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Mapping and Structural Analysis of Geological Fractures of the Tidili Region, Morocco, Related to South Atlas Fault Zone Using Remote Sensing on Landsat 9 OLI Imagery

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Abstract

This study utilizes Landsat 9 OLI images to map and characterize geological fractures in the South Atlasic Fault Zone in the Tidili region of Morocco, situated at the intersection of the Anti-Atlas and High Atlas Mountains. By integrating field data with lineament mapping tools, the research identifies four major fault orientations: NNW-SSE, E-W, NE-SW, and N-S. The N-S faults, associated with the Pan-African orogeny, are the oldest structures, while the NE-SW faults, linked to the proto-Atlantic Ocean opening, dominate the region. The NNW-SSE faults, though fewer, show evidence of recent tectonic activity, highlighting the dynamic nature of the landscape. Fracture density analysis reveals a strong correlation between rock rheology and fault distribution, with the highest densities found in the Precambrian basement and Triassic formations. This underscores the role of lithological controls in fracture development. The study also identifies major discontinuities critical to understanding the region's tectonic evolution. This multidisciplinary approach combining remote sensing and fieldwork improves the understanding of tectonic processes and offers potential applications for mineral resource exploration and geological hazard assessment. The findings provide insights into the region's structural complexity and tectonic reactivation during the Hercynian and Alpine orogenies, making the research a valuable contribution to both geological studies and resource management.

Keywords: Anti-Atlas-High Atlas; Lineament mapping; Epithermal mineralization; Geodynamics

1. Introduction

The Tidili region, located between the High Atlas of Marrakech and the Anti-Atlas mountain range (7°15'–8°W, 30°30'–31°25'N, WGS84), is characterized by rugged terrain and difficult accessibility, with altitudes ranging from 1700m to 3900 m (Fig.1). Access is primarily through the village of Agouim, 130 km south of Marrakech. The importance of the study area lies in its potential to reveal key geological features through the analysis of lineaments, which are critical in understanding the tectonic framework and mineralization potential of this region. Studying all types of lineaments allows the assess of subsurface structures, identify fault systems, and analyze fluid flow pathways. This makes the

comprehensive study of these features essential for both academic research and practical applications in geology.

Remote sensing, through satellite and airborne instruments, allows the acquisition of detailed surface images, providing a fast and efficient means of geological analysis without direct field contact. Previous studies in the region focused on structural geology, sedimentology, and geochemistry (Admou and Juteau, 1998; Regragui et al., 2000; Thomas et al., 2002; Touil et al., 2008; El Arabi et al., 2003; Emran and Medina, 2016). This article leverages remote sensing and GIS tools such as ArcGIS and Envi to generate a fault network map and conduct a statistical analysis of fractures, enhancing the understanding of the region's structural geology and its mineralization potential. Combining the survey lineaments on satellite imagery, together with the field work allows us to understand the geological structures of the studied area (Pepe et al., 1997; Kavak, 2005).

The complex interplay between tectonics and surface processes shapes the diverse landscapes, studies using various geophysical methods, such as gravity interpretations, have revealed important insights into the deep geological structure, providing context for understanding the structural features observed in the South Atlasic Fault Zone (Ouahzizi et al., 2023; Naitouacha et al., 2024; Nouayti et al., 2024). Geological fractures are key to understanding tectonic processes, subsurface fluid flow. Généreux et al. (2024) provide insights into such complexities along craton margins, which can be analogous to the structural settings observed in our study area.. In tectonically active regions like the Rif, studies highlight how tectonics and lithology influence landslides (Bouabadi et al., 2023; Chaaou et al., 2023; Akoudad et al., 2024; El Amrani et al., 2024; Ben Driss et al., 2024;).

Remote sensing techniques have become essential tools for structural mapping and lineament analysis. Recent studies in the High Atlas (Ait Inoh et al., 2023) and Anti-Atlas (Baid et al., 2024) regions have demonstrated the effectiveness of integrating various remote sensing datasets, including Landsat and other sources, for lineament extraction and analysis.

2. Geological Settings

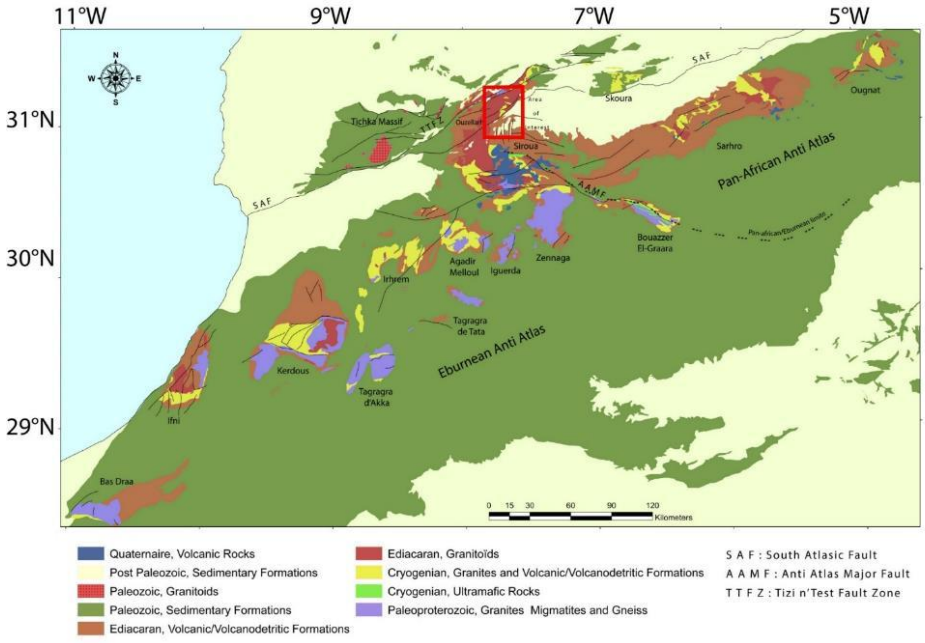


Fig.1. Geological units of the Moroccan Anti-Atlas (extracted and simplified from the geological map of Morocco 1/1000000)

The Ouzellarh-Siroua promontory is a Precambrian stretch of the anti-atlas in the southern slope of the Marrakech High Atlas. Geologically, the area lies between two domains, a series of Ediacaran

granitoids in the north representing the high atlasic domain (Ouzellarh), and the anti-atlasic field to the south represented by the massif of Siroua. The two terrains are separated by the South-Atlasic fault network, at the foot of the SAF is shaped a depression, allowing the deposit of Triassic sedimentary and/or volcanic formations (Fig.2). The Siroua Massif in these surroundings consists of a Cryogenian age basement and a late Ediacaran and Proterozoic to Meso-Cenozoic age laying over as cover. the most of the formations widespread in the Siroua district, has an arc tholeiites character with a combination of the Ediacaran and Late Proterozoic eruptions, which are the result of the functioning of a subduction belt after the setting of the Pan-African ophiolites in Siroua, product of magmatism related to collisional to extensional tectonics (Chabane et al., 1991; El-Boukhari et al., 1992 ; Huch, 1988 ; Rehdorf, 1988; Schermerhorn et al., 1986).

The Siroua massif constitutes the northern margin of the Anti-Atlas. It is bounded to the south by the major accident of the Anti-Atlas and covered by the great Cenozoic volcano of Siroua. The latter, is marked by the major accident, delimits two different structural domains during the Pan-African orogeny: a stable SW (eburnean Anti-atlas) zone corresponding to the West African craton and a mobile Anti-Atlasic zone to the NE (panafrican Anti-atlas; Choubert, 1963, El Boukhari et al., 1992; Thomas et al., 2004) (Fig.1).

The Ouzellarh promontory and the Siroua massif separate the Cenozoic Ouarzazate Basin to the NE and the Souss Basin to the SW that extends to the Atlantic Ocean. As both precambrian massifs are similarly elevated (Toummite et al., 2012) propose to integrate them into a single promontory called the "Ouzellarh-Siroua Promontory" and justify this by the extension of the Ouzellarh Promontory into the Siroua area.

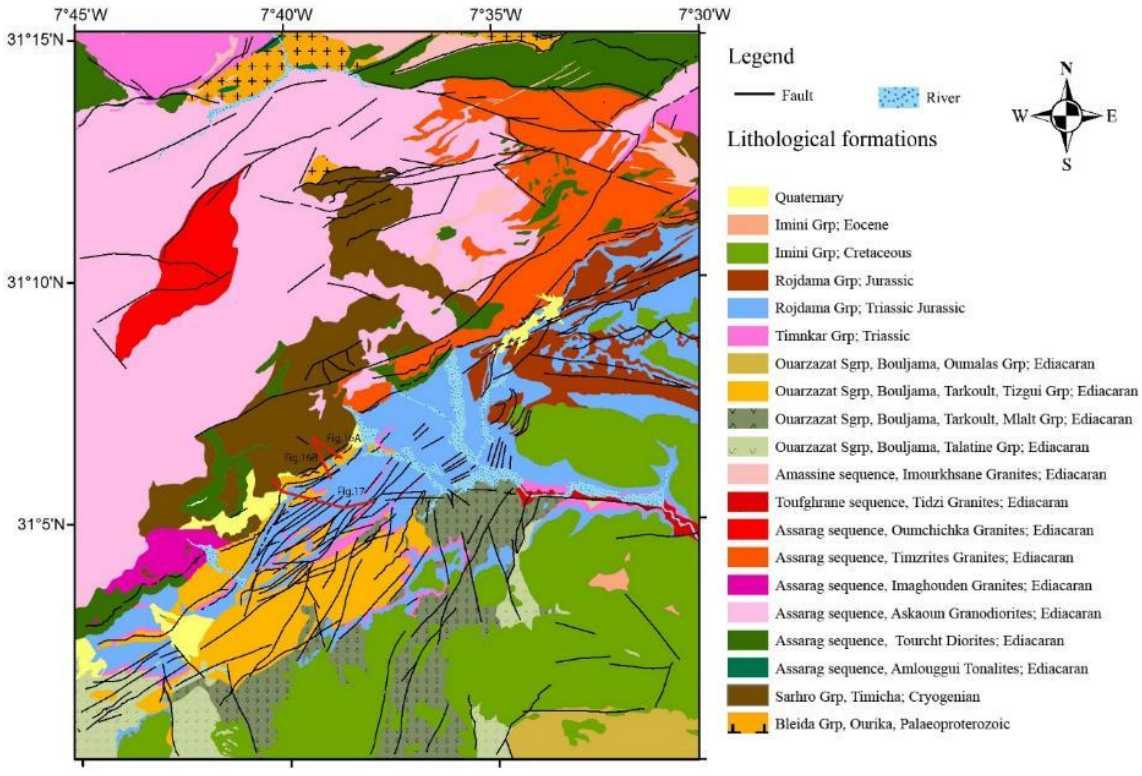


Fig.2. Geological map of the study area, the south atlasic fault relates the plutonic massif of Ouzellarh to the north represented in reddish colors, and the Siroua volcanic massif to the south along with the mesozoic sedimentary deposits (modified after chevallier et al., 2002)

