Structural analysis of the fracture networks controlling groundwater flow and discharge in the Agourai Plateau (Tabular Middle Atlas, Morocco)

Análisis estructural de las redes de fracturas que controlan el flujo y la descarga de las aguas subterráneas en la meseta de Agourai (Atlas Medio Tabular, Marruecos)

Toufik Khouya[1], Hmidou El Ouardi[1], Afaf Amine[2], Rida Haddane[2]*, Ali Ouargaga[3] and Soukaina Mouljebouj[2]

[1] Equipe CartoTec, Department of Geology, Faculty of Sciences, Moulay Ismail University of Meknes, PB. 11201 Zitoune, Meknès, Morocco.
[2] Geosciences laboratory, Department of Geology, Faculty of Sciences, Mohammed V University in Rabat, 4 Avenue Ibn Batouta, B.P. 1014-Morocco.
[3] Laboratory of Geology of the Environment and Natural Resources (GERN), Abdelmalek Essaâdi University, Faculty of Sciences of Tetouan, Avenue de Sebta, Mhannech II 93002, Tetouan, Morocco.
*Corresponding author

ABSTRACT

The circulation of water in the carbonate aquifer of the Agourai plateau and the outflow in the Ain Maarouf spring, on the border with the Saiss basin, is mainly controlled by fractures. In order to understand the functioning of the Spring and to ensure good management of the water resources, a fracture study was carried out in several representative sectors to establish the pattern, hierarchy and chronology of the fracture network. Four main fracture sets were identified, with the NW-SE and NE-SW families being predominant and the E-W and N-S families being least represented. The cross-cut relationships suggest that the NW-SE set of fractures are more recent. Their higher degree of connectivity and openness, and the absence of infill, favour preferential groundwater flow and flow within the Ain Maarouf spring.

Key-words: *Microtectonic analysis, Rock fracturing, Water flow, Ain Maarouf spring, Agourai plateau, Tabular Middle Atlas, Morocco.*

RESUMEN

La circulación del agua en el acuífero carbonático de la meseta de Agourai y la surgencia del manantial de Ain Maarouf, en el límite con la cuenca de Saiss, está principalmente controlada por fracturas. Con el objetivo de entender el funcionamiento del manantial y para una buena gestión de los recursos hídricos, se ha realizado un estudio de la fracturación en varios sectores representativos para establecer, el patrón, la jerarquía y la cronología de la red de fracturas. Se identificaron cuatro grupos de fracturas principales, siendo las familias NO-SE y NE-SO las dominantes, y las familias E-O y N-S las menos representadas. Las relaciones de corte sugieren que el grupo de fracturas NO-SE son más recientes. Su mayor grado de conectividad y apertura, y la ausencia de rellenos favorecen el flujo preferente de agua subterránea y la surgencia en el manantial de Ain Maarouf.

Palabras clave: *Análisis microtectónico, fractura de roca, Flujo de agua, Ain Maarouf spring, Agourai plateau, Tabular Middle Atlas, Marruecos.*

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Introduction

Characterizing the geometry of the fracture network affecting carbonatic aquifers is essential for understanding water circulation. The management of water resources is one of Morocco's greatest environmental challenges, as the country's demand for water increases (agricultural, industry, and individual needs) while climate change reduces rainfall.

The Tabular Middle Atlas lies between latitudes of 32° 55' to the north and 34° to the south, between the Saïs basin and the folded Middle Atlas, in north-central Morocco. Elevations gradually increase from NW to SE with Mediterranean to semi-aride climate conditions (Fig. 1). It consists of subhorizontal dolostones and limestones affected by faults, favouring a tectono-karstic landform. Mesozoic succession is covered by more recent deposits including plio-quaternary volcanic rocks.

The highly fractured and tectono-karstic landscape of the Agourai plateau (El-Ouardi et al., 2018) is the westernmost part of this chain. From bottom to top, the local stratigraphy is formed by Triassic clays and basalts, Liasic dolostones and limestones in tabular layers. Such conditions favor water flows and springs, with fairly large flows (Aïn Maarouf, Aïn Boujaoui, and Aïn Bouchermou). Nevertheless, little is known about the fracture network responsible for the water pathway. This reservoir discharges into a large aquifer located in the Sais basin (Fig.1), which provides water to small towns and two major cities of Meknes and Fez.

