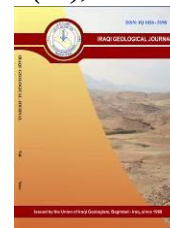




Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Hydrogeology of the Ribat El-Kheir Plateau and Its Relationship with Tectonics, Middle Atlas, Morocco

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Received:
1 March 2025
Accepted:
28 April 2025
Published:
30 June 2025

Abstract

The limestone plateau of Ribat El-Kheir is situated within Tabular Middle Atlas of Morocco, NW of the North Middle Atlas Fault. It is a limestone plateau bordered to the East and Southeast by anticlinal ridges that act as a watershed divide for surface waters. The geological formations that compose it mainly consist of Lias limestones and dolomitic limestones resting on the red saline clays of the Triassic. These fractured and karstified limestones form a significant aquifer, whose waters are used for supplying drinking water to the local population and irrigating apple and cherry orchards. Excessive groundwater exploitation and consecutive drought periods have significantly affected both the quantity and quality of these waters. Geological surveys and the piezometric investigation carried out have shown that groundwater flow initially occurs from SW to NE along major faults such as the NMAF, later faults oriented NW-SE redirect the flow in the NW-SE direction, the presence of Triassic red saline clays as an impermeable substratum of the Lias aquifer favors the emergence of several water springs along the edges of the limestone plateau, which are drained by faults, abnormally high conductivity and pH values observed in some boreholes and springs are associated with the red clays that release sulfates and sodium chlorides through dissolution. The ongoing hydrogeophysical study would be of great value in managing water resources for the sustainable development of the region.

Keywords: Middle Atlas; Morocco; Lias; Limestone; Fault; Piezometry; Flow; Conductivity

1. Introduction

In Morocco, the middle Atlas is a significant groundwater reservoir, mainly consisting of limestone and dolomitic formations from the lower and middle Lias. Identifying the hydrogeological characteristics of these fields largely depends on understanding their tectono-lithostratigraphic attributes. However, studies on the hydrogeology of the middle Atlas primarily focus on hydrological simulation (Amraoui, 2005; Msaddek et al., 2020), while analyses of hydrogeology in relation to brittle tectonics remain limited to the Tabular Middle Atlas. In contrast, this type of analysis is still rare in the folded Middle Atlas (El-Fartati et al., 2021; EL-Makrini et al., 2022; EL-Makrini et al., 2024).

Several studies have highlighted the influence of structural features on the development of karstic and hydrogeological systems in the Middle Atlas. Recent research on the El-Menzel Causse shows that karstification is closely controlled by faults oriented mainly NE-SW and NW-SE, influencing both the

distribution of karstic forms and the dynamics of groundwater flow (Muzirafuti et al., 2019; Naouadir et al., 2023). Additionally, studies on the morphogenesis of closed depressions in this Causse have revealed that their development is strongly linked to the tectonic inheritance and compressive-extensive tectonic phases from the Upper Miocene to the Quaternary (Naouadir et al., 2023).

The relationship between karstification and tectonics has also been emphasized in other Moroccan formations. For instance, studies conducted on the upper Jurassic evaporitic formations in the Safi region have shown that the dissolution processes of gypsum and carbonate layers are largely controlled by the orientation of faults and fractures (Habiballah et al., 2022). These tectonic-karst interactions are responsible for the formation of collapse and subsidence structures, which affect land stability and the dynamics of underground aquifers.

In this context, the hydrogeological basin of Ribat El-Kheir, located about 30 km southeast of Sefrou, is a key site for analyzing the interaction between tectonics and hydrogeology. This basin is defined by a lithostratigraphic succession that includes an Ordovician basement, a series ranging from the Upper Triassic to the Bathonian, as well as Mio-Plio-Quaternary sedimentary deposits (Sabaoui, 1987; Charrière, 1989; Charrière, 1990). These deposits contain an unconfined aquifer, the reserves of which are crucial for the Sefrou-Boulemane region. The basin's geological and structural features create a highly intricate hydrogeological system. Its primary aquifer is composed of carbonate deposits, while the impermeable substratum is formed by Triassic red saline clays. Groundwater flow is often guided by faults (Bouikbane et al., 2016; Allaoui et al., 2018; El Makrini et al., 2022, El Makrini et al., 2024), highlighting the importance of a detailed analysis of the fault network affecting the host formations of the Ribat El-Kheir hydrogeological system.

This study investigates the structural characteristics and hydrogeological of the Ribat El-Kheir basin, emphasizing the role of fracture-induced groundwater flow. Such analysis will aid in identifying recharge zones, mapping water distribution, and delineating the extent of groundwater-bearing formations. Additionally, water-rock interactions and hydrochemical processes will be analyzed through various physicochemical parameters, including pH, electrical conductivity, and dissolved element concentrations (Bense et al., 2013; Bisht et al., 2018; Amrani et al., 2019; El Fartati et al., 2021). The study of the spatial distribution of these parameters and their relationship with tectonic faults is also a central objective of this research.

