Seismotectonic and Geological Mapping around the High and Middle Atlas Junction: Integration of Satellite Imagery and Seismic Analysis in the Tizi N'Isly Basin, Morocco

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Abstract. The Tizi N'Isly basin, located between the Central High Atlas and Middle Atlas of Morocco, features a complex geological and seismic profile. This study aims to precisely identify areas of vulnerability, seismic zones, and regions exhibiting seismic amplification. The High Atlas is known for its seismic activity, with a notable earthquake of magnitude 6.8 occurring on September 8, 2023, at a depth of 10 km, attributed to an unidentified fault. This event, followed by significant aftershocks, represents the most substantial seismic activity in Morocco since the 1960 Agadir earthquake (magnitude 5.9). Our research combines geological mapping, lineament extraction from satellite imagery, and seismic analysis is to understand the surface and subsurface geology and tectonics. Processed satellite images enhance geological features, facilitating the identification of faults and fractures. Geostatistical analysis of meso-Cenozoic terrain fracturing reveals that lineaments predominantly align with NNE-SSW to NE-SW directions, with additional minor fracture directions. The seismic activity observed is closely linked to faults within this zone, highlighting regional weaknesses.

Keywords: Seismotectonic, Geological mapping, High-Middle Atlas, Remote sensing, Seismic activity.

1 Introduction

This study explores geological mapping in the Tizi Nisly basin, located within Morocco's Pre-Atlas zone. The Pre-Atlas area, characterized by less rugged terrain compared to the Central Atlas, offers an opportunity to utilize remote sensing techniques for efficient and cost-effective geological mapping [1]. Remote sensing coupled with Geographic Information Systems (GIS), offers a valuable tool for geo-environmental applications including resource exploration, hazard mitigation, and natural disaster prevention [2-5].This study utilizes Landsat 7-ETM satellite imagery for surface geological feature identification, including lithological units, faults, and fractures [6-9] . The targeted region is primarily composed of Mesozoic rocks, with limited pre-Mesozoic and Cenozoic occurrences [10-12]. Geological mapping aims to delineate boundaries of significant geological units and assess their implications for natural hazard mitigation [11], [13-16].

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This study bridges the gap by utilizing remote sensing for geological mapping, offering valuable insights for natural hazard
mitigation and disaster prevention in the Tizi Nisly basin. The study area occupies a critical zone at the geological junction between Morocco's Central High Atlas and the Meridional Middle Atlas Mountain ranges. This studied area located between latitudes 32°31'36 N and 32°12'30 N, and longitudes 5°00'04 W and 6°10'00 W. Encompassing a significant sector, the investigation zone extent from the northern region of Tizi N'Isly to the Imilchil zone, situated within the heart of the Central High Atlas. This selection allows for a comprehensive analysis of the geological transition between these two prominent Atlas sub-ranges [15].

1.1 Seismotectonic Setting:

Morocco, located at the convergence of the African and Eurasian plates, Morocco is known for its significant tectonic activity [17-18], driven by an oblique plate motion at approximately 4 mm/year in the Rif Mountain and 2mm /year in the Atlas system [19] (Fig.1).

