 9 OLI-2/TIRS-2 imagery for dolerite mapping in central Chad, but also in its multiscale integration of spectral, structural, and field datasets to elucidate the tectonomagmatic evolution of this underexplored segment of the Central African Mobile Zone.

From a conceptual standpoint, this study addresses two key questions: (i) what are the spatial and directional characteristics of dolerite dykes in the Aboutelfan region, and (ii) how do these structures relate to regional tectonic regimes linked to the Pan-African orogenic cycle? The main objective is therefore to identify, characterize, and analyze dolerite dykes through a combination of multispectral remote sensing, field mapping, and petrographic investigation. The results are expected to provide both a detailed lithostructural map and new insights into the geodynamic evolution of the central Chadian basement.

The paper is organized as follows: after this introduction, Section 2, Literature Review, presents the current state of knowledge on remote sensing for geological mapping, the geological significance of dolerite dykes, and the existing research gaps that motivate the present study. Section 3, Materials and Methods, describes the geological setting of the Aboutelfan Massif, the materials and software used, the field investigations, and the remote sensing and image-processing methodology adopted for lithological and structural mapping. Section 4, Results and Discussion, presents the spectral analyses, petrographic observations, structural interpretation, and lithological mapping results, followed by a discussion of their geological and tectonic implications. Finally, Section 5, Conclusion, summarizes the main findings, highlights the contribution of Landsat 9 OLI-2/TIRS-2 imagery to dolerite mapping in the Aboutelfan Massif, discusses the limitations of the study, and outlines perspectives for future research.

2. Literature Review

2.1. Remote Sensing for Geological Mapping in Arid Regions

Geological mapping is essential for understanding lithological distributions, structural frameworks, and tectonic evolution. However, conventional field-based investigations are often limited in vast arid regions where accessibility is difficult. Under such conditions, remote sensing has become a powerful tool for geological studies because it provides rapid, synoptic, and cost-effective observations over large areas. The sparse vegetation cover and extensive rock exposures that characterize desert environments further enhance the effectiveness of satellite imagery for identifying lithological units and geological structures [5].

The continuous development of Earth observation systems has significantly improved geological mapping capabilities. Multispectral sensors such as Landsat, ASTER, Sentinel-2, and more recently Landsat 9 provide spectral information in the visible, near-infrared (NIR), and shortwave infrared (SWIR) regions, allowing discrimination between rock types and mineral assemblages based on their spectral signatures [6]. To maximize the extraction of geological information, several image-processing techniques, including false-color composites, band ratios, principal component analysis (PCA), and decorrelation stretching, are commonly applied. These methods enhance lithological contrasts and facilitate the identification of alteration zones, lithological contacts, and geomorphological features.

Beyond lithological mapping, remote sensing has become an effective approach for structural analysis. Geological structures such as faults, fractures, shear zones, and dykes can be identified through lineament extraction from satellite imagery and digital elevation models. The integration of image enhancement techniques and geographic information system (GIS) analysis provides valuable information on deformation patterns and tectonic evolution [7]. Recent improvements associated with Landsat 9, particularly in radiometric quality and spectral stability, have further increased the reliability of geological interpretations. Consequently, the integration of multispectral imagery, GIS techniques, and field investigations has become a standard approach for lithostructural mapping in arid and semi-arid regions.

2.2. Remote Sensing Applications for Dolerite Dyke Mapping

Dolerite dykes are important markers of magmatic and tectonic evolution and can often be identified on satellite imagery because of their linear geometry and distinctive lithological characteristics. In arid environments, where bedrock exposure is generally good, remote sensing provides an efficient means of mapping dyke systems and associated structural features.

Several studies in Central Africa have demonstrated the usefulness of integrating satellite imagery with field observations for dolerite dyke investigations [2] documented the geological characteristics of doleritic intrusions in the

Guéra Massif, whereas Dourwe et al. [1] highlighted the role of structural discontinuities in controlling dyke emplacement using Landsat 7 ETM+ and SRTM data. Despite these advances, detailed investigations based on recent Landsat 9 imagery remain limited, particularly in central Chad, where the spatial distribution and structural significance of dolerite dykes are still insufficiently documented.

2.3. Geological Significance of Dolerite Dykes

Dolerite dykes are widely recognized as indicators of crustal extension and tectonic reactivation within Precambrian terranes. In the Central African Pan-African Belt, their emplacement is commonly associated with late- to post-orogenic tectonic events and provides valuable information on regional deformation patterns. Previous studies conducted in Chad and Cameroon have shown that the orientation of doleritic intrusions is closely related to major Pan-African structural trends and inherited basement discontinuities [2,8,9]. Consequently, the analysis of dyke orientation constitutes an important tool for understanding the tectonic evolution of the Central African Mobile Zone.

2.4. Existing Limitations and Research Gaps

Although remote sensing has considerably advanced geological mapping and dyke investigations, several limitations remain. Many studies conducted in Central Africa relied on Landsat 7, ASTER, or SRTM datasets, whose spectral and radiometric characteristics may restrict the discrimination of subtle lithological and structural features. Moreover, previous investigations have generally emphasized either lithological mapping or structural analysis, whereas integrated approaches combining remote sensing, field structural measurements, petrographic observations, and GIS analysis remain relatively uncommon.

This limitation is particularly evident in Chad, where geological knowledge remains unevenly distributed. Studies carried out in the Guéra Massif and neighboring regions have improved understanding of doleritic intrusions, but the Aboutelfan Massif remains poorly documented despite its strategic position within the Central African Pan-African Belt. To date, no study has comprehensively integrated Landsat 9 imagery, structural field data, petrographic observations, and lineament analysis to investigate the dolerite dykes of this area. The present study addresses this gap through a multidisciplinary approach aimed at improving our understanding of the lithostructural organization and tectonomagmatic evolution of the Aboutelfan Massif.