2. Characteristics of the Study Area

2.1. Geographic Frame

The study area (Fig. 1), covering approximately 125 km², is located on a plateau in the Atlas Causse zone. The topography ranges from 779 m to 1285 m (Fig. 2). The area is bounded by ridges that serve as surface water divides. The region includes depressions in the northwest (Douar Ifrah area). Administratively, this plateau belongs to the province of Sefrou. The main economic activity in the region is agriculture.

2.2. Geological Framework

The limestone plateau of Ribat El-Kheir, located in the eastern part of the Tabular Middle Atlas (MAT), illustrates a complex geology marked by a succession of formations and tectonic events. The Paleozoic basement, visible to the northeast in the form of buttonholes and in the Tazekka schist massif (Ordovician-Devonian) (Martin, 1981; Charrière, 1989; Charrière, 1990; Gharmane et al., 2023), is discordantly overlaid by a Mesozoic cover (Fig. 3). This begins with Triassic detrital deposits followed by red claystones, gray-greenish basaltic outflows, and marls and marl-limestones from the Hettangian-Sinemurian, (Obda, 2004). Above, a slab of dolomites (Lower Lias) reveals inter- to supra-tidal facies,

overlaid by marine bedded limestones dated to the basal domerian. The entire sequence is discordantly covered by Miocene deposits, highlighting a major tectonic structure predating the upper Miocene (El-Fartati et al., 2024), which associated with the North Middle Atlas Fault (NMAF) and complemented by subsequent fault displacements (Colo, 1961; Sabaoui, 1998). Fig. 4, on the other hand, reveal the Lithostratigraphic log of the Ribat El-Kheir Plateau.