Materials and Methods should be described with sufficient detail to allow others to replicate and build on published results. New methods and protocols should be described in detail, while well-established methods can be briefly described and appropriately cited. Please note that the publication of your manuscript implies that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose any restrictions on the availability of materials or information at the submission stage.

Research manuscripts reporting large datasets that are deposited in a publicly available database should specify where the data have been deposited and provide the relevant accession numbers. If the accession numbers have not yet been obtained at the time of submission, please state that they will be provided during review. They must be provided prior to publication.

Interventional studies involving animals or humans and other studies that require ethical approval must list the authority that provided approval and the corresponding ethical approval code.

3. Data and Methodological Approach

The research utilized a Landsat 9 OLI satellite image, specifically scene LC92020382021316LGN01, acquired on November 12, 2021. This image, with eight spectral bands at 30 m resolution and a panchromatic band at 15 m resolution, was instrumental in detecting structural details. Remote sensing techniques, especially using the Landsat data, played a crucial role in identifying key geological features. To enhance the accuracy of the satellite data, radiometric and geometric corrections were applied, ensuring the image represented the earth's surface accurately and aligned with real-world coordinates. The panchromatic band was particularly useful in addressing spatial resolution issues. Image enhancement techniques, such as histogram equalization, further improved the quality by removing noise and correcting errors. Digital Elevation Models (DEM) were also used as essential tools for generating hillshades, which helped highlight topographical variations and major faults, complementing the remote sensing data.

This study utilizes Landsat 9 OLI data for fracture mapping. Similar studies in the High Atlas, such as that by Ait Inoh et al. (2023), have used Landsat 8 OLI and ASTER-GDEM data. While Landsat 8 and 9 have similar spectral characteristics, the use of ASTER-GDEM provides additional topographic information that can aid in lineament interpretation. Other studies in the Anti-Atlas have explored the use of Sentinel-2B, Sentinel-1A, and ALOS PALSAR DEM data for lineament extraction (Baid et al., 2024), highlighting the potential benefits of using radar data in certain geological settings, although Landsat data offers a valuable balance of spatial resolution and spectral information for regional-scale fracture analysis

Principal Component Analysis (PCA) was employed to reduce the dimensionality of the data while retaining essential variance (Argialas et al., 2004; Thannoun, 2013; Mah et al. 1995; Si Mhamdi et al. 2017; Saidi et al. 2020; Bentahar et al. 2020; Es-Sabbar et al. 2020; Ouhoussa et al. 2022). The analysis showed strong correlations between the visible and infrared spectral bands, with the first four bands containing over 99.5% of the total data. This allowed for detailed geological interpretations using false-color composite images. Histogram equalization, particularly using a Gaussian filter, was applied to improve the contrast of the images, highlighting low-contrast areas while spreading intensity values across the image. Lastly, spatial filters, including Edge Detection, Laplacian, and Sobel filters, were used to refine the lineaments and enhance their visibility. The 5×5 size filters, along with sharpening tools, provided optimal results, producing lineaments closely aligned with the geological structures of the terrain.

Fieldwork was the basis of this study, providing critical ground-truthing and verification of remote sensing data. The importance of combining on-the-ground geological data with satellite imagery cannot be overstated, as it allowed for a more precise faulting system analysis. This integration of field data

helped refine the identification and mapping of lineaments, which culminated in the creation of a fracturation map. The data collected during fieldwork were indispensable for interpreting and validating remote sensing findings, ensuring a robust and accurate geological interpretation.

By synthesizing remote sensing tools like DEM and satellite imagery with comprehensive fieldwork, the study produced a faulting system analysis that revealed key geological features. This combination enabled the creation of detailed maps that provided insights into the region's geological structures, which are vital for understanding mineralization potential and structural complexities.

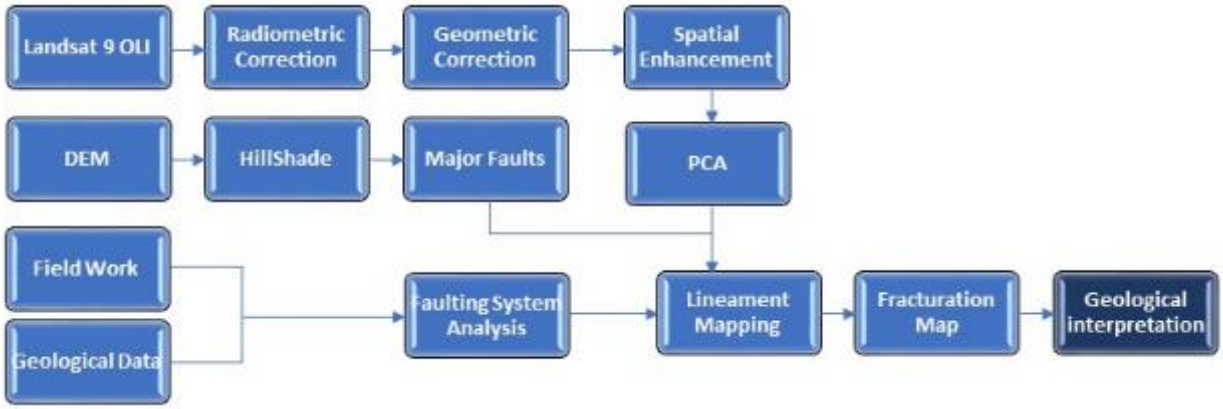


Fig. 3. Flowsheet of the methodology adopted in the present study

4. Results

4.1. Lineament Map Modelling

The application of different filters on the PCA bands and, which were used as input images, allows to highlight linear structures either in the form of shifts between the lines in the study area. These filters provide grayscale or colored images (in case of composition of PCA bands), where the structural lineaments based on the selected direction appear brighter and/or larger than the other features. The maps of discontinuity images were modelled, by manual extraction of lineaments that are often highlighted perpendicular to the direction of the selected filter trend. The final step would be to characterize and remove the stratification lines and rivers, which are nevertheless longer and wavy.

When the directional filter is applied, the gradients highlight all gap imagery corresponding to any lithological (contact between different lithological units) and/or structural (fault, fracture, and joint) discontinuity. To give significance to the lineaments corresponding to structural lines extracted by remote sensing, the discontinuity map (Fig.4). is cross-referenced with additional support data (geological map, topographic map, and field observations) to eliminate lithological discontinuities, contour lines, and man-made lineaments (asphalt roads, railroads, etc.). The resulting map shows a peak of corrected structural lineaments in the study area.

The fracture map of the studied area, highlights the directions and frequencies of manually extracted lineaments. These fractures represent potential zones of structural weaknesses, which could be associated with mineral deposits, Sassioui et al. (2023) demonstrated a clear relationship between lineaments and hydrothermal alteration zones, suggesting that fractures can act as conduits for mineralizing fluids. The extracted lineaments were derived from the enhanced imagery through a combination of spatial filtering and manual extraction techniques, which provide insights into the tectonic setting and potential mineralization trends (Fig.4).