In this study, we focus on the direction of hydrological flow by analyzing the different fracture sets observed in the field and validating the results obtained from the isobase map in the Aïn Maarouf spring area.

Geological and setting

The Agourai plateau is located at the NW side of the Tabular Middle Atlas (Fig.1). It is drained by two rivers (Oued El Kell and Oued Rdom) (Fig. 1). The Paleozoic basement is overlain by slightly deformed Mesozoic rocks corresponding to the Upper Triassic-Lower Jurassic. These are red silty clay intercalated by basalt, and overlain by Jurassic dolomitic limestones, where drag folds occur especially near NE-SW oriented major faults. Fractures affecting the Liassic limestone have different orientations, defining many blocks in the Agourai Plateau, which shows sometimes half-grabens, containing continental Mio-Plio-Quaternary sedimentation (Bouya et al., 2013).

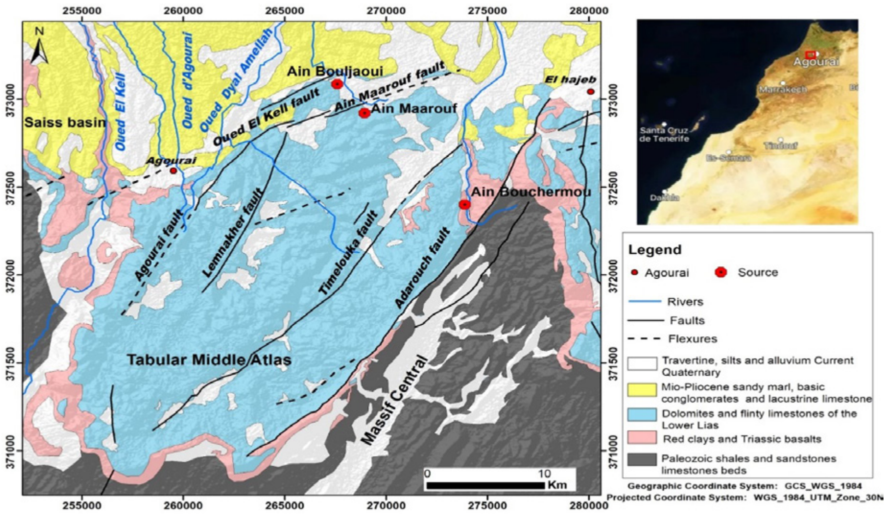

Fig. 1.- Simplified geological map of the Agourai plateau. See color figure in the online version.

Fig. 1.- Mapa geológico simplificado de la meseta de Agoura. Ver figura en color en la versión web.

Hydrogeological setting

The piezometric map (Fig. 2) shows that piezometric levels in the Agourai plateau fluctuate between 680 m and 1160 m, with altitudes ranging from 750 m to 1250 m. The lowest piezometric readings are found in the northern section of the plateau, particularly around the Ain Maarouf - Ain Boujaoui spring complex. This observation indicates a predominant direction of groundwater flow from SSW to NNE, which seems to align with significant structural discontinuities such as faults and fracture systems.

Methodology

The isobase maps analysis (Amine and El Ouardi, 2017, Amine *et al*., 2024) states the relationship between hydrographic and topographic pattern to reveal the tectonic-erosion influence (Grohmann et al., 2011b). it was also a very effective tool to identify faultline even the trace does not appear in surface and their orientation in homogeneous lithology (Grohmann et al., 2011a). By using the digital terrain model (DEMs), we attributed the height of the contour lines to the hydrographic network after its extraction by the D8 method in ArcGis 10.3 environment. Then the isobase surfaces are obtained by the interpolation, from which the isoline curves (isolines) are generated (Fig. 3). The 2nd and 3rd isoline orders allow drawing fractures in comparison with the structural and lithological map of the region. Their determination is based on their inflexion due to tectonic disturbance (Grohmann et al., 2011b). At the outcrop scale, fracturing was analyzed in the Liassic limestones at two locations: in the resurgence zone and upstream of the Ain Maarouf spring, to study local and regional fracturing away from the perimeter of the resurgence, and also compare fracturing between the two areas. For each station, fracturing were analyzed and several parameters were measured including length, orientation, aperture, and interconnection between fractures.