3. Materials and Methods

3.1. Geological Setting

The Central African Mobile Zone (CAMZ) extends from the northern margin of the Congo Craton to eastern Nigeria, encompassing Cameroon, Chad, and the Central African Republic. This extensive Pan-African Belt crops out in several massifs in Chad, including the Tibesti in the north, the Ouaddaï in the east, the Guéra in the centre, and the Mayo-Kebbi in the southwest [10]. **Figure 1** illustrates the geographical location of the study area, showing the position of the Aboutelfan Massif in central Chad, within the northern domain of the Central African Pan-African Belt.

According to Toteu et al. [8], the Central African Pan-African Belt is subdivided into three main structural domains: southern, central, and northern. The Aboutelfan Massif, which forms the focus of the present study, belongs to the northern domain and represents the southwestern extension of the Ouaddaï Massif [11]. Following Liégeois et al. [12], the Guéra Massif, located in central Chad, is part of the Saharan Metacraton, interpreted as an ancient Precambrian basement that was rejuvenated and reworked during late Pan-African orogenic events.

Regional investigations, notably those conducted around Mongo [2,13], identified four main rock groups based on their relative emplacement chronology. These lithological units record four successive deformation phases (D1–D4). The final D4 phase, which is ubiquitous throughout the region, is characterized by the development of brittle structures, including dykes, faults, and joints. As shown in **Figure 2**, the major structural domains of Saharan Africa are centred on the Saharan Metacraton [12,14]. The structural outlines and boundaries are derived from the Tectonic Map of Africa [15], whereas internal subdivisions are based on Fezaa et al. [16] for the Murzuq Craton, Küster [17] for the Bayuda Terrane, and Liégeois et al. [12] for the regional synthesis.

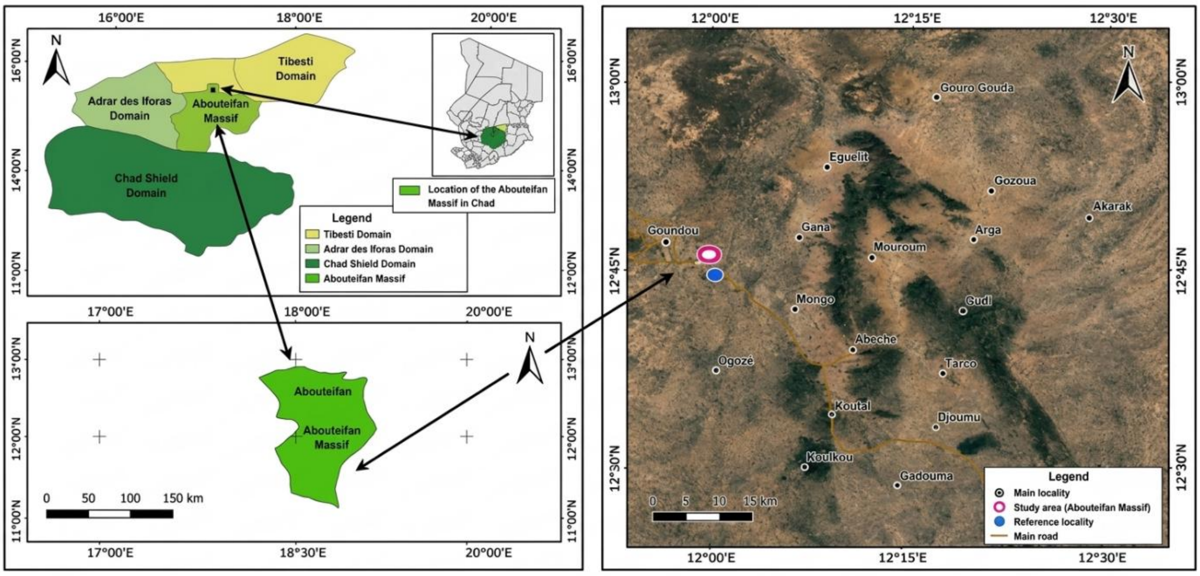

Figure 1. Location map of the study area showing the position of the Aboutelfan Massif in central Chad within the Central African Pan-African Belt.

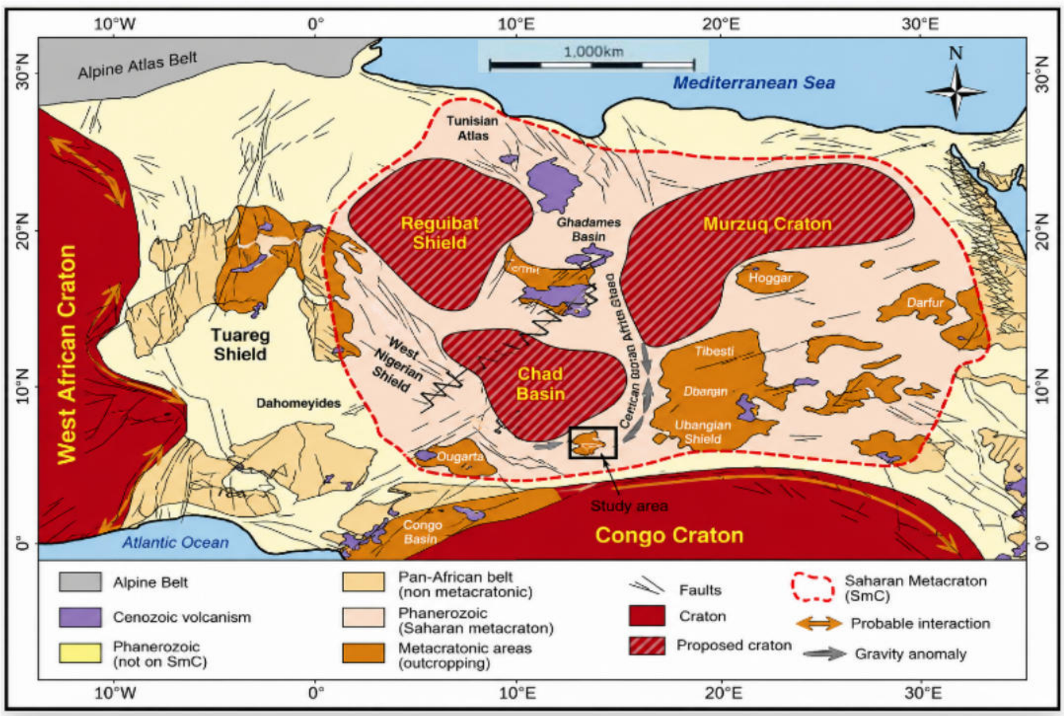

Figure 2. Major structural domains of Saharan Africa centred on the Saharan Metacraton (after Liégeois et al., 2013) [12].