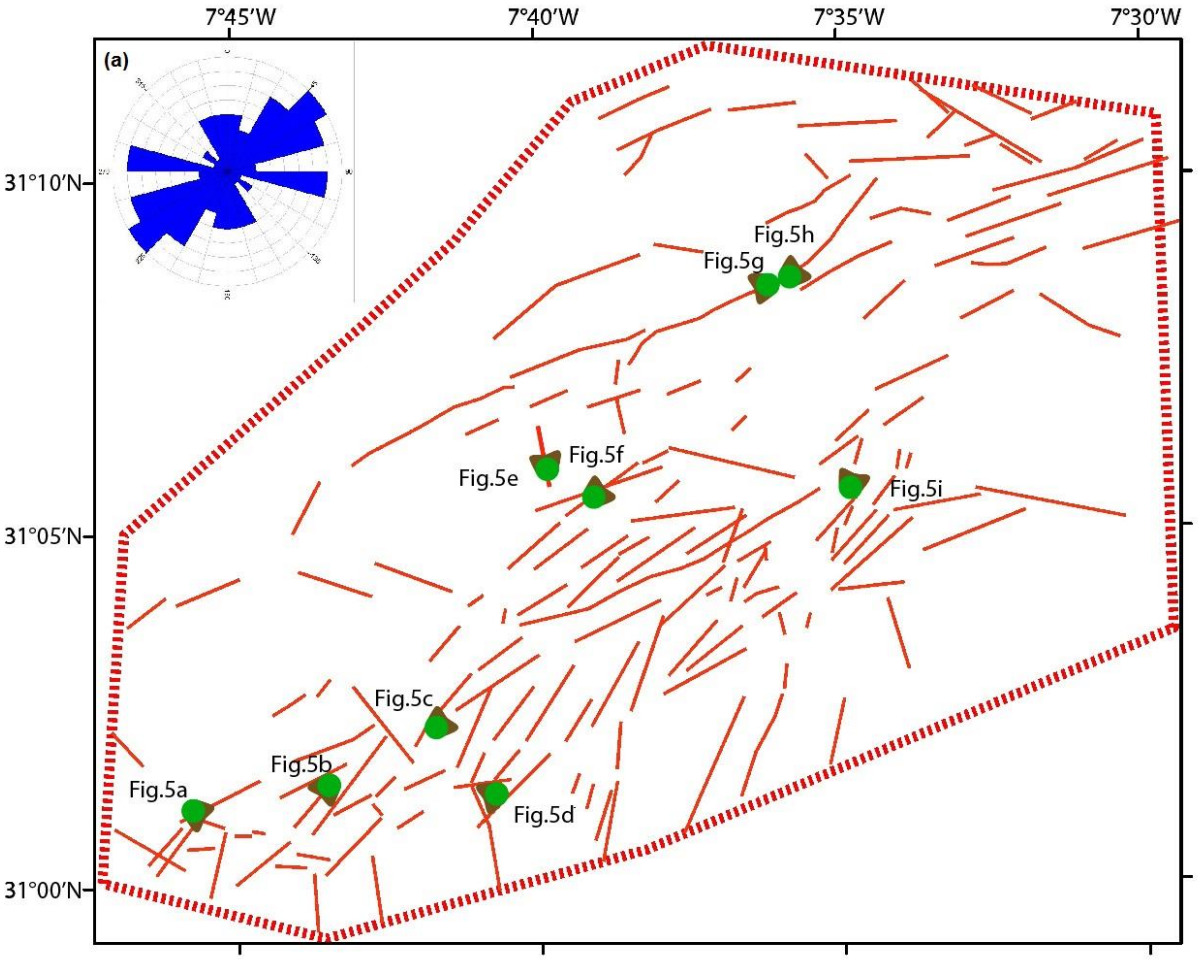


Fig.4. Fracture map resulting from manual extraction (a) direction diagram of the manually extracted lines

4.2. Directional Distribution

The lineament map indicated that the area is subject to brittle deformation materialized by four families of faults oriented N-S, E-W "NE"-"SW" and "NNW"-"SSE" affecting all the formations of the study area (Fig.4), which is consistent with findings in both the Western High Atlas (Ait Inoh et al., 2023) and other regions of Morocco (Ouahzizi et al., 2023), suggesting a regional control on fracture development related to the Hercynian orogeny. The influence of NE-SW and NW-SE oriented faults on the morphogenesis of karst depressions in the Middle Atlas (Naouadir et al., 2023) further supports this regional trend. The structural analysis by remote sensing alone is incapable of defining several properties essential to characterize these faults, therefore it was essential to schedule several field missions, in order to better quantify the distribution, and especially the chronology between these faults, and thus the age of the functioning or re-working of these faults, and finally, to validate some of the fractures resulting from satellite detection in the field to give the map more credibility.

The present structural configuration of the Atlas domain results from the superimposed effects of the Hercynian and Alpine orogenic cycles (Mattauer et al., 1972, 1977; Charrière, 1990 ; Laville and Pique, 1991 ; Laville et al., 2004). The central Anti-Atlas took its turn to be damaged more intensely since the Pan-African orogeny, materialized by the major Anti-Atlas fault, followed by a phase of relaxation in the Cambrian where it was hidden under the deep paleozoic sedimentary bassin, its basement reappears in the terminal Carboniferous, during its flexing uplift in the Hercynian buttonholes

"boutonnières" (Leblanc, 1975 ; Hassenforder, 1987 ; Soulaimani, 1998 ; Burkhard et al., 2006 ; Baidder et al., 2008 ; Michard et al., 2008 ; Soulaimani et al., 2014; Hejja et al., 2020 and Aabi et al., 2022b). The fact that the Tidili region lies between the South Atlas Fault and the Major Anti-Atlasic Fault implies that it would have been influenced by branching and meeting of two major structural lineaments anti-atlasic in the south and high atlasic in the north.

4.2.1. "NNW-SSE" structures

This is a relatively limited network found across the whole study area, but with a small percentage (4% from total detected faults). Trending from N140 to N160 and dipping to the west, these structures are wide, long and easily distinguished chemically or by the bed foldings in the south of the map, (Ait Qalla fault), on the other hand they are generally narrow in the other parts of the map. Structurally, the pitch shows several traces, the last of which is of a dexterous and inverse pattern. These faults show the trace of the Hercynian orogeny on the Siroua Massif (Thomas et al., 2000), however this network is the youngest, crossing all the other structures as well as the para-(SAF) faults, and hence it has re-functioned during the final phases of the Alpine orogeny.

4.2.2. "E-W" structures

Two families of faults are distinguished in this region. The first family has a direction ranging from N70 to N100 with a moderate dip mainly towards the north (E-W/N). The second family ranges from N90 to N120, with a strong dip towards the south and southeast (E-W/S). These are long, slim faults representing 20% of the faults mapped. The E-W/N structures are present in all geological formations, and the measured kinematics of the pitch show mainly a senestral strike-slip with a reverse component. This network cuts the NE-SW structures, indicating it is a manifestation of the alpine orogeny, with the Imini fault being a notable example (Algouti et al., 2022). The E-W/S structures, although restricted, are rich in iron. These faults are absent in the Mesozoic formations, and the pitch is often of the thrust type. This network is more ancient and only cuts the N-S fault family. (Fig.5a and c), following the general pattern of the major anti-Atlasic fault (E-W in the Siroua massif) then this network is probably pan-african (De Lamotte et al., 2009).

4.2.3. "NE-SW" structures

By far, this is the most dominating network reported all around the map, it includes faults with a direction between N30 and N60 and moderately dipping towards the north-west. These faults are sub-parallel to the directions of the lithological formations in the study area, sometimes implicating the reversing of the triassic beds, or uplift of basement rocks. They are marked by their kilometric lengths and their metric openings (Fig.5b, f, g and h). In many areas, the fault mirror is marked by striations testifying to a sinister strike-slip fault, they sometimes keep the remnants of the collapse during the atlasic extension phase (Fig.5i), The age of this network should be considered of infra-cambrian linked to the opening of the proto-Atlantic ocean, given that, firstly, this network representing many kilometric faults such as Azdem fault, Tawayalt-Agandiy fault, and primarily the SAF, geometrically the same equivalent of the Tizi-n-Test fault (or Setti Fadma fault) which was well described by Qarbous et al., (2003), these authors concluded that the mechanism of these faults dates back to the Early and Middle Cambrian. Additionally, to that El Moume et al., (2020) have dated the superabundant dyke swarms of the Tidili region to the Ediacaran-Cambrian period and were associated with the Central Iapetus Magmatic Province (CIMP), these dyke swarms record the same NE-SW trend all over the map (Fig.5j, Fig.8b). This orientation is a key feature linked to the opening of the proto-Atlantic Ocean during the infra-Cambrian period, which has been debated in the discussion chapter.