Results and conclusions

Isobase maps

Three main directions are observed from the isobase map (Fig. 3). Based on the abutting relationships between interconnecting fractures, the dominant NE-SW oriented fractures are interpreted to be the oldest. They are probably inherited from the Hercynian basement and reactivated during the Triassic- lower Liassic times controlling the Atlas rifting and during Miocene and Quaternary times (Charrière, A. 1990; Hinaje, 2004; Bouya et al., 2013). The NW-SE oriented lineaments coincide with the alignment of three spring sources (Aïn Maarouf, Aïn Boujaoui and Aïn Bouchermou) and would be linked to a NE-SW extensive tectonic phase attributed to the upper Tortonian-Messinian (Hinaje, 2004; El Fartati et al. 2023) (Fig. 3). These fractures generally correspond to normal faults reactivated in the Middle-recent Quaternary, that drain water and along which groundwater flows from the Agourai plateau towards the Saiss basin in the same direction as tectono-karst alignments (El Ouardi et al., 2018).

Field analysis around the Ain Maarouf

The Ain Maarouf spring is located in the contact zone between the Agourai plateau and the Saiss Neogene basin, along the so-called Ain Maarouf N80 normal fault. It emerges at the base of the Liassic limestone in several places.

Analysis fracturing around the Ain Maarouf spring

The carbonate rocks around the Ain Maarouf spring exhibit intense fracturing. These fractures correspond to joints

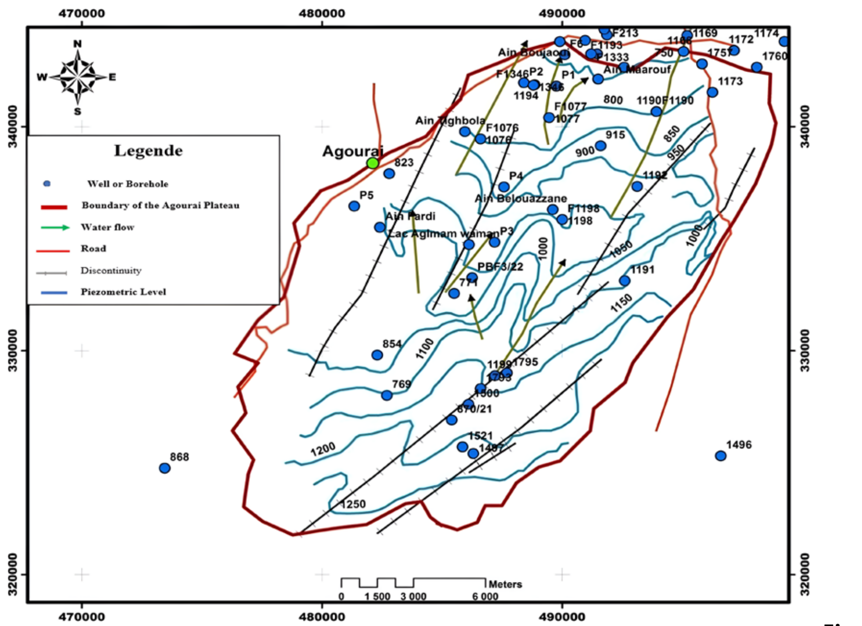

Fig. 2.- Piezometric map of the Agourai Plateau (Allaoui, 2019). See color figure in the online version.

Fig. 2.- Mapa piezométrico de la meseta de Agourai (Allaoui, 2019). Ver figura en color en la versión web.