Note: This framework highlights the structural relationships and tectonic interactions between the Saharan Metacraton and the Central African Mobile Zone, within which the Aboutelfan Massif is situated.

3.2. Materials

To achieve the objectives of this study, a combination of remote sensing tools, specialized software, and field instruments were employed. The materials used included both digital and conventional geological equipment, enabling a comprehensive and accurate data collection strategy.

3.2.1. Software Tools

ENVI 5.3 (Environment for Visualizing Images) was used for preprocessing, radiometric, and atmospheric correction of Landsat 9 OLI-2/TIRS-2 satellite images. This software facilitated image enhancement, structural interpretation, and spectral discrimination of lithological units. Quantum Geographic Information System (QGIS) was employed for geological mapping and spatial data integration, allowing the combination of satellite imagery and field observations. StereoNet software was used to perform structural analysis, particularly for constructing rose diagrams that illustrate the orientations of geological features, including dolerite dykes.

3.2.2. Field Instruments

- A Global Positioning System (GPS) receiver was used to acquire the geographic coordinates of outcrops, sampling points, and structural measurements.
  A compass-clinometer was used to measure the orientation (strike and dip) of structural elements, including fractures, faults, and dykes.
- A digital camera was used to capture high-resolution photographs of outcrops and structural features. A standard-sized reference object (such as a pen, hammer, or coin) was included in each photo to provide a consistent scale. Geological hammers and chisels were employed to collect fresh rock samples from representative outcrops.
- A permanent marker, a field notebook, and a geologist's backpack were used for labeling samples, recording field observations, and transporting heavy materials securely.
- The integration of remote sensing tools with in-situ field equipment ensured that both spatial and structural data were collected in a systematic and reliable manner, providing a robust basis for subsequent analysis.

3.3. Methods and Data Processing

Remote sensing encompasses a suite of techniques for determining the physical and biological characteristics of objects from a distance, without direct contact. In practice, remote sensing involves capturing, recording, and analyzing electromagnetic radiation either emitted or reflected from Earth's surface. The processed data can then be visualized as images, which provide quantitative and qualitative information about lithological and structural features.

For this study, Landsat 9 OLI-2/TIRS-2 images were downloaded and preprocessed using ENVI 5.3 to correct radiometric and atmospheric errors introduced by sensor characteristics and atmospheric effects. Preprocessing included calibration, correction, and enhancement steps to ensure accurate analysis. The spectral characteristics and spatial resolutions of the Landsat 9 OLI-2/TIRS-2 bands used in this study are summarized in **Appendix A, Table A1**. Particular emphasis was placed on Bands 5 (NIR), 6 (SWIR-1), and 7 (SWIR-2), which were combined in the 7–6–5 false-color composite to enhance lithological discrimination between dolerites and surrounding lithologies. These bands were subsequently used as input for lineament enhancement and structural interpretation through Sobel directional filtering. The processed images were subsequently imported into QGIS for cartographic representation and integration with field observations. Reflectance values were extracted from Landsat 9 OLI-2 imagery and subsequently used for spectral signature analysis.

Field structural measurements, including strikes and dips of dolerite dykes, were analyzed using StereoNet to construct rose diagrams. These rose diagrams reveal the principal orientation trends of the dykes and fractures, providing key insights into the tectonic regime and deformation history of the Aboutelfan Massif. By combining satellite data, digital processing, and field measurements, a coherent and high-resolution understanding of both the lithological distribution and structural architecture of the study area was achieved.

Field investigations were conducted at the most accessible outcrops within the Aboutelfan Massif. Although only eleven dolerite dykes could be directly measured because of limited accessibility, rugged terrain, and discontinuous outcrop exposure, these measurements were complemented by the analysis of lineaments extracted from Landsat 9 imagery. The combined use of field structural observations and remotely sensed lineaments provides a more representative basis for assessing the regional structural framework.

4. Results and Discussion

4.1. Results

The mosaic map of the study area was extracted after radiometric and atmospheric calibration of the Landsat 9 images (**Figure 3**). Following calibration, the study area was delineated from the Landsat 9 image for detailed analysis

(**Figure 4**).

To enhance image quality and extract spectral information, dolerites were discriminated from other lithologies using satellite imagery. The typical spectral signature of dolerite is presented in **Figure 5c**. The spectral signatures presented in **Figures 5–6** were derived from reflectance values extracted directly from Landsat 9 OLI-2 imagery over representative field-validated dolerite, granite, and basalt outcrops. The corresponding numerical values are reported in **Appendix A**, **Table A2**.

