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Impact of fracturing on the hydrological flow in the Liassic nappe of the Causse d'Agouraï, Middle Atlas, Morocco

Impacto de la fracturación en el flujo hidrológico en el manto de corrimiento Liásico del Causse d'Agouraï, Atlas Medio, Marruecos

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ABSTRACT

The study of fracturing at Ain Bouchermou, Ain Maârouf, and Ain Boujaoui water sources used satellite image analysis, isobase analysis, and structural field study to reveal new data on hydrological flows and water storage in karsts and breccias. Mapping the fracture network identified three groups of oriented fractures: N-S, NE-SW, and NW-SE, with the latter being crucial for the drainage and filling of karsts. Upstream measuring stations provided a complete assessment of fracture patterns, aiding in understanding groundwater flow and storage in the aquifer system. The study emphasizes the importance of NW-SE fractures and karst features in groundwater evaluation and recharge mechanisms in the Agouraï Plateau.

Key words: *Remote sensing, Isobasic lineaments, structural study, Agourai Plateau, Tabular Middle Atlas.*

RESUMEN

Para el estudio de la fracturación en las fuentes de agua de Ain Bouchermou, Ain Maârouf y Ain Boujaoui se utilizó el análisis de imágenes por satélite, el análisis de isobases y el estudio estructural de campo para revelar nuevos datos sobre los flujos hidrológicos y el almacenamiento de agua en karst y brechas. La cartografía de la red de fracturas identificó tres grupos de fracturas orientadas: N-S, NE-SW y NW-SE, siendo estas últimas cruciales para el drenaje y relleno de los karsts. Las estaciones de medición situadas aguas arriba proporcionaron una evaluación completa de los patrones de fractura, ayudando a comprender el flujo y almacenamiento de agua subterránea en el sistema acuífero. El estudio subraya la importancia de las fracturas NW-SE y las características kársticas en la evaluación de las aguas subterráneas y los mecanismos de recarga en la meseta de Agouraï.

Palabras clave: *Teledetección, Lineamientos isobásicos, estudio estructural, Meseta de Agourai, Atlas Medio Tabular.*

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Introduction

The study of the Agouraï Causse in the western Middle Atlas highlights its intense fracturing and karstification, responsible for major springs (El Ouardi et al., 2018), such as Ain Maârouf, Ain Bouchermou, and Ain Boujaoui, crucial for the water supply of the Saïs basin. The analysis combines the use of satellite imagery to detect lineaments, isobases to map fractures not visible by imagery, and a structural field study to validate these observations. This approach enriches our understanding of groundwater transfer and the hydrogeological behavior of fractures in this semi-arid region of Morocco.

Understanding the hydrogeological framework is essential for sustainable water management in karstic regions (Fig. 1-2) like the Agouraï plateau (Bouya and El Ouardi, 2014).

Geological and hydrological setting

The study area, situated between the Saïs basin and the Agouraï plateau, (Fig. 1), exhibits significant fracturing and karst features within its Liasic limestone, profoundly impacting groundwater dynamics. Characterized by semi-arid precipitation patterns with dry summers and brief, intense winter rains, the region's hydrology influences aquifer recharge. Analysis of regional fractures identifies four main families: N-S, NE-SW, (predominant in the Middle Atlas), E-W, and NW-SE (Hinaje, 2004; El Fartati et al., 2023).

The NE-SW fractures, originating from the Hercynian orogenesis and reactivated during subsequent geological periods, control the Atlas rift system (Charrière, 1990; Hinaje, 2004; Bouya, 2014). NW-SE fractures coincide with alignments of major water sources (Aïn Maarouf, Aïn Boujaoui, Aïn Bouchermou), indicating recent tectonic activity (Hinaje, 2004; El Fartati et al., 2023). These fractures act as conduits, directing water from the Agouraï plateau to the Saiss basin, crucial for aquifer replenishment and karst system function (El Ouardi et al., 2018).

The tabular Middle Atlas, due to its karstic nature, has a poorly developed hydrographic network with temporary watercourses. Aquifer transmissivity is mainly influenced by the thickness of the water table and the permeability of the carbonate formations. The water is generally soft, with a magnesian bicarbonate facies and low nitrate content. The water table flows in a north-westerly direction, with a gradient of 2%. The hydrogeological system is highly capacitive, favoring good storage and regulated flow throughout the year (Amraoui, F., 2005).