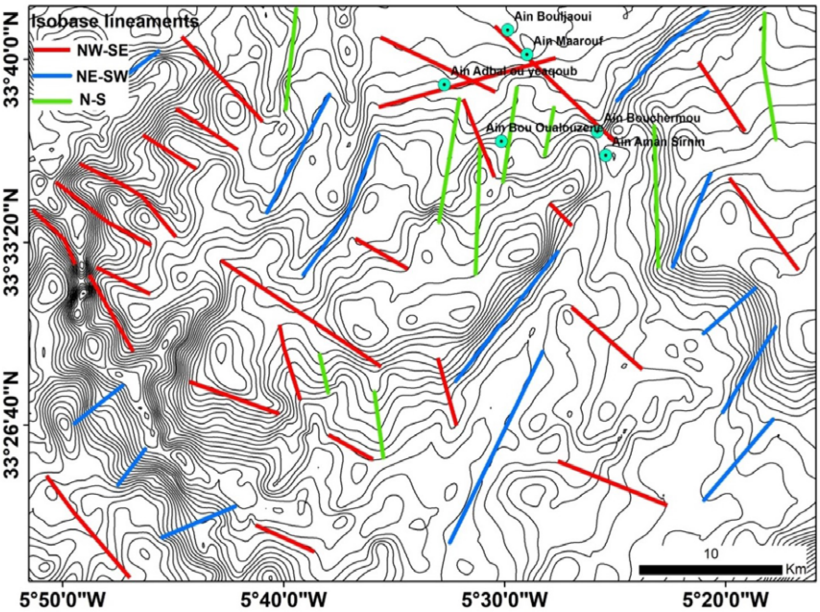

Fig. 3.- Isoline map of the Agourai plateau and main isoline lineaments. See color figure in the online version.

Fig. 3.- Mapa isolíneo de la meseta de Agoura y principales lineamientos isolíneos. Ver figura en color en la versión web.

formed during various tectonic phases, with the primary types being extension joints (diaclases). Fracturing analysis shows two main families oriented NW-SE and NE-SW and two secondary families oriented E-W and N-S, with a clear dominance of the NW-SE direction.

The NW-SE oriented fractures intersect the other families and are therefore posterior to them (Figs. 4B and D). They have lateral openings and closures, and sometimes end in step fractures. Some of them are conjugate, forming acute (0°<α<90°) and obtuse (90°<β<180°) angles. The latter are oriented N120 and N90 and intersect the N60 oriented fracture family. The NE-SW oriented fractures show large openings of up to 15 cm (Fig. 4A and C).

The two main NW-SE and NE-SW oriented fracture families, measured on tabular bed limestone, form lozenge-shaped blocks, where the most dominant of which are oriented NW-SE (Fig. 4D).

At the main water resurgence of Ain Maarouf, water gushes from the main fracture oriented N122, 70NE (Fig. 4A), which is a normal fault with metric displacement and collapsing the NE compartment towards the Sais basin (Fig. 5A).

Finally, all the measurements collected at the Ain Maarouf spring show a clear dominance of the NW-SE direction, which is the late direction in this site.

Analysis of fracturing upstream of the Ain Maarouf spring

In this limited area (1m²), we note the presence of two families of fractures oriented E-W and N-S cutting the limestone into lozenge-shaped pieces. The N-S oriented fractures offset those oriented E-W, and thus they are later and the most dominant. The other main directions detected Around the Ain Maarouf spring (NE and NW) were not measured, probably because the sample area is very limited.