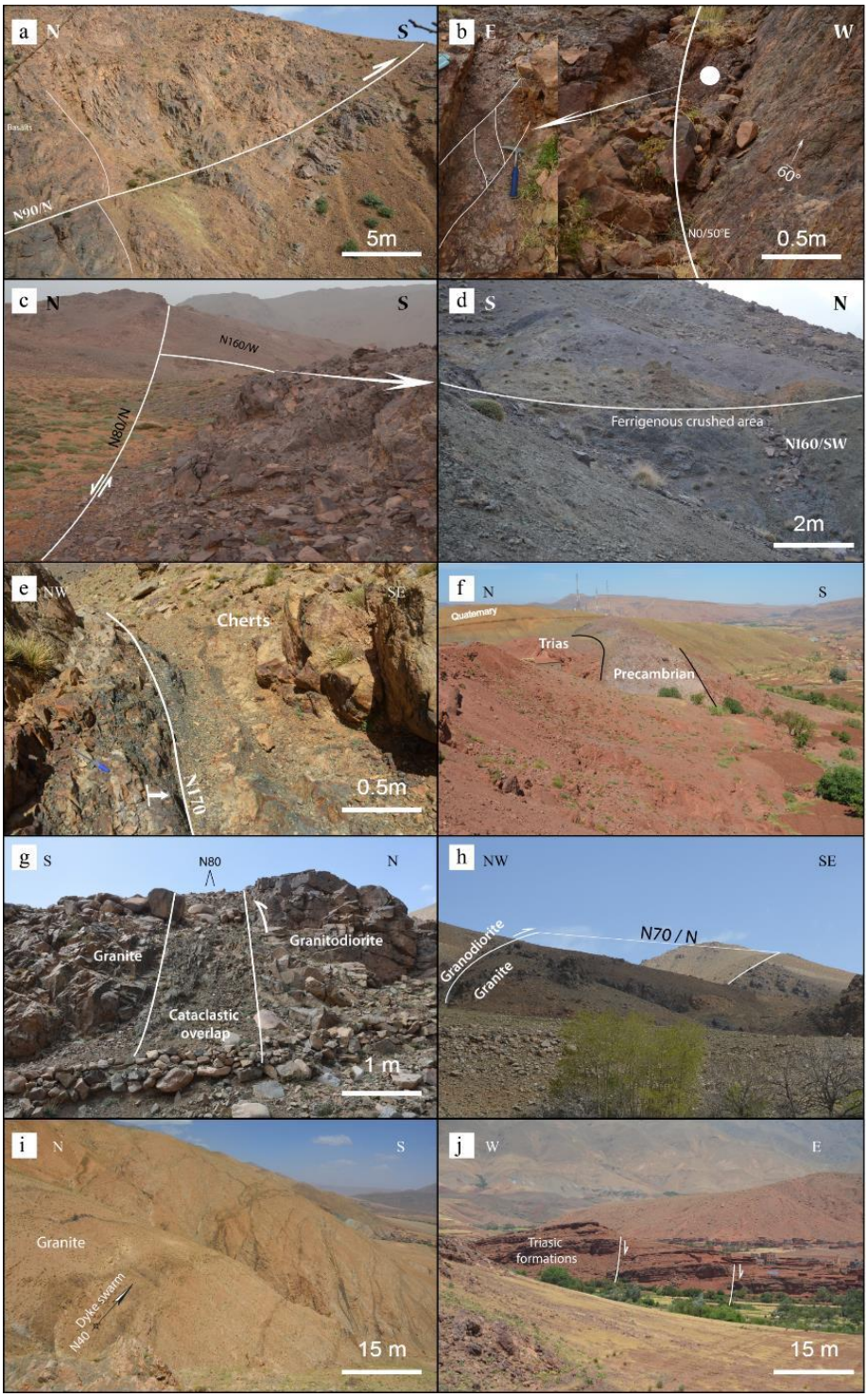


Fig.5. Many structures from the field showing (a) thrust fault of the Tourecht diorites on andesites, (b) Offset fault between right andesite and rhyolitic flows, (c) N70 reverse fault in the andesites cutting a N40 fault, (d) metric fault embedded in volcanic deposits filled with crushed materials rich in mineralization traces, (e) chlorite clay rich structure in the quartzites of the Sarhro group, (f) Faulting in triassic clays tied to the SAF, the core of the faulted fold exposes ediacaran volcanic materials, (g) Metric fault sloping towards the north connecting, to the right, the granodiorites of Askaoun and the leucogranites of Timzrite, the crushed material of the fault is similar to greywackes of Saghro present there more towards the south of the image under the granites, (h) the same "g" fault taken towards the east, (i) triassic tilted blocks on normal faults (j) network of infracambrian dykes invading the Assarag magmatic sequence.

4.2.4. "N-S" structures

Counts N170 to N10, this network holds 15% of the total number of detected lineaments, mainly it has short faults except for the structure in the south of the map laying in the Ait Maghlif plateau described thoroughly (Emran and Medina, 2016), field measures have concluded that this network's well expressed in the Precambrian basement (Ouarzazate Group, Assarag sequence and Sarhro group) and almost absent in mesozoic formations, this fault network is dominantly a reverse fault with a dextral strike-slip component dipping 45° to the west with a 60° Pitch, which are also quite oxidized, ferruginous and large in diameter (Fig.5d). Chronologically this network is considered the oldest in this, being cut by all other fault families, Following the description of other fault networks, a pan-African age is suggested for this network.

4.3. The south atlasic fault typical case from field

A clear illustration of the southern Atlasic fault is well expressed in Fig.6, in this area the SAF crosses the Assarage plutonic bodies, the thrust is marked by fragments deciphering the vergence of the fault and a crushing zone, the thrust traces a boundary between diorites and altered Rose granite. The granites are crossed by aplitic veins (Fd>Qz), the infracambrian opening phase filled the earliest by basic dykes in major N100 and N45 direction at northern vergence, the northern front of the dyke is more altered and chloritized with a highly iron-oxidized and brecciated fringe, implying emplacement of the dyke in a tectonically active location with increasing deformation.

The alteration halos observed in the zone contain parts with little alteration and others with cataclasite alteration, raising the question of the cold alpine deformation phase. Several parts of the granitic batholith display rounded fragments of diorite bathed in magma "magmatic intrusion breccia" meaning that the fault wall was emplaced as it was crushed, in line with the location of the magma body. NE-trending dykes are passively emplaced, implying tectonics preceding dyke uplift, the boundary between the dyke and the granite is sometimes filled with goethite iron oxide, and a hydrothermal phenomenon affects the dykes, making them laminated. Alteration is mainly amphibolite and chlorite. The dykes occur in two networks

N40, the main network and the most widespread in the region.

N70 is a satellite network always linked to the first network.

This implies a dextral transtensional opening in a major direction N145 and a sinister compression in direction N55 contemporaneous with the Hercynian orogenic phases.

Triassic basic dykes are to be differentiated from the dykes of the region since they have high levels of iron concentration, and they are polygenic and mainly basic, with reworked Triassic fragments with a conglomeratic aspect. The reworking took place in a soft state, and to explain this phenomenon, the triassic normal faults reworked from magmatism to hematitized breccia lenses as deposition progressed, the massive basalt became brecciated near Ediacaran acid volcanic breccias.

The tuffs are crisscrossed by a network of fractures and hematite, goethite and quartz ferritic levels.

Probably linked to triassic events, the hydrothermal veins are composed of two superimposed phases that can be distinguished macroscopically and by mineralogical microscopy.

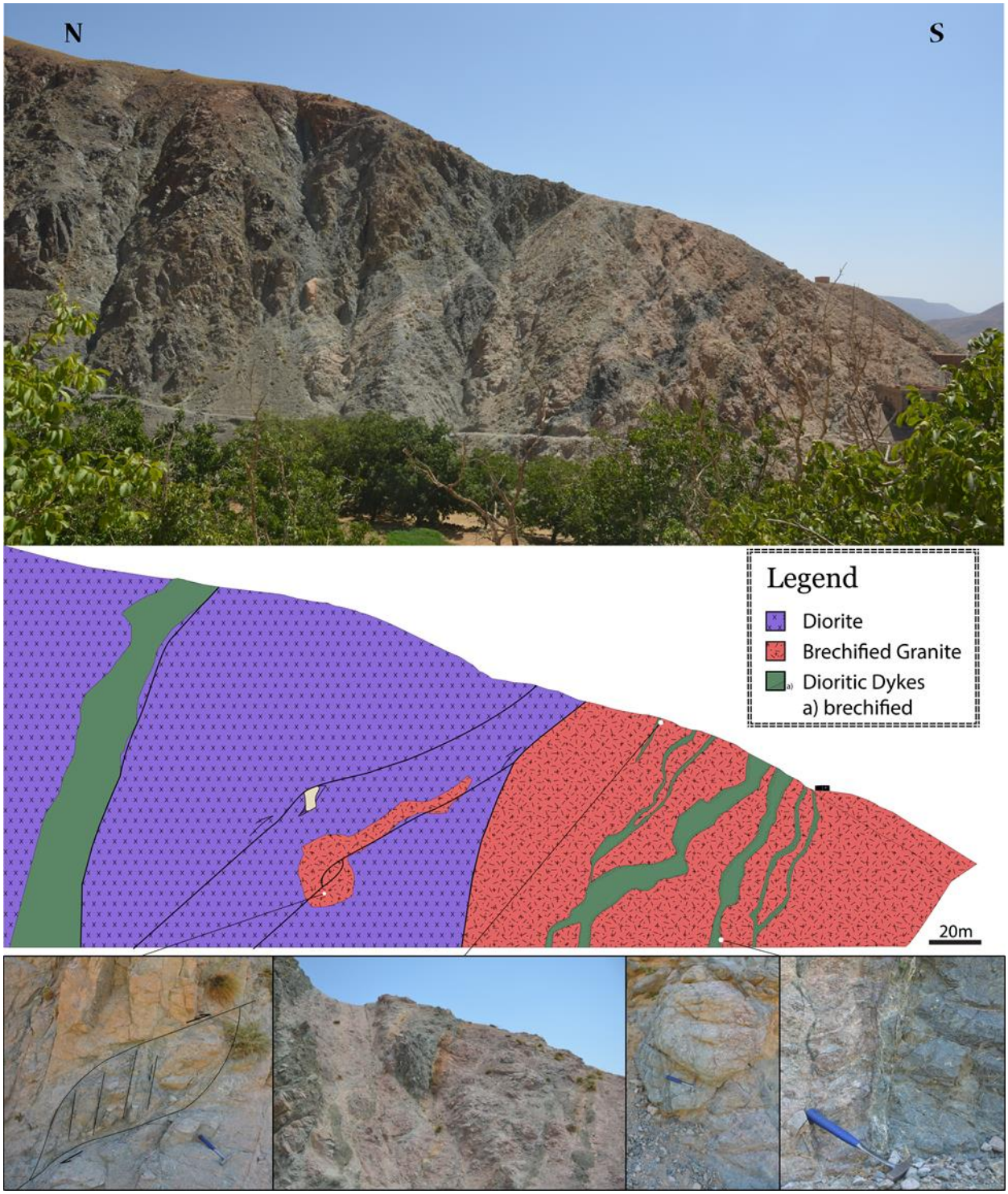


Fig.6. A cross-sectional representation of the southern Atlasic fault and several morphologic and clastic consequences

4.4. Comparison between the Geological Map and the Lineaments Map

It appears most reasonable to compare first between the geological map established by Chevallier et al., (2004) and the lineaments deduced from the analysis of satellite images and based on this interpretation that the reasoning for establishing a new map of fracturs was established for the area of adjustment between the High Atlas and the Anti-Atlas on the southern atlas fault (Fig.7). The comparison between the fractures extracted by teledetection in the study area and the faults modelled

from the 1:50,000 geological map (chevallier al., 2002) displays a high level of resemblance, in particular with regards to the fractures of the recent Alpine orogeny. More faults have been generated by this new method than those existing in the geological map.