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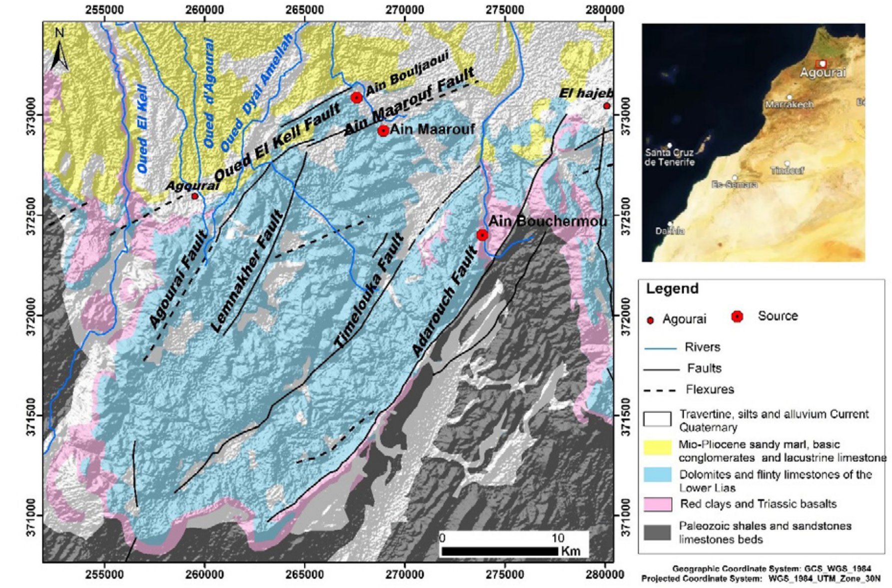

Fig. 1. Simplified geological map of the Agourai plateau. See color figure in the web. (Mouljebouj et al., in press).

Fig. 1. Mapa geológico simplificado de la meseta de Agoura. Ver figura en color en la web. (Mouljebouj et al., en prensa).

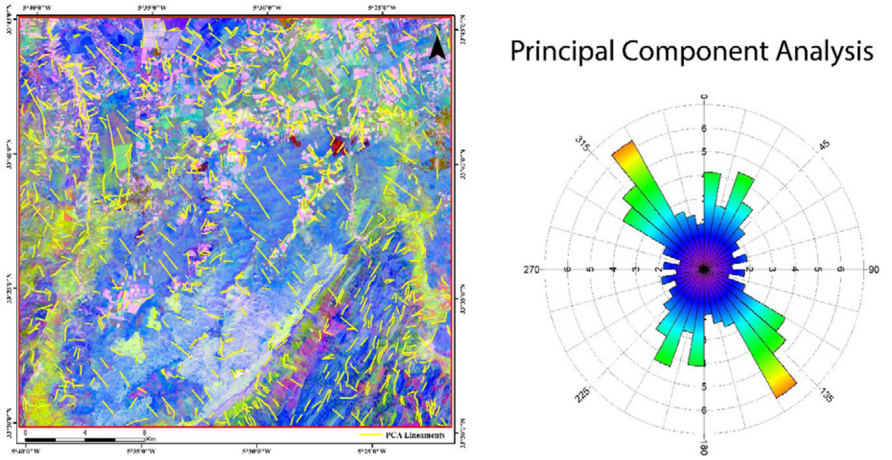

Fig 2. Map of lineaments extracted by directional filters (N-S, NE-SW, E-W and NW-SE) and analysis of orientations. See color figure in the web.

Fig. 2. Mapa de lineamientos extraídos mediante filtros direccionales (N-S, NE-SW, E-W y NW-SE) y análisis de orientaciones. Ver figura en color en la web.