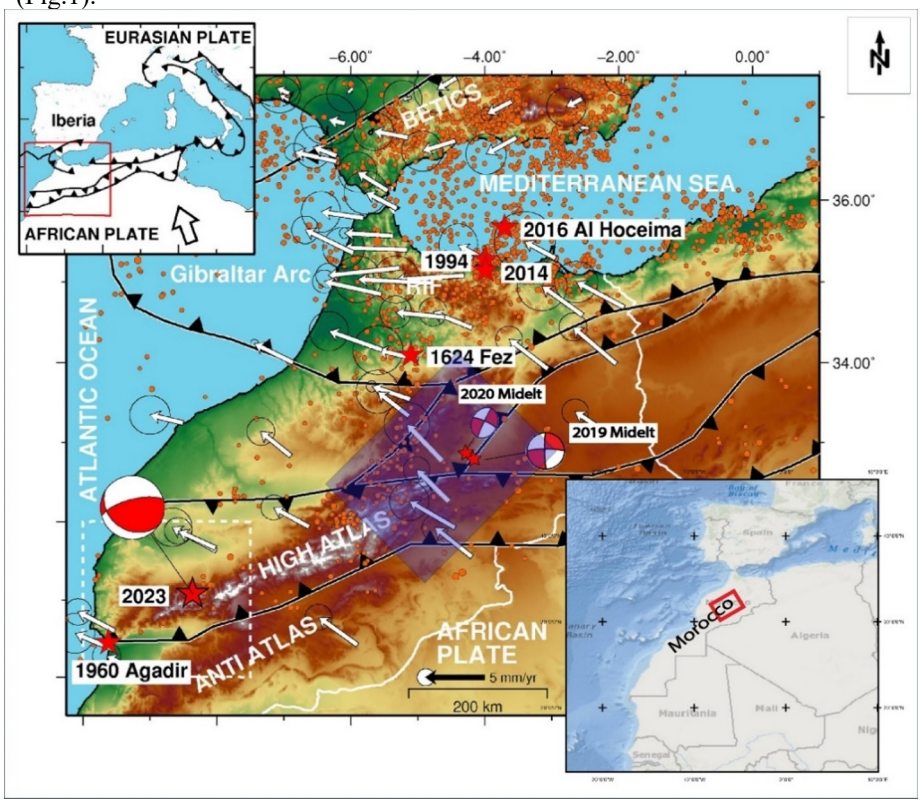

Fig. 1. Seismotectonic of the High atlas, the study area with The Transparent blue box. The upper inset shows a tectonic sketch of the western Mediterranean region, with the red box indicating the area of the main figure. The bottom left inset is a sketch of the active faults and seismic sequence of the Morocco for 2023 [12], [18-19].

Seismic activity in Morocco is distributed across the western Alboran Sea, Rif region and Atlas Mountains. The highest concentration of seismic events occurs in the Rif region and

the Alboran Sea, marking the northern collision zone. Further south, the Middle and High Atlas Mountains experience moderate seismicity.
The Atlas Mountains exhibit tectonic stresses predominantly oriented to the northwest , [18-21]. Prominent seismic events Occur in the Atlas Mountain include the 1624 Fez earthquake (M > 6.5), the 1960 Agadir earthquake (Mw 5.8), the 2019 and 2020 Midelt earthquakes (Mw 5.3). The 2023 El Haouz earthquake (Mw 6.8) stands out as the most powerful instrumentally recorded event since 1960, highlighting the vulnerability of the High Atlas [16-23]. The seismicity of the Atlas Mountains reflects a compressive tectonic regime with stress axes trending NNW. Geodetic data indicate a shortening rate of about 1 mm/year in the WNW-ESE direction, associated with major fault systems such as the North Atlas Fault (NAF), [19] South Atlas Fault (SAF).

2 Data Selection and Methodology

This study aims to create an accurate geological map of the Tizi n'Isli region using satellite imagery. Orthorectified and WGS84 projected ETM+ Landsat 7 satellite images. Multispectral classification techniques, both supervised and unsupervised, were employed to segment the images into different geological classes. The extraction of lineaments enhanced by principal component analysis (PCA) and directional filters, highlighted significant geological structures such as faults and fold zones. These insights are crucial for understanding the seismotectonics of the region, as they reveal areas of crustal stress and deformation, which are essential for assessing seismic risks [18], [22-24].

3 Results and Discussion

In the present study, we utilized both unsupervised and supervised multispectral classification techniques on Landsat 7 ETM images. Initially, unsupervised classification revealed 13 distinct signature classes, which were further validated through field observations along provincial and regional roads. This process highlighted predominant geological formations from Triassic to Quaternary periods, including continental red clay beds, marine limestones, basaltic volcanic rocks, and various sedimentary deposits. Despite initial successes, discrepancies were noted in the classification of certain geological features around Issl and Tisslit lakes (Fig. 2), necessitating subsequent validation and refinement.

Supervised classification further refined our understanding, identifying six specific geological classes with a 71.43% accuracy rate. These findings are crucial not only for deciphering the region's geological evolution but also for assessing its seismic activity. By pinpointing key geological structures such as faults and fold zones, our study provides essential insights into crustal stress and deformation, contributing significantly to seismic risk assessment and natural hazard management strategies in this complex geological setting.