Statistically the orientation rosettes of the extracted fractures and those of the faults of the established map (Fig.8a), show a great similitude in the main trends. In summary, this method suggests new major faults by specifying their continuities and confirms the structural work already recognized, which will be useful for future studies, especially the structural interpretation of the chronology of the action and reworking of fractures during the various orogenies that have brought into profile this part of the link between the central anti-Atlas and the high Atlas, and the interaction basement-cover.

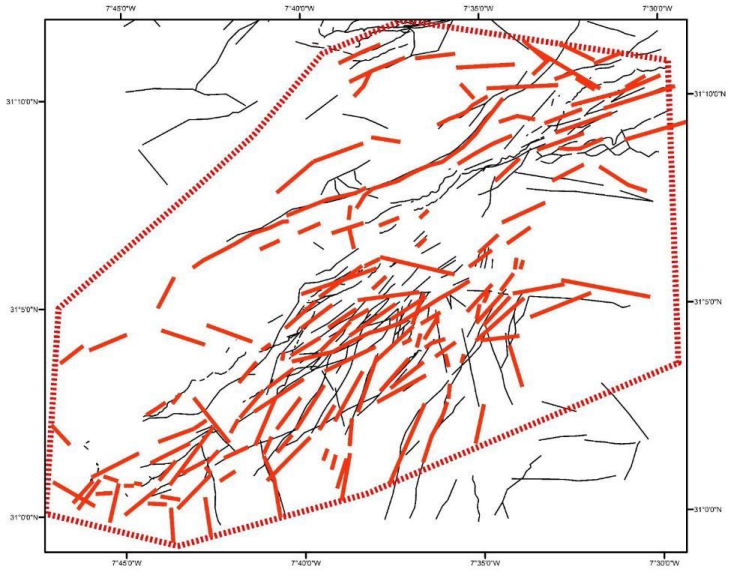


Fig.7. Combination of manual extracted lineaments (in red) and faults drawn on the geological map of the area (in black)

4.5. Lithological Control Over the Fracture Distribution

To understand the parameters controlling the fracturing distribution and their link to lithological properties, the thickness of lines in each domain was examined. This was achieved using lineament density analysis produced from automatic mapping methods, using ENVI (Fig.9), this analysis calculates the relative ratio of lines and their intercrossing in each corner of the map. This analysis reveals high fracture densities shown in the Precambrian basement and triassic formations close to the SAF, the Mesozoic formations have the lowest line densities, this is also checked in the field, as they correspond to calm horizontal plateaus, sometimes mildly tilted in failing ground. The fracturing is evident particularly between the volcano-detrital units and emphasizes each one of the units, while the major structures in the granitoids are thrusting overlaps over the Ouarzazat group and the triassic detrital formations, with no trace of these plutonic rocks left behind on the southern flank of the SAF, which indicates that the rheology of the rocks has controlled the distribution of fractures, and has implied the materialization of other formations as soap layers in front of the hard plutons. Another fracture density is recorded in the precambrian basement of Sarhro group. In addition, high line density matches the SAF direction, this explains the high stress and tension this major fault had been through during a large time frame. Based on the field investigations, a summarized column of this part of the Siroua-Ouzellarh link has been established, recapitulating all mesozoic sedimentary formations deposited unconformably on precambrian volcano-sedimentary groups and associated magmatic intrusions (Fig.12).

In short, the rheology of the geological formation as a whole, plays a decisive factor in the spatial fracture distribution.

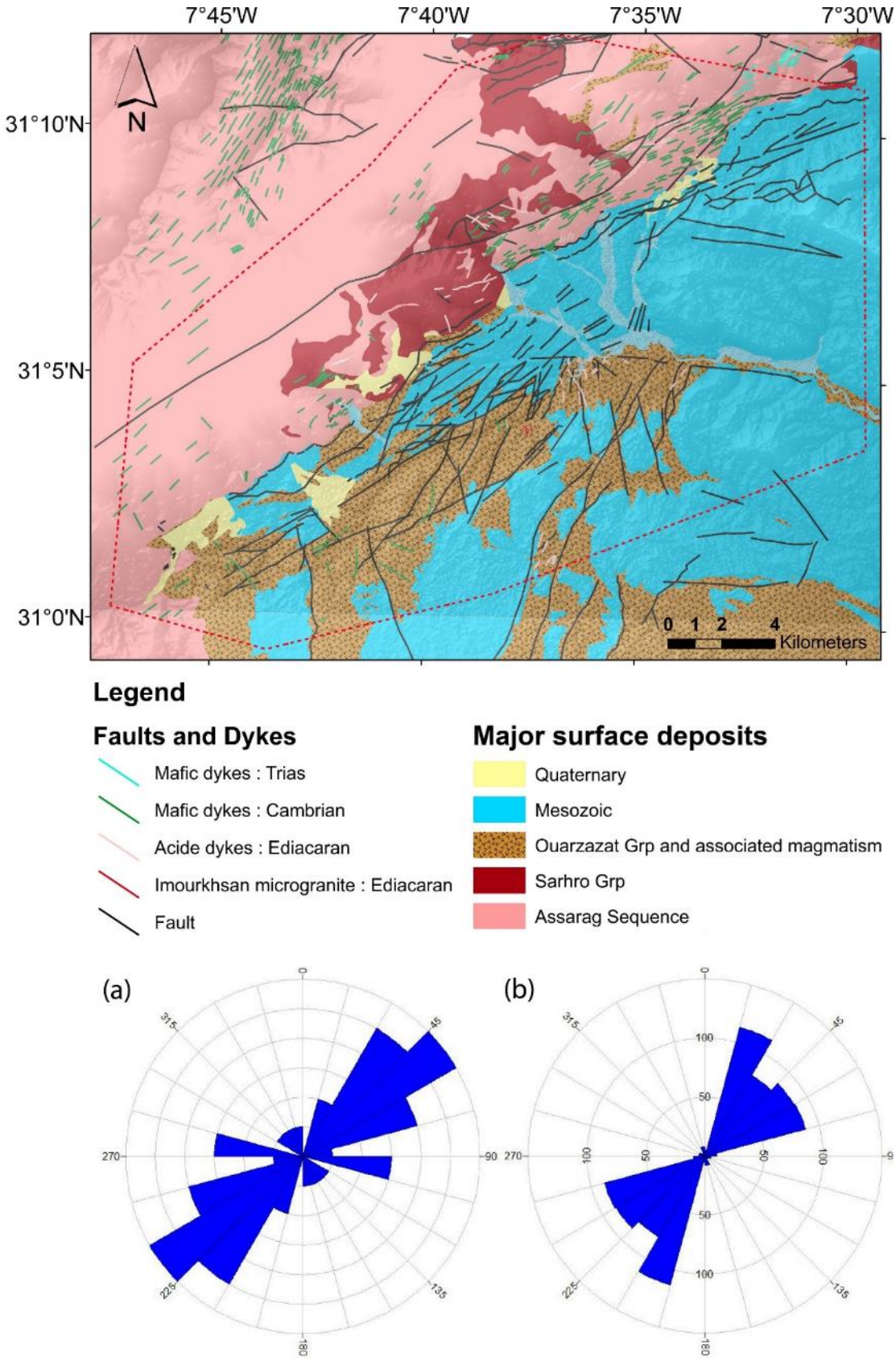


Fig.8. Simple map of the area showing major geological groups and intrusions (redrawn after chevallier et al., 2002). (a) directional rosette of geological map fractures. (b) rosette of infracambrian dyke swarm directions