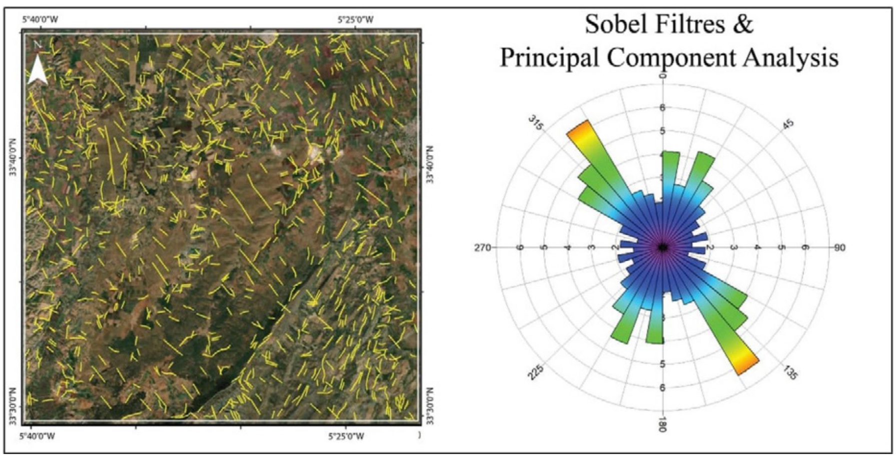

Fig. 3- Final fracturing map of the Agourai region, extracted by FD and ACP. See color figure in the web.

Fig. 3- Mapa final de fracturación de la región de Agourai, extraído por FD y ACP. Ver figura en color en la web.

Methodology

In this study, we employed a three step approach beginning with satellite image analysis, followed by isobase analysis, and validated through on ground structural studies. Satellite imagery was used to extract lineaments, crucial for identifying dominant directions in the study area using both manual and automatic methods (ACP and Directional Filter). Isobase mapping highlighted fractures and lineament orientations within uniform lithology (Filosofov, 1960; Amine and El Ouardi 2017), aided by contour lines derived from digital terrain models using the D8 method for hydrographic network extraction. Fieldwork involved lithological analysis and microtectonic measurements around three water sources, processed with Dips software to visualize fault layout, geometry, density, and directional patterns. Comparison across these methods was essential for result.

Results

The study utilized directional filtering and principal component analysis (PCA) to identify four main regional lineament directions: N-S, E-W, NE-SW, and NW- SE (Fig. 2). However, PCA and Fourier transform analysis (FD) indicated that the dominant direction near the three water sources is NW-SE (Figs. 3). Isobase mapping further highlighted fractures and lineament orientations within dolomitic limestone lithology, using contour lines derived from digital terrain models (DTM) via ArcGIS 10.3 software (Grohmann et al., 2011). This method revealed that the sources Aïn Maarouf, Aïn Bouchermou, and Aïn Boujaoui align along a major NW-SE lineament (Fig. 4), emphasizing its significance in the regional hydrogeological framework. The field visit validated findings from previous methods. Ain Bouchermou's source, situated at the southernmost point, aligns with a kilometric NW- SE fault responsible for a corresponding talweg, evidenced by vertical fault plane observations and intense brecciation (Fig. 5 A to B). Statistical analysis of nearby fractures confirms NW-SE as the predominant direction compared to N-S and NE-SW (C, Fig. 6). Similarly, the Ain Boujaoui's source at the extreme northwest exhibits pronounced decametric NW-SE fracturing, accompanied by significant brecciation Microtectonic measurements further underscore the prevalence of NW-SE fractures (Fig. 6). Ain Maârouf, positioned between these sources, shows analogous decametric structural features with clear NW-SE (F to G). Comprehensive microtectonic surveys near this source reinforce the predominance of NW-SE fractures (Fig. 6), emphasizing their role in shaping the local hydrogeological condition.

Discussion

Manual and automatic extraction of lineaments identified four main regional directions in our study area: NE-SW, N-S, NW-SE, and E-W, consistent with geological map data. Isobase mapping further confirmed that the resurgence of the three sources primarily correlates with the NW-SE direction. Microtectonic analysis around Ain Maarouf, Ain Boujaoui, and Ain Bouchermou revealed four dominant directional families, with NW-SE and NE-SW being most prominent, and E-W and N-S secondary.

NW-SE fractures notably facilitated water resurgence at these sources, supported by significant karstification in the liasic dolomitic limestones, underscoring their crucial role in groundwater circulation and supply (Figs.3).

Conclusion

Comparative analysis of laboratory data, such as satellite images and isobase analysis, with structural field in the Ain Maarouf, Ain Boujaoui and Ain Bouchermou springs along the northern edge of the Agouraï causse, has established the hierarchy of the fracture network and the importance of drainage related to the NW-SE direction. Four directional families were determined: NW-SE and NESW are the most dominant, while EW and N-S are second-order. Drainage is mainly responsible for the resurgence of water at the springs of the three fountains. Water storage is provided by abandoned karsts in the dolomitic reservoir.