3.1 Geological mapping

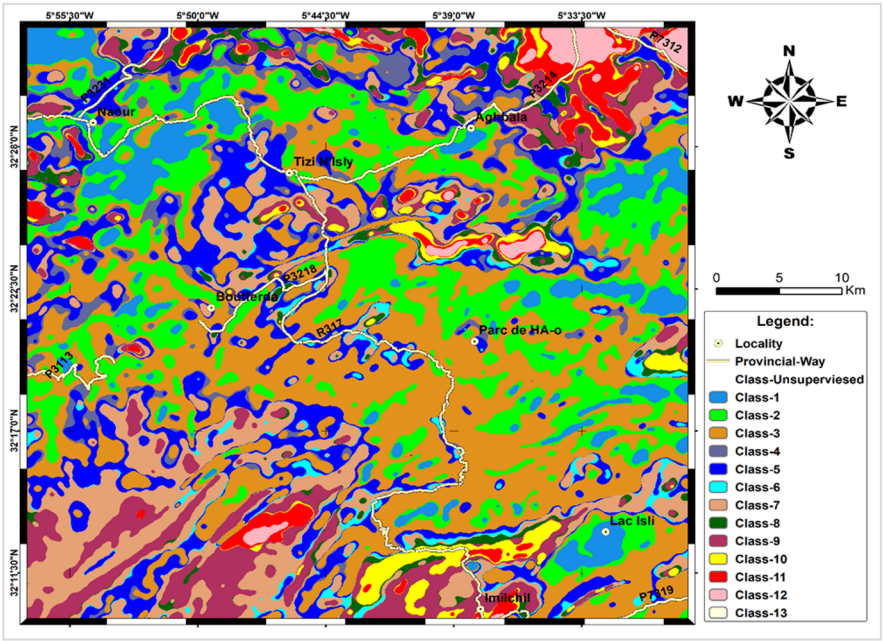

Fig.2. Geological map obtains from unsupervised multispectral classification of Landsat Imagery.

3.2 Geological Lineament Detection and Lineament Density

Geological lineament detection is a critical aspect of geospatial analysis, employing directional filtering to identify patterns and structures within images (Table1). Various algorithms, including the method outlined by [24-27] in a five-step process, are utilized. This process involves noise reduction, enhancing line and edge contrast, and numerically processing images to optimize directional alignments and reduce noise. Principal Component Analysis (PCA) is employed to maximize geological information while minimizing band usage. Lineament detection plays a pivotal role across disciplines such as geology, agriculture, mapping, and shape recognition. Integrated techniques like filtering enhancement and convolution enhancement (Fig.3), using Geographic Information Systems (GIS), offer a robust method for precise identification and analysis of lineaments in geospatial datasets.

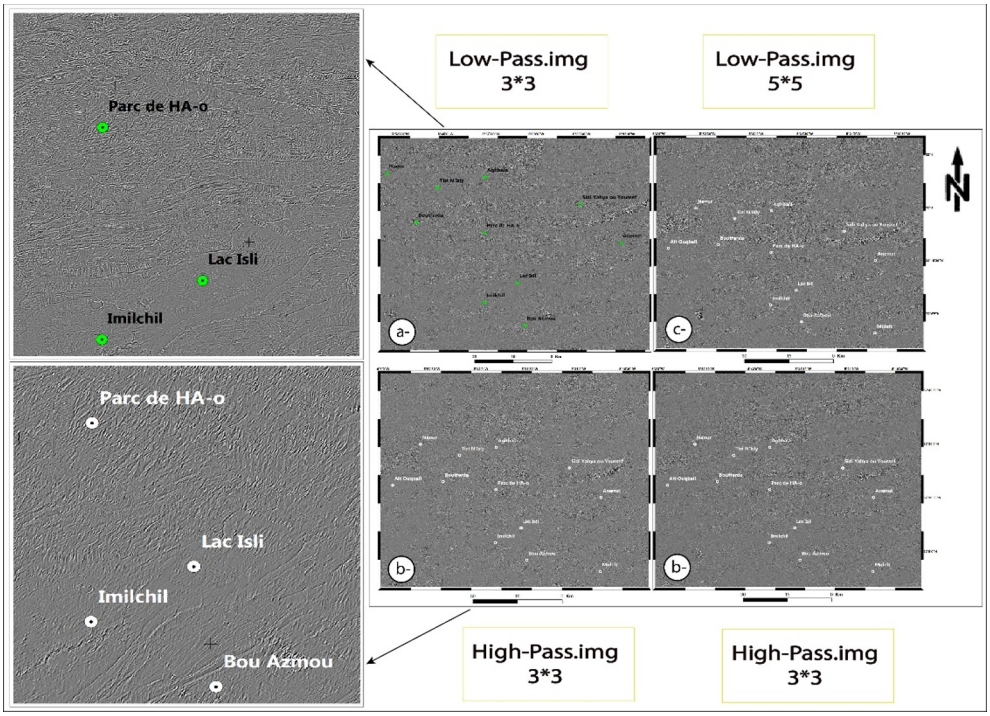

Fig.3. Spatial Convolution enhancement for directional filtering

3.2.1 Fracture Distribution and Lineament Density Analysis

In this study area, the distribution and shape of fractures were analysed comprehensively in the kilometres scale. These fractures result from various factors, including tectonic movements, ground deformation, and human activities such as mining and infrastructure development.