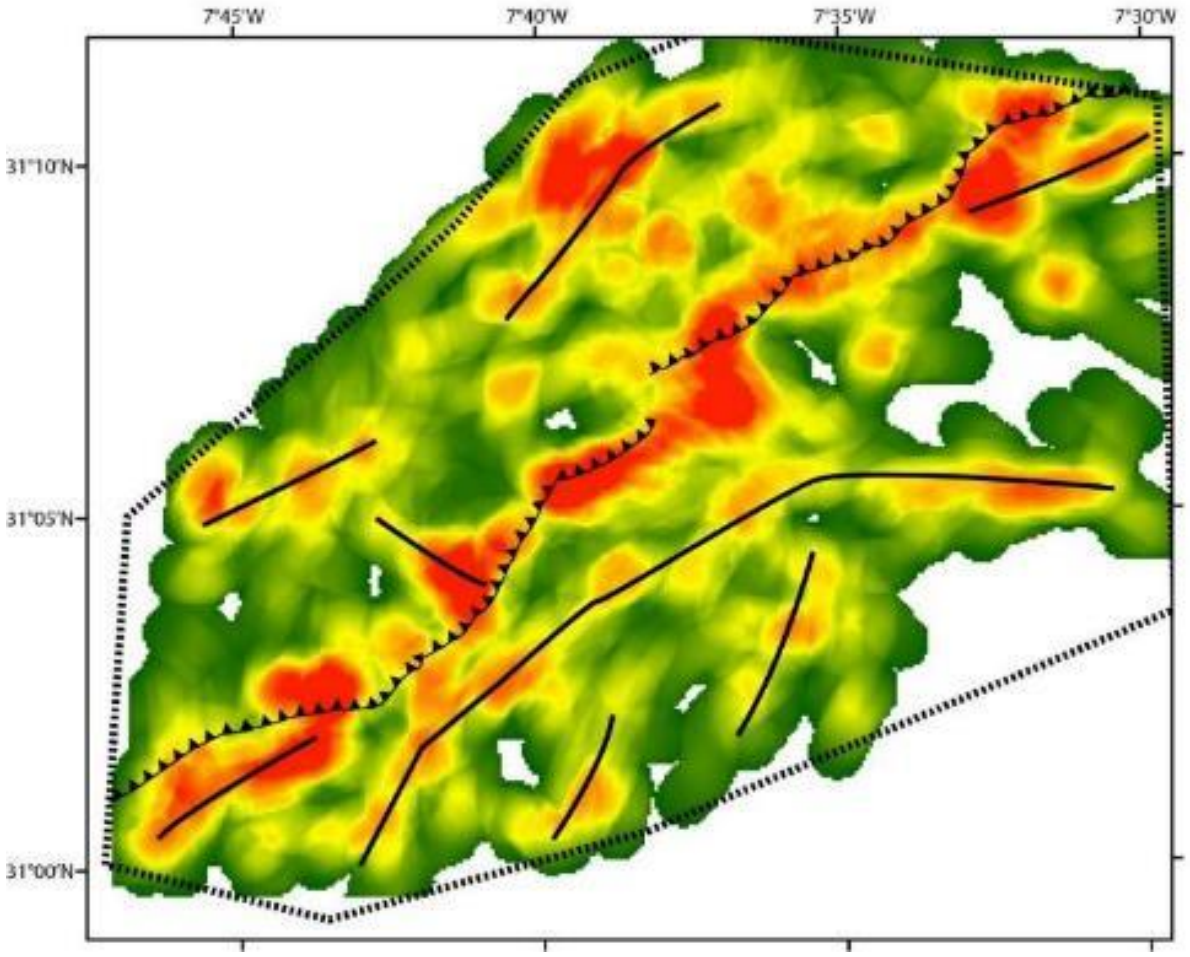


Fig.9. Fracturing density map produced from automatic lineaments

4.6. Major Discontinuities along the Tectonic Style

Geological formations in Tidili know two main gaps (discontinuities), The first one is set between the massive volcanic group of Ouarzazat and the sequence of Assarage, Although these two formations are relatively close in age, it is only through faults that they are connected, in which the volcanic group is formed of tuff and conglomerates that can generate zones of weakness in front of the granite, The second is the contact between the ediacaran-trias, with the triassic rocks overlying the ediacaran in unconformity. The lower Mesozoic succession consist mainly of siltstone and sandstone and basalts These formations played the role of slides, facilitating the overlapping of magmatic materials of Ouarzazat or Assarage according to the SAF network, all these information are well described in Fig.10 and 11

Another gap lays between the volcanic Sarhro group and the Assarage sequence, despite the proximity of both formations, no direct conform relation is deduced in this area, moreover the age of Sarhro group is still up for debate. In summary, the two mechanical discontinuities described above play an important role in the propagation and distribution of fractures.

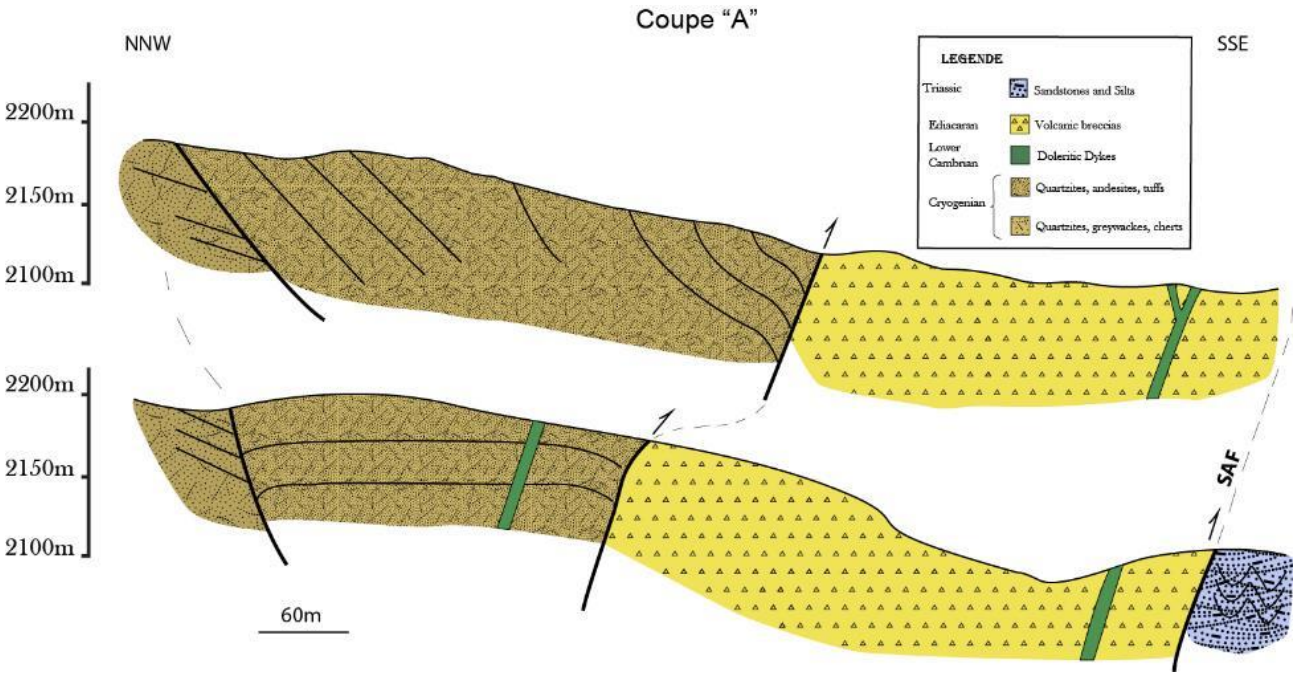


Fig.10. Geological sections made perpendicular to the southern atlasic fault network, showing a first overlap of quartzites, greywackes and associated volcanism of the Sarhro group drawn in brown (the left of the Fig.) on the volcanic breccias of the Ouarzazat group at the same overlapping on the triassic detrital sediments very folded, by means of NE faults dipping northward

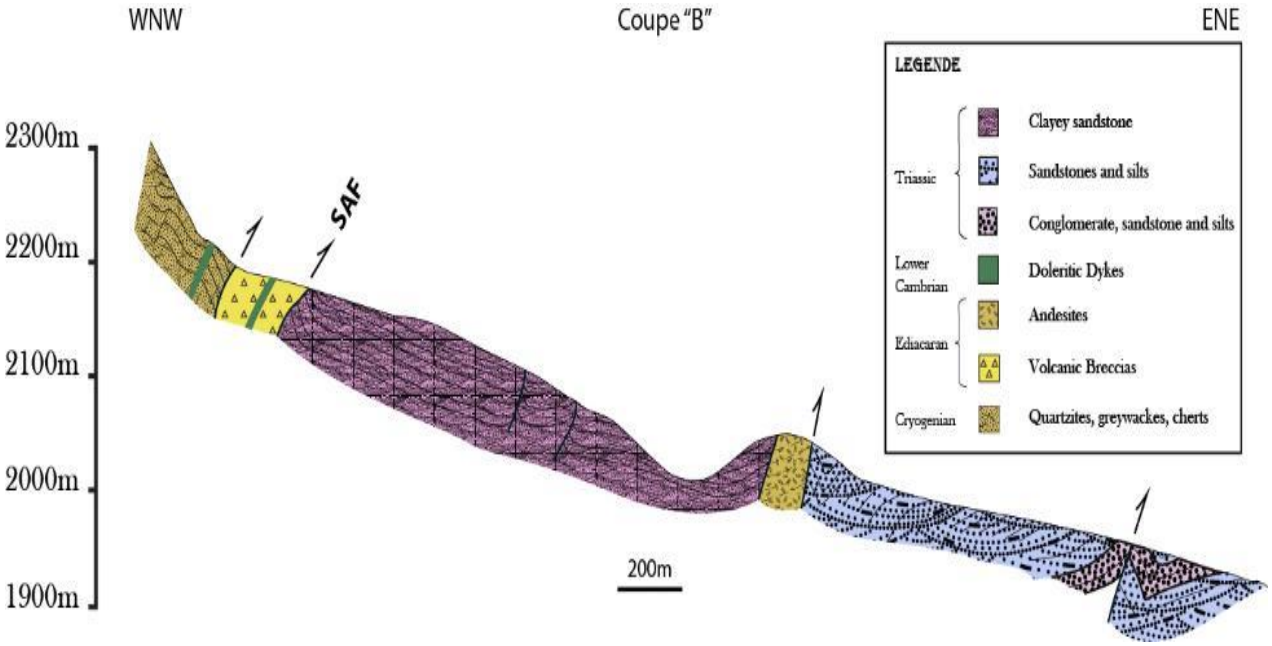


Fig.11. Geological profile demonstrating a double overlap in unconformity, the Sarhro group on the Ouarzazat group thus, on the Triassic deposits following the SAF, the folds of the Triassic basin are characterized by the exhumation of Ouarzazat group materials