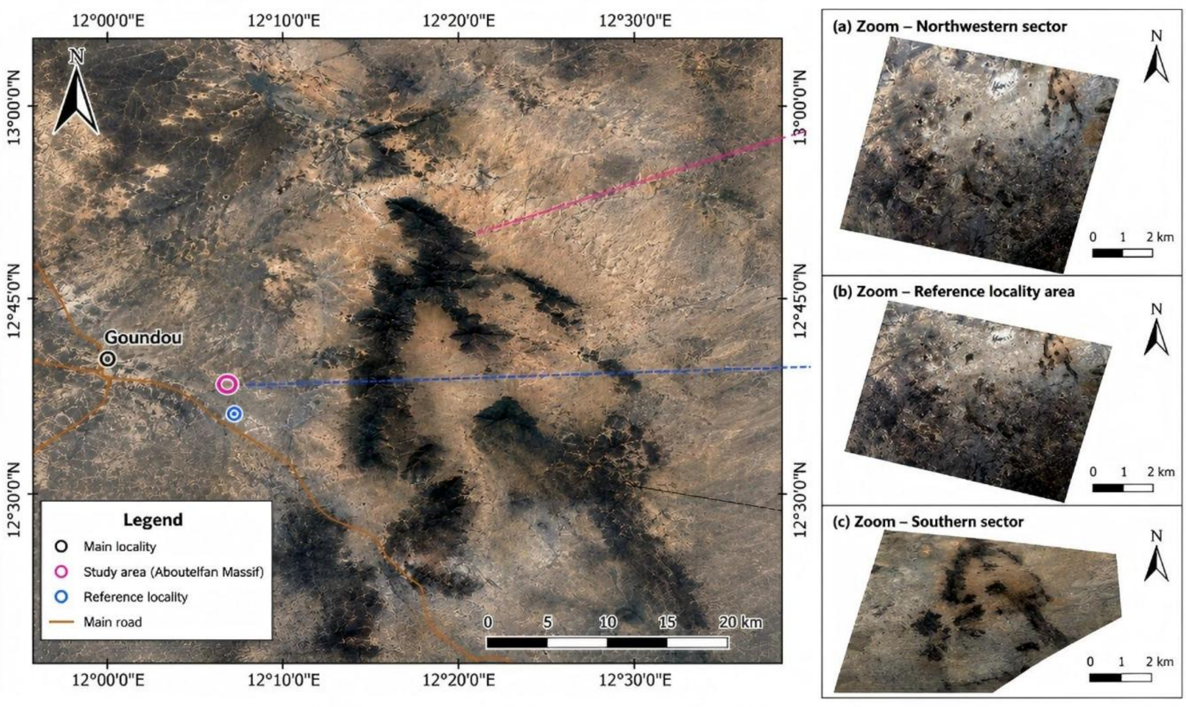

Figure 3. Extraction of the study area from Landsat 9 imagery.

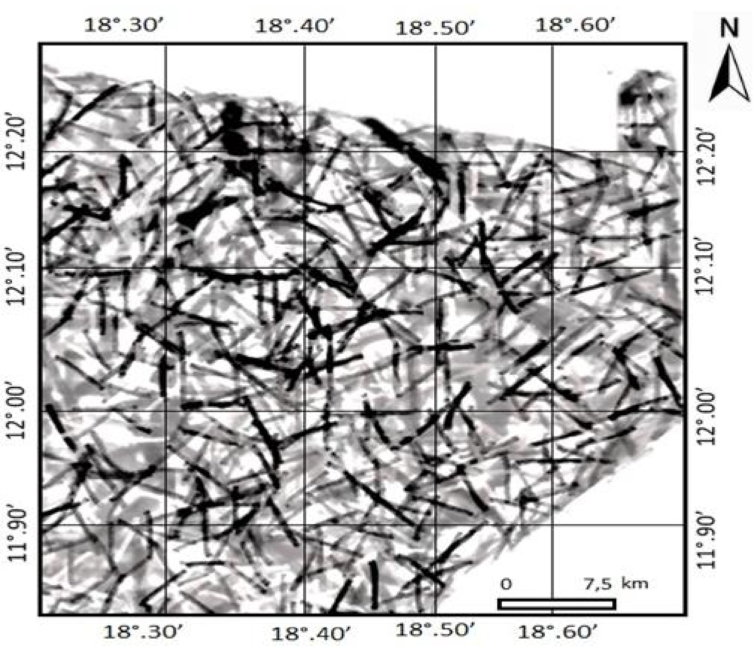

Figure 4. Lineament map of the study area obtained using Sobel directional filter.

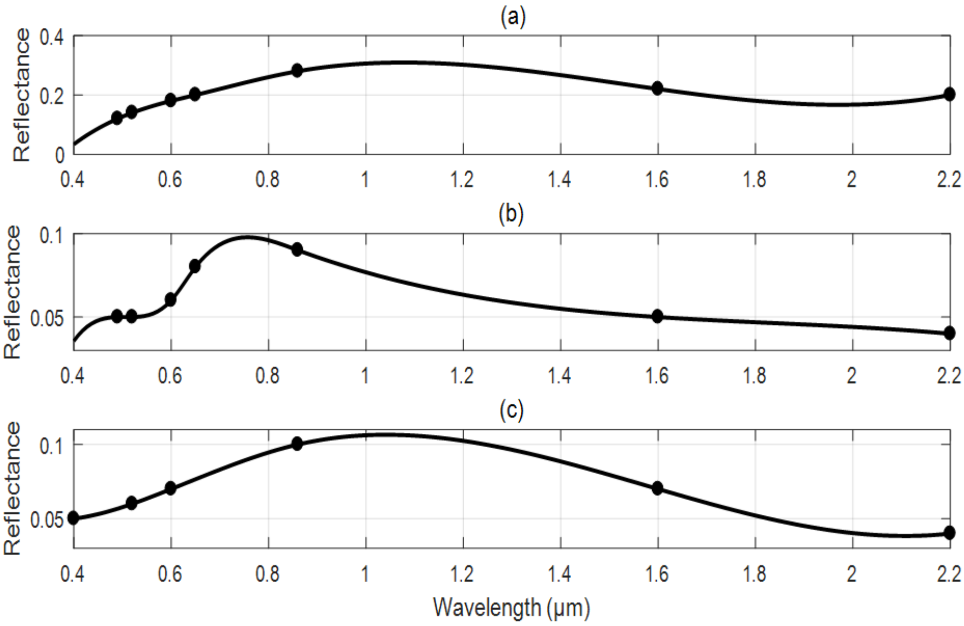

Figure 5. Typical spectral signature of (**a**) Granite, (**b**) Basalt, (**c**) Dolerites, derived from reflectance values extracted from Landsat 9 OLI-2 imagery.