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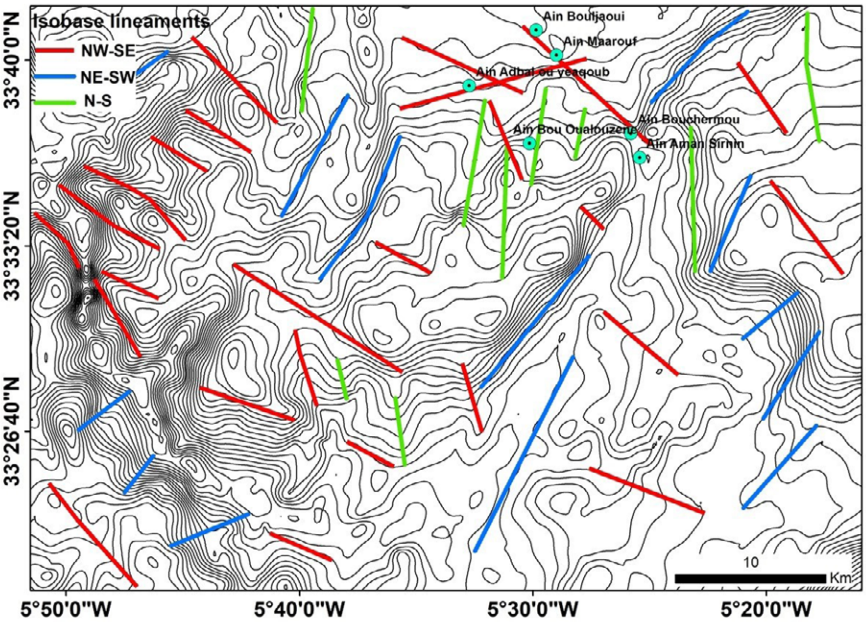

Fig. 4- Isoline map of the the Agourai plateau and main isoline lineaments (Mouljebouj et al., in press). See color figure in the web.

Fig. 4- Mapa isolíneo de la meseta de Agoura y principales lineamientos isolíneos. (Mouljebouj et al., en prensa) Ver figura en color en la web.