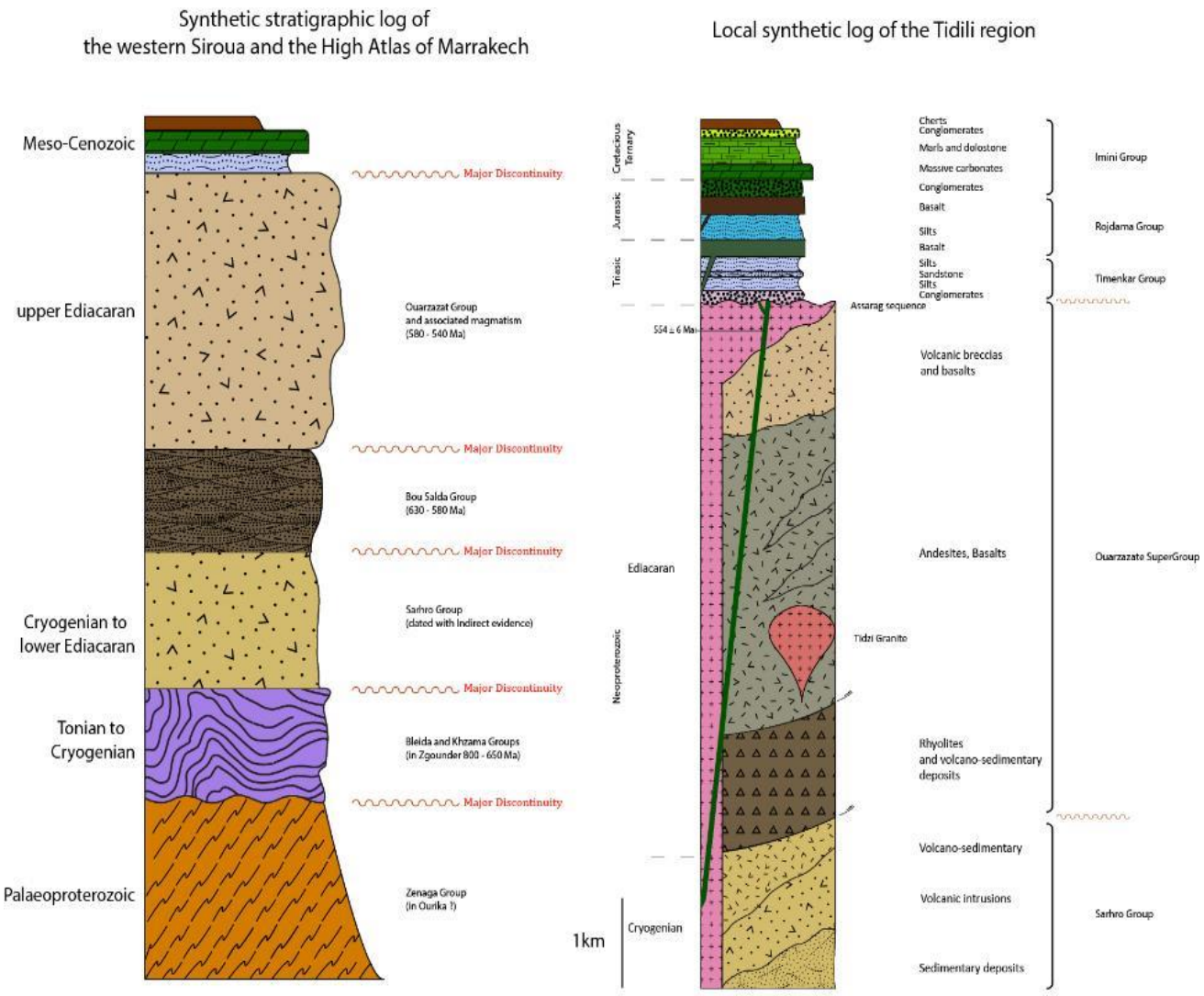


Fig.12. Simplified synthetic lithostratigraphic column of the Tidili area (studied zone).
MD: major discontinuity LD: local discontinuity

4.7. Pitch Measures and Recent Tectonics

Certain authors have proposed, on the basis of apatite fission track and (U Th)/He ages, that the entirety of the faults in the Eç-çour zone have a replay age lower than the Triassic (Missenard et al., 2008; Balestrieri et al., 2009; Domènech et al., 2016), concordant to that, a systematic measuring done in the study area distributed along the SAF, calculating the data obtained were analyzed to provide a stress direction specific to (Admou and Juteau, 1998) each stereogram of the focal mechanism (Fig.13), almost all stereos demonstrate NNW-SSE to N-S trending stress direction consistent with a left slip-thrust mechanism of the NE fault family (SAF), and a right lateral for the NW, some areas would show a normal or an uncompensated mechanism (Fig.5i), the major stress mechanism changes slightly to NNE in the eastern part of the map and southern part where the lithology is mainly composed of ediacaran volcanism of Ouarzazat group in Siroua, combining all the fracture families

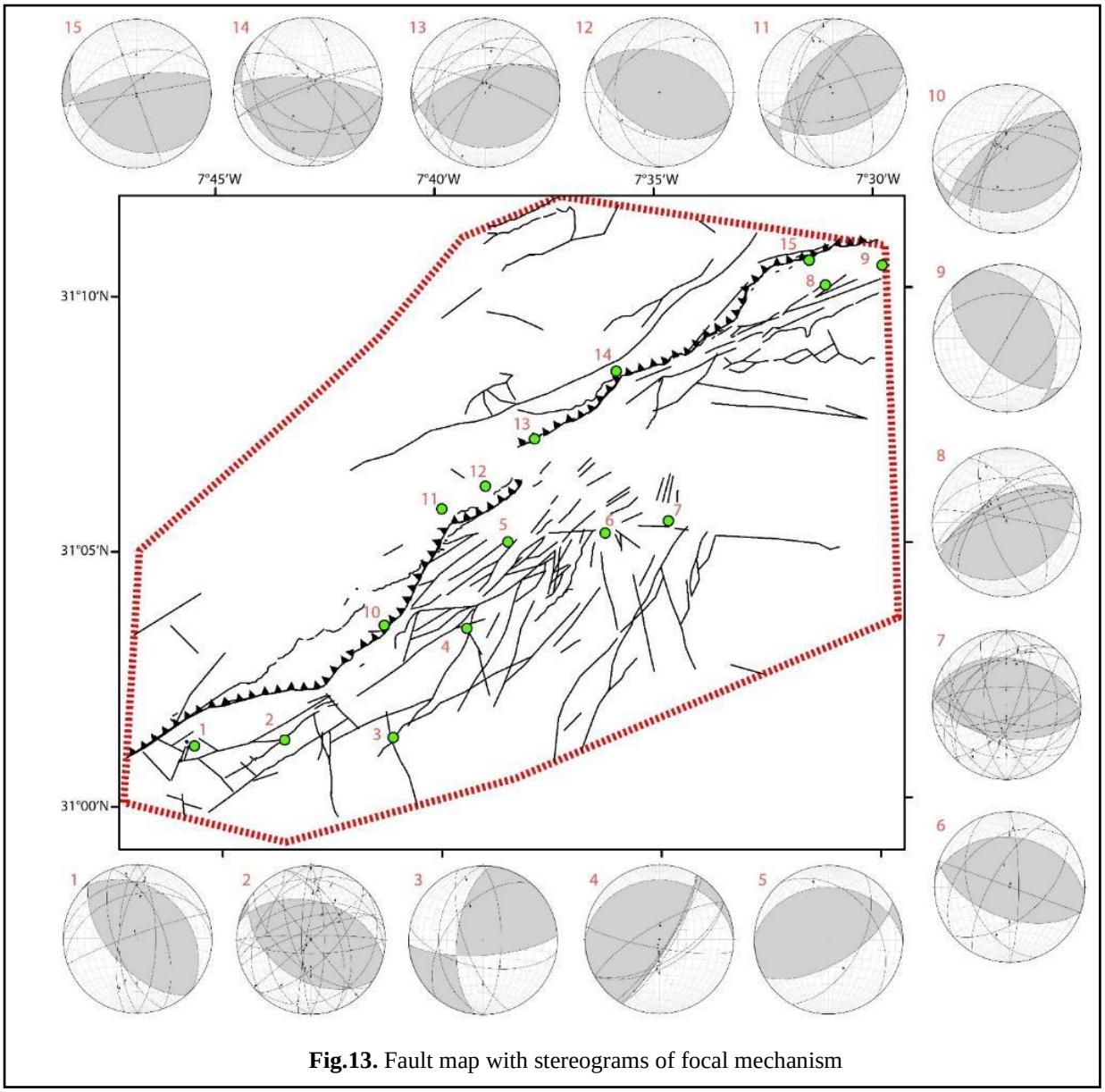


Fig.13. Fault map with stereograms of focal mechanism

5. Discussion

The study provides a comprehensive analysis of the Tidili region's structural features, with a focus on the identification and characterization of lineaments using remote sensing techniques. The findings show a complex network of faults and fractures, which reflect the region's dynamic geological history shaped by multiple orogenic cycles. This discussion will synthesize the key findings, contextualize them within the larger geological framework, and explore their implications.

5.1. Structural Lineaments and Their Geological Significance

The identification of lineaments through the application of directional filters on PCA bands has provided a detailed map of the region's structural discontinuities. The study's approach to cross-referencing these lineaments with additional geological data, such as topographic maps and field observations, has allowed for the distinction between lithological and structural discontinuities. This methodological rigor has ensured the reliability of the structural map produced, echoing similar approaches used in structural geology studies (El Janati et al., 2014; Mahdy et al., 2024)

The structural analysis of the study area revealed four primary fault orientations: “NNW-SSE”, “E-W”, “NE-SW”, and “N-S”. The “NNW-SSE” faults, although limited in number, are significant for their width and chemical distinctiveness, particularly in the southern region, and are likely reactivated during the Alpine orogeny. These structures, representing the youngest network, highlight the importance of ongoing tectonic activity in the region. The “E-W” faults, comprising two distinct families, demonstrate both senestral and reverse movements, with origins possibly related to the Alpine and Pan-African orogenies. The “NE-SW” faults dominate the region, associated with significant lithological features and traced back to the infra-Cambrian period, linked to the proto-Atlantic Ocean opening. Finally, the “N-S” faults, the oldest in the area, exhibit reverse and dextral strike-slip movements and are also attributed to Pan-African tectonics.