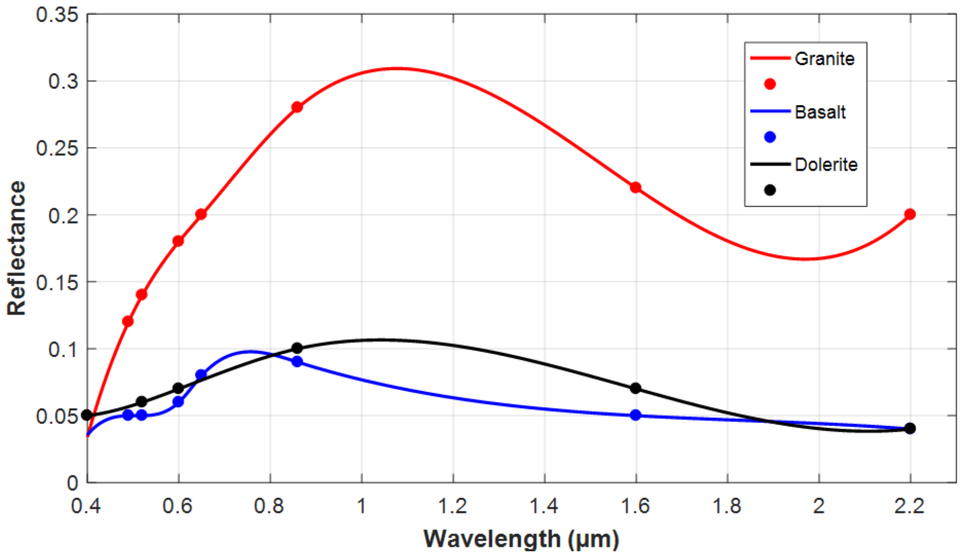

Figure 6. Comparative spectral signatures of dolerite, granite, and basalt, derived from Landsat 9 OLI-2 reflectance data.

The spectral signature shows generally low reflectance across the entire spectrum, with a slight increase in the near-infrared (NIR) region (~0.86 μm) followed by a decrease in the shortwave infrared (SWIR) region (1.6–2.2 μm). This behaviour reflects the dark and weakly reflective nature of dolerites.

For a comparative assessment, the spectral signatures of three rock types: dolerite, granite, and basalt were analyzed (**Figure 6**). The numerical reflectance values used to construct the spectral signature curves are provided in **Appendix A**, **Table A2**, allowing a quantitative comparison between dolerite, granite, and basalt.

The analysis highlights the following trends:

- Dolerite: Generally low reflectance, slightly higher in NIR, remaining dark;
- Granite: Higher reflectance across the spectrum, particularly in NIR, making it more conspicuous;
- Basalt: Very low reflectance, similar to or even darker than dolerite.

Spectral enhancement of the natural-color composite (bands 4-3-2) and true-color composite (**Figure 7a**) produced a map that did not allow accurate delineation between dolerite and other lithologies. To improve lithological discrimination, a false-color composite (bands 7-6-5) was applied (**Figure 7b**), utilizing different regions of the electromagnetic spectrum. This enhanced composition enabled better identification of lithofacies across the study area. Finally, a Sobel directional filter was applied for lineament analysis, also referred to as linear feature extraction [18]. This method highlights lineaments corresponding to dykes, lithological boundaries, and potentially hydrographic networks, which are expressed as strong reflectance transitions due to textural changes (**Figure 4**).

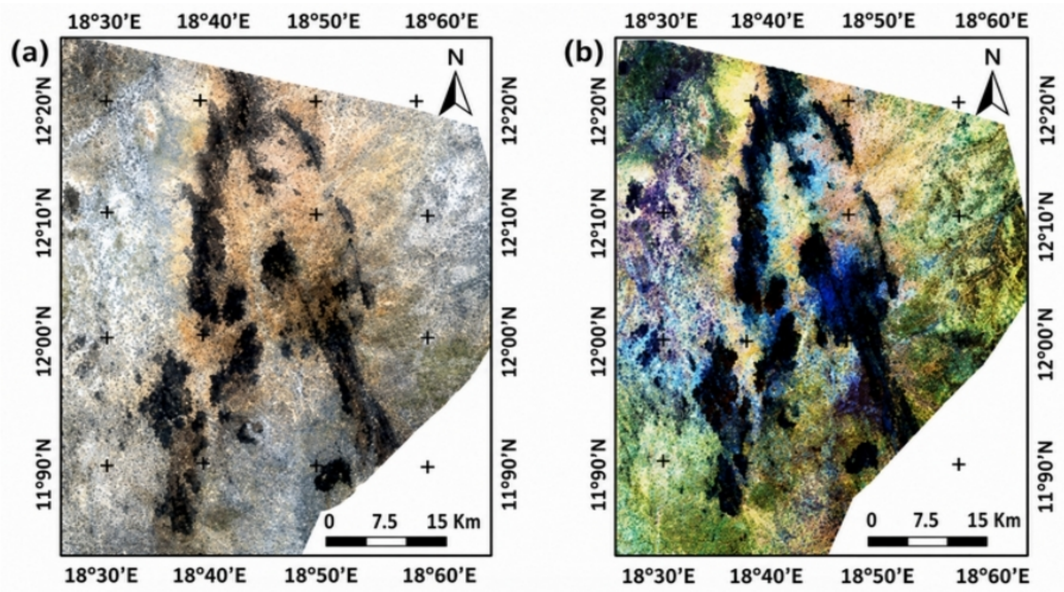

Figure 7. (**a**) Natural-color composite (bands 4-3-2); (**b**) False-color composite (bands 7-6-5) for lithological discrimination.