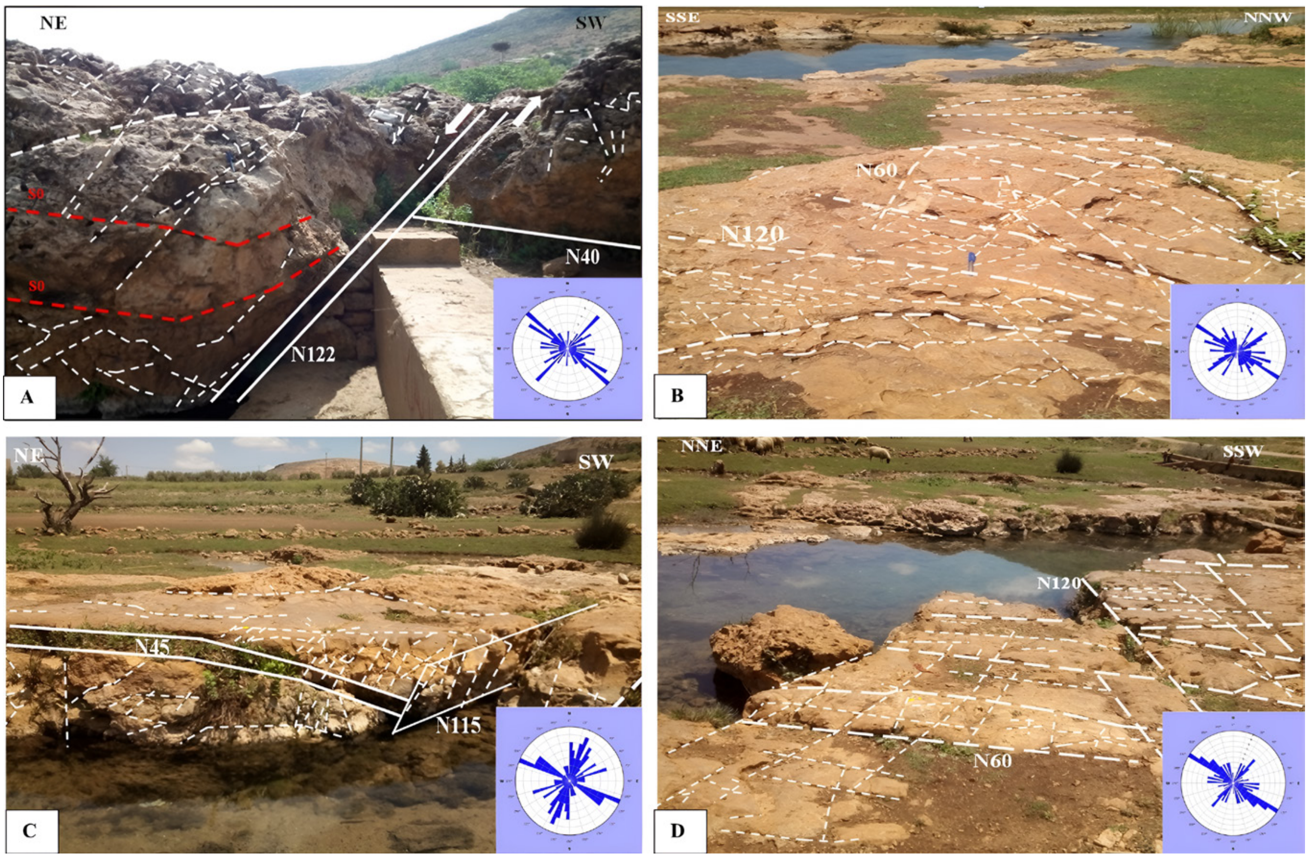

Fig.4.- (A, B, C, D) fracturing measurement at different stations around Ain Maarouf spring. See color figure in the online version.

Fig.4.- (A, B, C, D) medición de fractura en diferentes estaciones alrededor de la primavera de Ain Maarouf. Ver figura en color en la versión web.

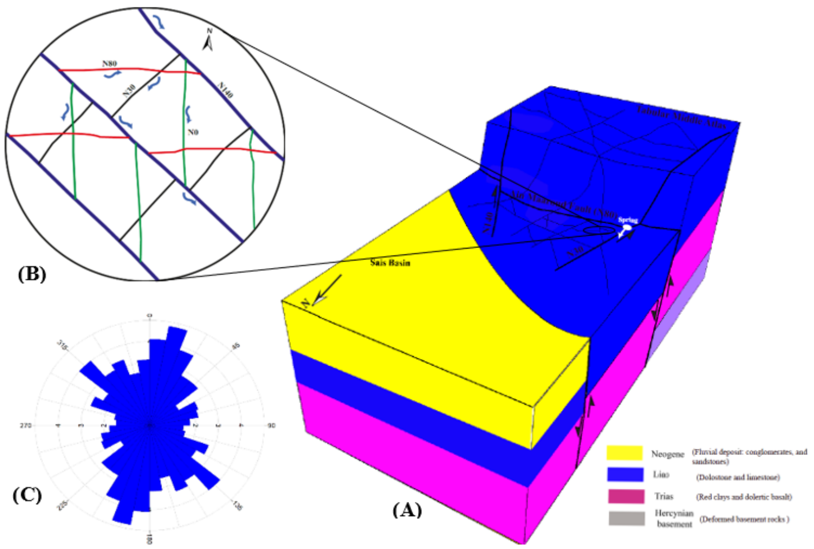

Fig. 5.- (A) 3D model of fracture orientation and connectivity controlling the overall direction of flow (B) interpretation of the four family sets of fractures represented in Ain Maarouf spring area, and (C) Rose diagram of the fracturation in The Tabular Middle Atlas. See color figure in the online version.