Table 1. Processed Lineament Statistics (preferential)

Angle Range	Lineaments Filters Number	Length (m) Range	Lineaments Percentages (%)
5-15°	2442	173-5693m	24.23%
15-25°	3069	108-6707m	30.45%
25-35°	2632	195-6478m	26.11%
35-45°	1937	182-4910m	19.21%
Total	10080	-	100%

The density of geological lineaments provides critical insights into tectonic activity and the structural framework of regions, particularly in mountainous and seismically active areas (Fig.4). In Morocco, the correlation between the orientation and density of lineaments and major fault systems such as those in the Central High Atlas and Southern Middle Atlas highlights the reactivation of pre-existing zones of weakness. These faults, aligned with the

broader tectonic regime driven by the African-Eurasian plate convergence, exhibit orientations consistent with seismic activity clusters, particularly in Jurassic formations.

This alignment indicates that faults considered dormant may remain tectonically active or prone to reactivation, contributing to the region's seismicity (Fig.4). The observed overlap between fault patterns and seismic events emphasizes the role of lineament density in identifying active structures and understanding the interplay between geology and seismotectonic in Morocco.

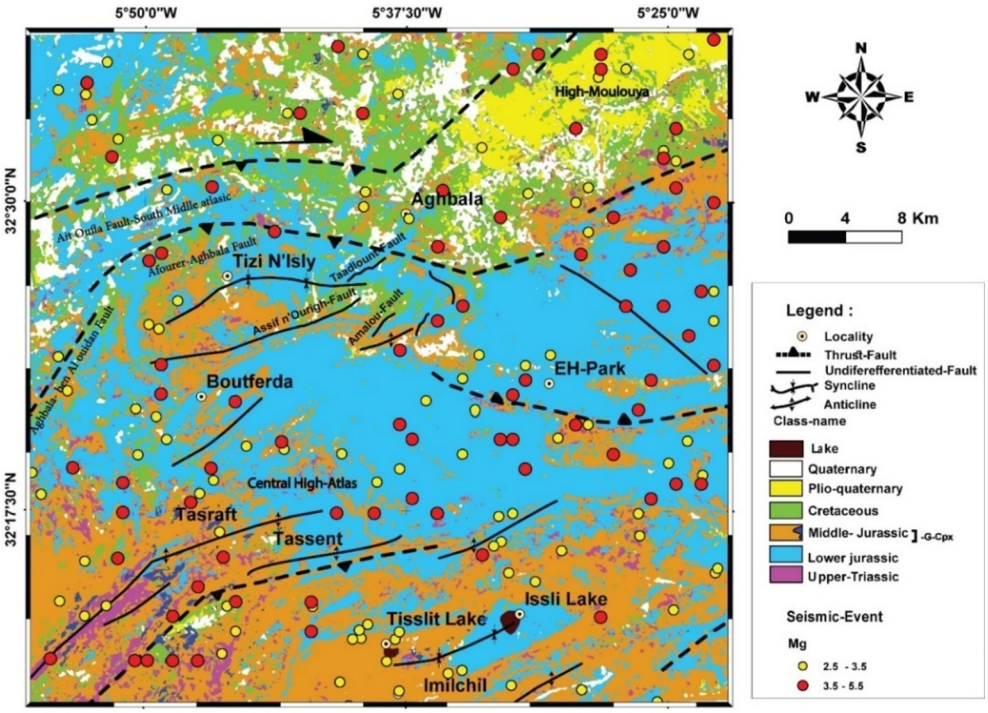

Fig.4. shows a geological map obtained from multispectral classification imagery alongside seismic activity recorded the seismic catalogue from CNRST (National Center for Scientific and Technical Research).

4 Conclusion

The satellite imagery is useful tool for mapping the geological formations of the Tizi N'Isly basin. A combination of supervised classification, PCA, noise reduction, and directional filtering techniques revealed the distribution of surface sedimentary deposits, as well as, the underlying meso-Cenozoic basement and structural lineaments. Accuracy assessments confirmed the reliability of these methods for classifying geological units; Lineament detection identified a preferential orientation in the NE-SW and ENE-WSW directions, potentially indicating zones of weakness and seismic amplification. Integrating lineament density analysis with seismic activity allowed for the identification of potential active seismic zones, contributing to a better understanding of the Central High Atlas' geodynamic evolution. This study demonstrates the potential of remote sensing techniques for geological exploration and seismic hazard assessment in the region.

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Author contribution
All authors approved the final manuscript. A. Najim led the study design, data interpretation, and manuscript drafting. Y. Timoulali supervised the study, contributed to data analysis, and refined the manuscript. M. El Hilali and M. Bouiflane provided valuable feedback and reviewed the manuscript.

Ethics approval and consent to participate
Not applicable.

Consent for publication
All the authors have agreed to publish this article.

Competing interests
The authors declare that they have no competing interests.

Data availability statement
Seismic data were provided by CNRST (Morocco), and satellite imagery was accessed through the USGS Earth Explorer platform.

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