4.2. Petrography and Structural Overview

4.2.1. Petrography

Field studies were conducted at several sites to characterize the dolerite dykes.

At Gamé, dolerites outcrop as dykes composed of centimetric (20–60 cm) to metric (1–1.5 m) blocks, with thicknesses of 8–10 m and lengths exceeding 40 m. These dykes are oriented along a NE–SW direction.

At Djikoukouli, dolerites occur as extensive dykes at the foot of the massif, with thicknesses reaching 10–15 m in some locations and lengths exceeding 15 km, oriented along a NW–SE trend. The contact between dolerite and the granitic host rock is sharp and well-defined, and the weathering rind is thin (<1 cm) and greyish.

The dolerites consist of metric-scale blocks (1–2 m) of dark grey color. The dark-grey matrix contains feldspar crystals, black pyroxene or amphibole/oxide crystals, and whitish plagioclase (**Figure 8b**).

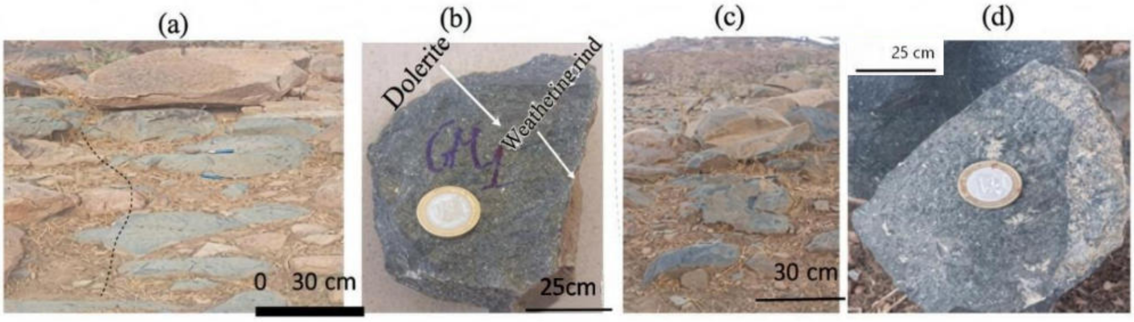

Figure 8. (**a**) NE–SW trending dolerite dykes; (**b**) Dolerite sample showing mineral composition; (**c**) E–W trending dyke; (**d**) Sharp granite–dolerite contact.

4.2.2. Structural Overview

Rose diagrams constructed from measured dolerite dyke orientations, as shown in **Figure 9**, according to **Table A3** in the **Appendix A**, highlight a dominant NE–SW structural orientation, with a strong concentration of azimuths between N 30° E and N 70° E. This preferential alignment indicates that dyke emplacement was primarily controlled by a regional stress field that promoted fracture opening along NE–SW planes. A secondary but significant cluster appears between N 135° E and N 153° E, corresponding to a subordinate NW–SE trend. The coexistence of these two structural families suggests the influence of multiple tectonic phases, with the NE–SW set representing the major extensional direction affecting the Aboutelfane region.

Similarly, the rose diagram of **Figure 10** (following **Table A4** in the **Appendix A**) shows a clear predominance of NE–SW–oriented lineaments, with a major concentration of directions between N 30° E and N 70° E. This strong directional clustering suggests a structurally controlled pattern, likely reflecting regional tectonic stresses that favored the development of fractures and doleritic intrusions along NE–SW trends. A secondary but less pronounced group appears around N 135° E–N 150° E, indicating a subordinate NW–SE structural family. Overall, the distribution is markedly anisotropic, highlighting the influence of pre-existing tectonic fabrics on the emplacement and propagation of lineaments within the Aboutelfane area [19,20].

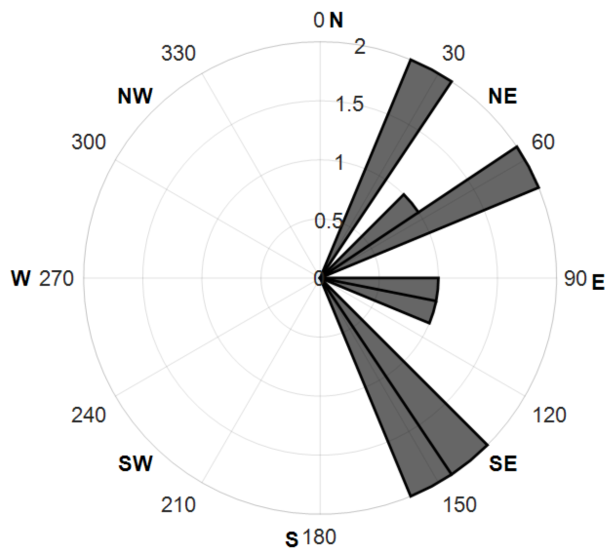

Figure 9. Rose diagram of dolerite dyke orientations in the study area.

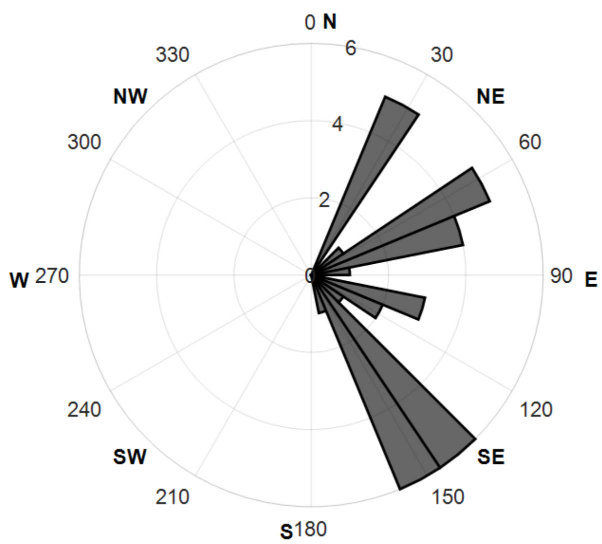

Figure 10. Rose diagram of lineament orientations in the study area.