Fig. 5.- (A) Modelo 3D de orientación de fractura y conectividad controlando la interpretación de la dirección general del flujo (B) de los cuatro conjuntos de familias de fracturas representadas en el área de resorte de Ain Maarouf, y C) diagrama en rosa de orientaciones de las fracturas en el Atlas Medio Tabular. Ver figura en color en la versión web.

The NE-SW to E-W oriented fractures appear to be the earliest fractures followed by those oriented N-S. On the other hand, the NW-SE oriented ones are the latest to affect the carbonate formations, which has allowed for water drainage and the establishment of the Ain Maarouf spring in this area and probably associated with the Ain Maarouf normal fault (Fig. 5).

Conclusion

Structural analysis of the fracture networks around Ain Maarouf spring highlights the significant impact of secondary NW-SE fractures probably associated with a major normal fault. Microtectonic study established a chronology of four directional fracture sets, with NW-SE and NE-SW being the most dominant. The Ain Maarouf spring emerges at the tectonic junction between the N80 normal fault (Mid-Upper Pliocene) and the N30 sinistral strike-slip fault (Mid-to-Recent Quaternary). Further research could expand on these findings to enhance fracture modeling and reservoir characterization in this region.

Contribution of the authors

Toufik Khouya: Data acquisition, figure editing, fieldwork, surveys, sample collection, data analysis, manuscript writing.

Hmidou El Ouardi: Fieldwork, surveys, Data acquisition, revision of the manuscript, supervision, and coordination.

Afafe Amine: Supervision, coordination, manuscript revision of the manuscript, realization and interpretation of isobase maps of the region.

Rida Haddane: Design, manuscript writing, drafting the manuscript, realization, and interpretation of isobase maps of the region.

Ali Ouargaga and Soukaina Mouljebouj: Design and conceptualization, manuscript writing, drafting the manuscript.

All authors read and approved the final manuscript.

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References

Allaoui, A. (2019) *Hydrologie. Université Moulay Ismail Meknès (Maroc)*. Français.

Amine, A. and El Ouardi, H. (2017). *Geogaceta* 61, 71–74.

Amine, A., El Ouardi, H., Elabouyi, M., Masror, S.Z., Saadi, M., Al-Hashim, M., Taher, M., El Amrani, M., Oudy, A., Mdiker, N. and Benbaqqal, H. (2024). *Journal of African Earth Sciences* 216, 105309. https://doi.org/10.1016/j.jafrearsci.2024.105309

Bouya, N., Ouardi, H.E., Habibou, H.E., Ansan, V. and Mercier, E. (2013). *Central European Geology*, v. 56, p. 381–395. https://doi.org/10.1556/CEuGeol.56.2013.4.5

Charrière, A. (1990). Scientific Research Publishing. https://www.scirp.org/reference/referencespapers?referenceid=2946056

El-Ouardi, H., Boualoul, M., Ouhaddach, H., habibi, M., Muzirafuti, A., Allaoui, A. and Amine, A. (2018). *Geogaceta* 63, 119-122. https://sge.usal.es/archivos/geogacetas/geo63/geo63_30.pdf

El Fartati, M., Hinaje, S., Yaagoub, D., El Fellah Idrissi, B., Amrani, S., Gharmane, Y., Laiche, M., Drissi, Y. and Tagma, T. (2023). *Journal of African Earth Sciences* 205, 104996. https://doi.org/10.1016/j.jafrearsci.2023.104996

Grohmann, C.H., Riccomini, C. and Chamani, M.A.C. (2011a). *Hydrology and Earth System Sciences*, v. 15, p. 1493–1504. https://doi.org/10.5194/hess-15-1493-2011

Grohmann, C.H., Smith, M.J. and Riccomini, C. (2011b). *IEEE Transactions on Geoscience and Remote Sensing*, v. 49, p. 1200–1213. https://doi.org/10.1109/TGRS.2010.2053546

Hinaje, S. (2004). *Thèse d'Etat Es- Sciences, Rabat*, 393 p.