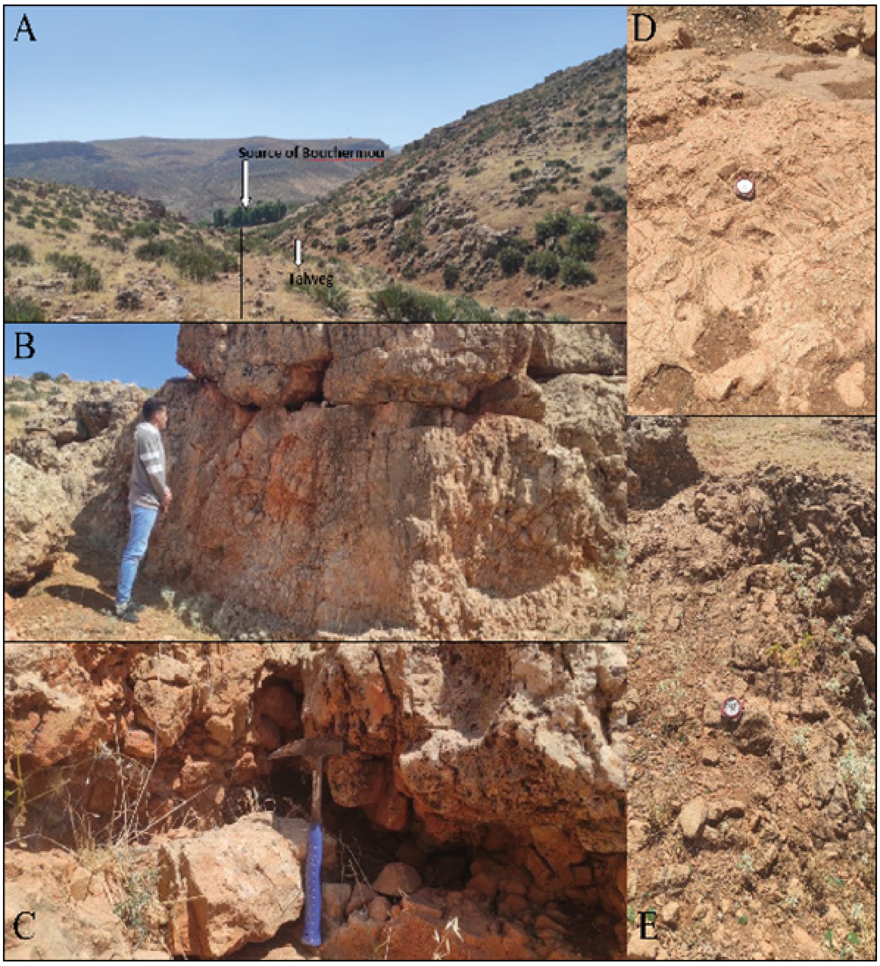

Fig. 5. (A) Source of Boucharmou which is located on the extension of the NW-SE fault (view towards the SE). (B) and (C) Mirror of the NW-SE fault et Karstification in the liasic dolomitic limestone of the Bouchermou spring. (D) and (E) dominant NW-SE breccias showing intense tectonic brecciation. See color figure in the web.

Fig. 5. (A) Manantial de Boucharmou situado en la prolongación de la falla NW-SE (vista hacia el SE). (B) y (C) Espejo de la falla NW-SE et Karstificación en la caliza liasico-dolomítica del manantial de Bouchermou. (D) y (E) Brechas dominantes NW-SE mostrando intensa brechificación tectónica.

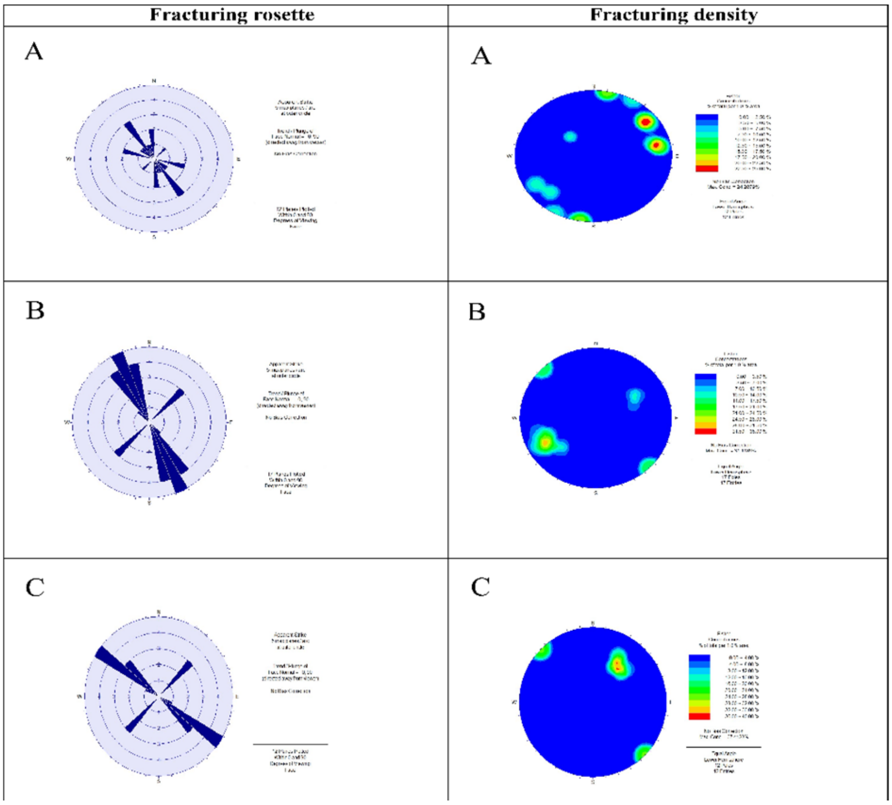

Fig. 6.- Rose diagrams of fracture direction and density diagrams of the dip directions of fracturing measured at the Ain Bouchermou (A), Ain Boujaoui (B) and Aïn Maârouf (C) springs. See color figure in the web.

Fig. 6.- Diagramas de rosa de la dirección de fracturación y diagramas de densidad de las direcciones de buzamiento de fracturación medidas en los manantiales de Ain Bouchermou (A), Ain Boujaoui (B) y Aïn Maârouf (C). Ver figura en color en la web.

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