The structural interpretation proposed in this study is based on the convergence between field-measured dyke orientations (**Table A3**; **Figure 9**) and the orientations of remotely sensed lineaments (**Table A4**; **Figure 10**). Despite the limited number of field measurements, the similarity of the dominant NE–SW and subordinate NW–SE trends observed in both datasets supports the reliability of the inferred tectonic framework and suggests that the measured dykes are representative of the main structural patterns affecting the study area.

The integration of field observations, spectral analysis, and structural measurements allowed the construction of a detailed and original lithological map, highlighting the distribution of dolerites in the Aboutelfan zone (**Figure 11**).

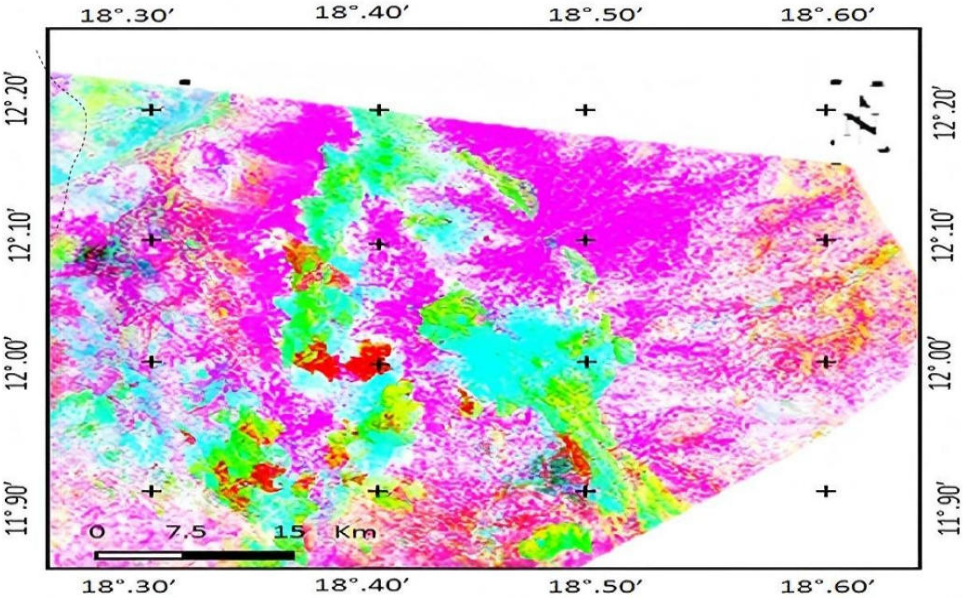

Figure 11. Lithological map showing dolerite distribution in the Aboutelfan study area.

4.3. Discussion

The investigations carried out in the Aboutelfan Massif underscore the growing importance of satellite imagery in high-resolution geological mapping, particularly for dolerite dyke systems. The employment of Landsat 9 data—specifically its OLI-2 (Operational Land Imager 2) and TIRS-2 (Thermal Infrared Sensor 2) sensors—marks a significant advance over earlier generations of Landsat satellites (e.g., Landsat 7 ETM+), providing enhanced spectral resolution, improved signal-to-noise ratios and superior discriminative capability for lithological and structural features. This is consistent with recent work showing that Landsat 9 successfully delineates lithological units through combined VNIR–SWIR band analysis and structural lineament extraction [21].

Field evidence from Aboutelfan reveals dolerite dykes with widths ranging from approximately 3 m to 25 m, surpassing the typical widths reported in earlier studies, e.g., Vicat et al. [22], and thereby approaching the classification of "giant dykes" as defined by Bryan et al. [23]. These broader dykes and the sharp contacts with the host granitic rocks suggest a post-tectonic emplacement (deformation phase D4) within the regional structural framework. Such observations align with petrographic and geochemical studies of dolerite swarms in the Central African Fold Belt (CAFB), indicating multi-phase tectono-magmatic histories [24,25].

The orientation data, represented by rose diagrams derived from both dyke measurements and lineament mapping, reveal major directional trends: N 30° E, N 65° E, N 135° E and N 153° E, with secondary directions including N 45° E, N 95° E, N 105° E and N 195° E. These structural orientations are in excellent agreement with the regional tectonic framework:

The N 153° E trend corresponds to fault systems bounding the Cretaceous Série de Lamé south of Pala and the boundary between the Yadé massif and the Doba Basin [26].

The N 135° E orientation aligns with the large Tibesti lineament in northeastern Chad and reflects a Pan-African shear direction affecting the mobile belt basement [9,27].

By integrating remote sensing, structural analysis and field petrography, the study demonstrates the power of a multi-disciplinary approach for dissecting complex dyke systems within mobile belts. The successful mapping of lithological units and structural fabrics using Landsat 9 reinforces the potential for satellite imagery to revolutionise geological mapping in remote or difficult terrain [28]. Recent methodological advances, such as machine-learning frameworks applied to Landsat data for lithological discrimination, e.g., Zhang et al. [29], further emphasise the growing role of digital image processing in geosciences.

Thus, the Aboutelfan dolerites not only document a distinct magmatic event tied to deformation phase D4, but also illustrate how modern remote sensing techniques can be effectively applied to intraplate dyke systems in Pan-African orogenic settings. Future work may further benefit from higher spatial resolution sensors, UAV imagery, hyperspectral data and integration with structural modelling to refine the emplacement mechanism and tectonic implications of the dyke swarm.

5. Conclusions

This study has demonstrated the significant potential of Landsat 9 OLI-2/TIRS-2 imagery for high-resolution mapping of dolerites in the Chadian Central Massif, particularly in the Aboutelfan area. The integration of image processing techniques, including color composites, spectral analysis, and directional filtering, with field observations allowed reliable discrimination of dolerites from other host lithologies, such as granites and basalts. The spectral signatures highlighted distinctive characteristics of dolerite, notably generally low reflectance with a slight peak in the near-infrared region, enabling precise lithological differentiation.