5.2. Tectonic History and Fault Chronology

The results suggest that the present-day structural configuration of the Tidili region is the product of overlaid tectonic events. The region's proximity to two major sutures (the South Atlas Fault and the Major Anti-Atlasic Fault) has played a critical role in shaping its geological landscape. The influence of the Pan-African orogeny is evident in the older fault networks, particularly the N-S structures, which are primarily associated with the Precambrian basement (Ennih and Liégeois, 2008).

The NE-SW network includes several major faults, such as the Azdem fault and the Tawayalt-Agandiy fault, which have been reactivated during subsequent tectonic phases. The study's findings align with previous research, which has also identified the NE-SW trend as a significant feature in the region's tectonic evolution (Thomas et al., 2002)

Emran and Medina (2016) concluded that the active faulting system in the area is a relay system with the Imini and Tawyalt Agandiy faults. Following the same study, the data collected show that the submeridian faults are mostly reverse basement faults with a senestral component. The N-S fault system ends in the north at the Imini fault, after which it vanishes, giving way to NE-SW to E-W reverse faults. To the south, the easternmost faults intersect the ENE-WSW-trending Tawyalt-Agandiy arc fault (Chorowicz et al., 2001). Thus, it can be deduced that the E-W faults (Imini, Tawyalt-Agandiy) are either subsequent to the N-S network or that the entire system represents a relay system connecting these major sequential faults (Fig.14).

The geological history of the Tidili region in Morocco reflects a series of major tectonic and magmatic events that have shaped its structural and lithological framework. Initially, during the Ediacaran and Paleozoic, significant convergence involved the collision of the southern Pan-African and Ediacaran terrains with an ancient Hercynian-Avalonian block to the north. This collision produced prominent east-west (E-W) trending structures in the south and northeast-oriented structures in the north. The tectonic activity also led to the emplacement of late-orogenic granitic magmatism, characterized by Ediacaran granitic intrusions and an associated system of acidic rhyolite dykes. These magmatic events are likely linked to crustal thickening and partial melting due to the orogenic processes (Gasquet et al., 2005). Following this phase, extensive subsidence occurred during the Triassic period, forming a graben or rift valley in the Tidili area. This rift developed parallel to similar structures in the Argana and Oukaimden regions to the north, controlled by a system of normal faults under extensional tectonics. During this period of crustal stretching and thinning, a series of basic dolerite dykes intruded, marking the Triassic-Jurassic boundary. These dolerite intrusions further indicate the region's response to extensional forces and associated magmatism, which is documented in Morocco's rift basins (Laville et al., 2004; Saddiqi et al., 2009). The final major tectonic episode, the Alpine orogeny, brought about the uplift of the Atlasic block to the north and the thrusting of the Hercynian basement, causing northward overthrusting of the Triassic block and reactivating many of the pre-existing structures. This Alpine convergence did not involve any acidic magmatic activity in the region, suggesting that

compressional forces dominated without significant melting of the crust. The Alpine orogeny is extensively studied in the Moroccan Atlas Mountains, providing insights into tectonic deformation and structural reactivation (Michard et al., 2008; Frizon de Lamotte et al., 2000). Together, these geological events reveal a complex tectonic history for the Tidili region, characterized by cycles of convergence, subsidence, and uplift that have formed and reactivated the structural features observed today.

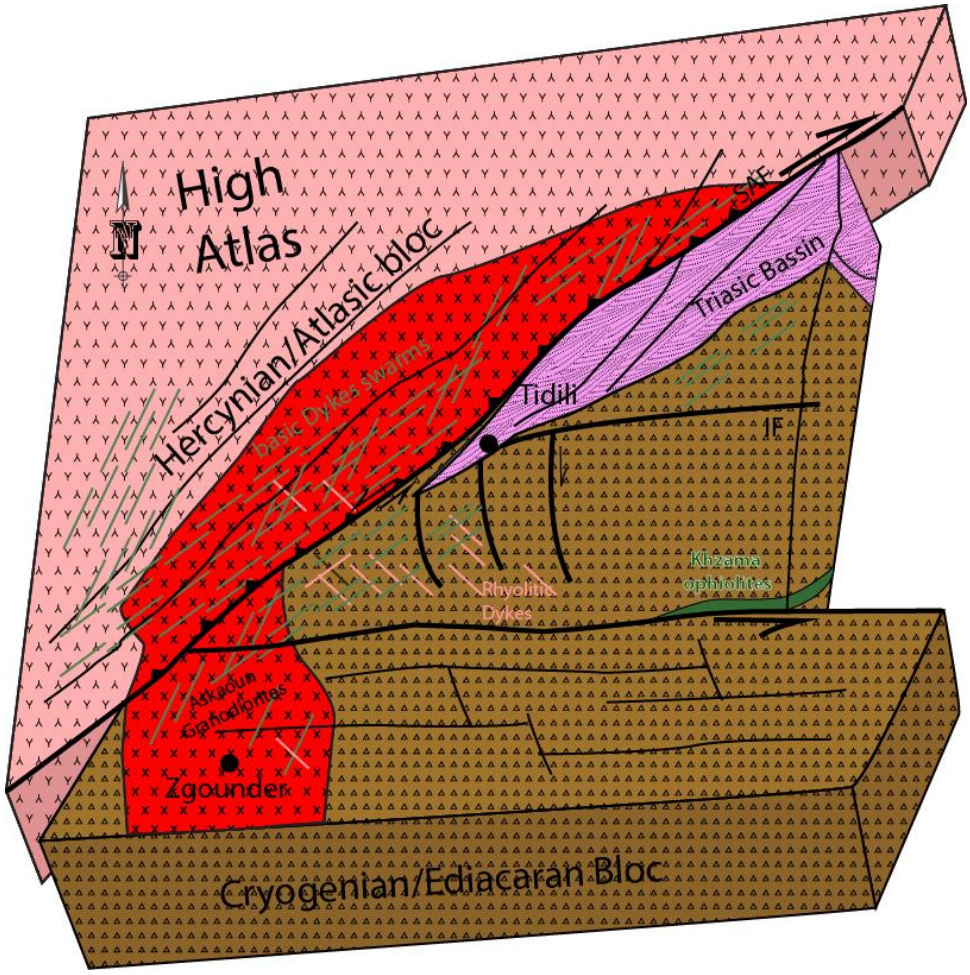


Fig.14. Relay tectonic system of the area; SAF: South Atlasic Fault, IF: Imini Fault

5.3. Lithological Control and Fracture Distribution

The study's analysis of fracture density across different lithological units has revealed a strong correlation between rock rheology and fracture distribution. The Precambrian basement and Triassic formations, particularly those near the SAF, exhibit high fracture densities. This pattern suggests that the mechanical properties of these rocks have influenced the propagation of fractures, with more rigid formations such as granitoids playing a significant role in guiding the development of major structures.

The identification of major discontinuities, particularly between the Ouarzazat volcanic group and the Assarage sequence, further emphasizes the role of lithology in fracture distribution. These mechanical discontinuities have likely facilitated the reactivation of older faults and the formation of new fractures during subsequent tectonic events (Thomas et al., 2002)

5.4. Implications for Regional Tectonics

The findings of this study contribute to a more detailed understanding of the tectonic evolution of the Tidili region. The identification of new faults and the confirmation of previously recognized

structures provide valuable insights into the region's complex tectonic history. The study's methodological approach, combining remote sensing with field validation, offers a robust framework for future research in similar geological settings.

The study also raises important questions about the timing and mechanisms of fault reactivation, particularly in relation to the Hercynian and Alpine orogenies. The evidence of recent tectonic activity, as indicated by the NNW-SSE structures, suggests that the region remains geologically active, with implications for both natural hazard assessment and resource exploration (Missenard et al., 2008; Barakat, 2015; El Aouad et al., 2021). The mapped fracture network in the region can have significant implications for both groundwater resources and slope stability. As demonstrated by Ben Driss et al. (2024) in the Moulouya region, fracturing is a key factor controlling groundwater potential. Areas with high fracture density identified in this study may represent zones of enhanced permeability and potential groundwater accumulation. Furthermore, similar studies in the Rif region highlight the importance of considering fracture orientations when assessing slope stability in tectonically active areas (Akoudad et al., 2024).

6. Conclusions

The structural lineaments in the Tidili region have been carefully examined in the research, which further revealed a complex network of faults and fractures that have shaped the region's geological history. The identification of four main fault orientations "NNW-SSE," "E-W," "NE-SW," and "N-S" is one of the key findings. The "N-S" faults are the oldest structures, connected to the Pan-African orogeny, whereas the "NE-SW" faults dominate the area and are connected to important lithological features and the proto-Atlantic Ocean opening. The "NNW-SSE" faults, which are less numerous but nevertheless exhibit evidence of recent tectonic activity, are another feature of the study that shows the region's active geological activity.

A close relationship between rock rheology and fracture distribution was found by analysing fracture densities across various lithological units. The highest fracture densities were found in the Precambrian basement and Triassic formations. This pattern emphasizes how lithological controls affect the formation and spread of fractures. The study's rigorous methodological approach, which combines field validation with remote sensing, not only offers a solid framework for future research in similar geological settings but also advances our understanding of the tectonic evolution of the Tidili region. The results provide significant insights for mineral resources exploration in the region, and they have significant implications for regional tectonics, particularly with regard to fault reactivation during the Hercynian and Alpine orogenies.

Future research could integrate the mapped fracture network with hydrogeological data (Ben Driss et al., 2024), slope stability models (Akoudad et al., 2024), studies of karst systems (Naouadir et al., 2023), and other geophysical datasets (e.g., Ouahzizi et al., 2023) to provide a more complete understanding of the region's hydrogeological potential, hazard susceptibility, and subsurface structural architecture.

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