Structural analysis, through rose diagrams and lineament extraction, revealed major trends (N 30° E, N 65° E, N 135° E, N 153° E) and secondary trends (N 45° E, N 95° E, N 105° E, N 195° E) that are consistent with the principal tectonic orientations of the Central African Pan-African Belt. These findings suggest that the Aboutelfan dolerites were emplaced post-tectonically, associated with deformation phase D4, and reflect the complex tectonic dynamics that affected the Chadian Metacraton. The combination of remote sensing and field observations provided an integrated understanding of lithostructural relationships in this otherwise difficult-to-access area. Although the number of field-measured dolerite dykes was limited by accessibility constraints and discontinuous outcrop exposure, the consistency between field observations and remotely sensed lineament orientations provides confidence in the structural interpretation and the inferred tectonic framework of the Aboutelfan Massif.

Beyond mapping, this study offers promising avenues for future research. The use of higher spatial resolution sensors, hyperspectral data, and UAV platforms could allow more detailed characterization of dolerite units, their mineralogy, and structural contacts. Additionally, integrating machine learning approaches applied to Landsat data and field measurements could further automate and enhance lithological discrimination and lineament identification over large regions. Ultimately, these results contribute to a refined understanding of regional tectonics and can serve as a comparative basis for studies in other sectors of the Central African Pan-African Belt.

Author Contributions

Conceptualization, M.A.A., M.M.A. and F.K.; methodology, M.A.A., M.M.A., A.M.B., and F.K.; software, M.A.A. and A.K.; validation, M.A.A., F.K., O.F.N. and M.M.A.; formal analysis, M.A.A., M.M.A., and F.K.; investigation, M.A.A., M.M.A., A.M.B., M.H.T., O.F.N., A.K., A.A., L.A.C., H.A., A.M.F., G.R.N., G.K.A., A.H. and F.K.; resources, M.A.A., M.H.T., A.A., G.K.A. and A.H.; data curation, M.A.A., A.M.B., and L.A.C.; writing original draft preparation, M.A.A., M.M.A., and F.K.; writing review and editing, M.A.A., M.M.A., F.K., O.F.N. and A.M.B.; visualization, M.A.A., A.K. and A.M.F.; supervision, F.K., M.M.A. and O.F.N.; project administration, F.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language editing, grammar correction, and improvement of readability. No AI tools were used for data collection, data analysis, interpretation of results, scientific reasoning, or the generation of scientific conclusions. All AI-assisted outputs were carefully reviewed, verified, and edited by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the content presented in this work.

Appendix A

Table A1. Spectral characteristics of Landsat 9 OLI-2 bands used in this study.

Band	Spectral Region	Wavelength (µm)	Spatial Resolution (m)	Application in This Study
Band 2	Blue	0.45–0.51	30	True-color composite (4-3-2)
Band 3	Green	0.53–0.59	30	True-color composite (4-3-2)
Band 4	Red	0.64–0.67	30	True-color composite (4-3-2)
Band 5	Near Infrared (NIR)	0.85–0.88	30	False-color composite (7-6-5)
Band 6	Shortwave Infrared 1 (SWIR-1)	1.57–1.65	30	Lithological discrimination
Band 7	Shortwave Infrared 2 (SWIR-2)	2.11–2.29	30	Lithological discrimination and lineament enhancement

Source: USGS Landsat 9 OLI-2/TIRS-2 sensor specifications.

Table A2. Reflectance values extracted from Landsat 9 OLI-2 imagery for representative dolerite, granite, and basalt outcrops used to construct the spectral signature curves.

Rock	Reflectance	Wavelength
Granite	0.12	0.49
	0.14	0.52
	0.18	0.60
	0.20	0.65
	0.28	0.86
	0.22	1.60
	0.20	2.20
Basalt	00.5	0.49
	00.5	0.52
	0.06	0.60
	0.08	0.65
	0.09	0.86
	0.05	1.60
	0.04	2.20
Dolerite	0.05	0.40
	0.06	0.52
	0.07	0.60
	0.10	0.86
	0.07	1.60
	0.04	2.20

Table A3. Coordinates and directions of the dolerite dykes of Aboutelfane.

No	Site	Coordinates		Altitude	Direction
1	Gamé	18°48′45″ E	12°15′03″ N	442 m	N 30° E
		18°48′46″ E	12°15′04″ N	442 m	N 135° E
		18°50′49″ E	12°17′03″ N	445 m	N 30° E

Table A3. *Cont.*

No	Site	Coordinates		Altitude	Direction
2	Djoukoulkouli 1	18°49′25′′ E 18°51′15′′ E 18°51′50′′ E 18°60′10′′ E	12°18′06′′ N 12°12′06′′ N 12°12′45′′ N 12°12′45′′ N	437 m 440 m 440 m 442 m	N 105° E N 65° E N 65° E N 153° E
3	Djoukoulkouli 2	18°49′24′′ E 18°51′24′′ E 18°50′24′′ E 18°52′10′′ E	12°17′52′′ N 12°19′88′′ N 12°18′88′′ N 12°20′02′′ N	432 m 437 m 437 m 445 m	N 135° E N 153° E N 45° E N 95° E

Table A4. Directions of the main lineaments of Aboutelfane.

Directions						
N 30° E	N 65° E	N 30° E	N 86° E	N 65° E	N 110° E	N 60° E
N 30° E	N 60° E	N 135° E	N 135° E	N 56° E	N 30° E	N 135° E
N 153° E	N 153° E	N 153° E	N 146° E	N 168° E	N 70° E	N 110° E
N 156° E	N 106° E	N 70° E	N 153° E	N 65° E	N 32° E	N 153° E
N 70° E	N 146° E	N 115° E	N 70° E	N 124° E	N 140° E	N 120° E

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