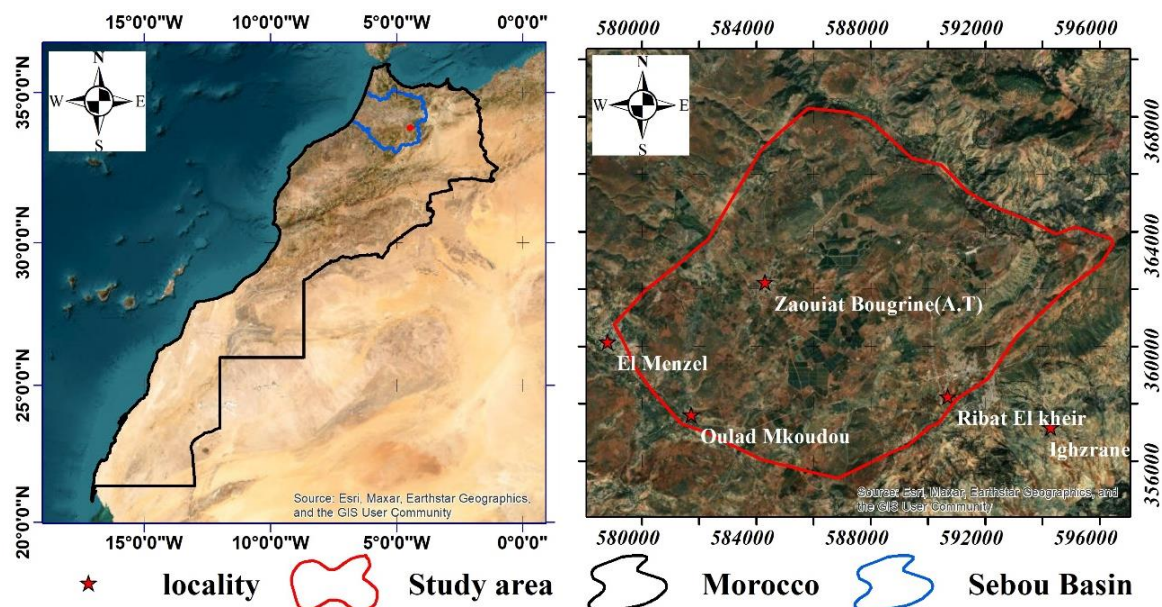


Fig. 1. Geographical location of the Ribat El Kheir plateau

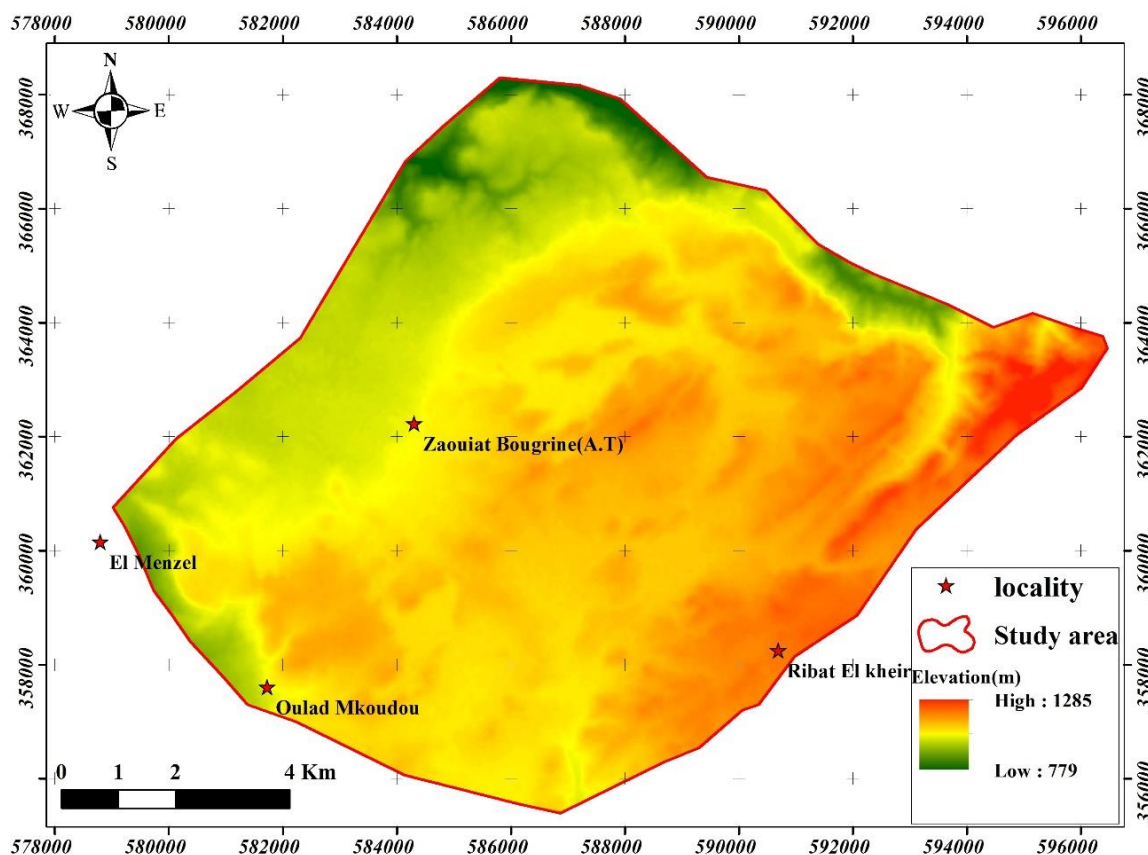


Fig. 2. Digital elevation map DEM of the Ribat El Kheir plateau

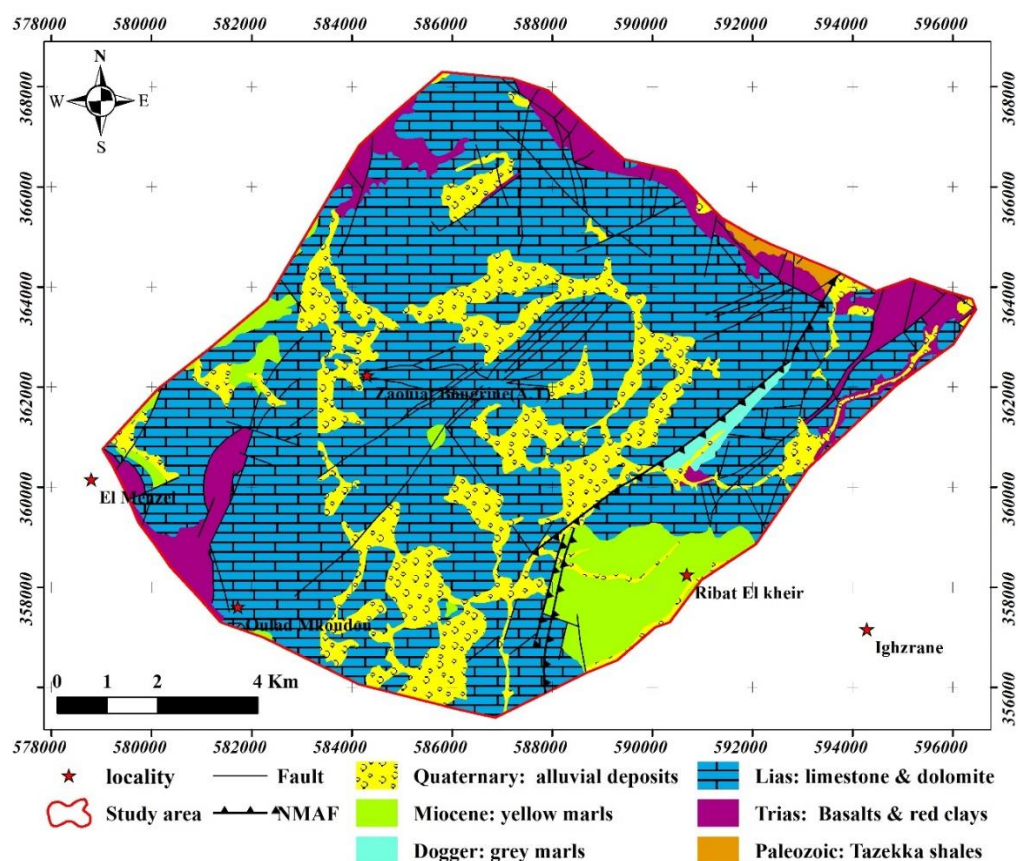


Fig. 3. Geological map of the Ribat El Kheir Plateau. After the geological map of Sefrou 1/100 000 and the geological map of Ribat El Kheir 1/50000

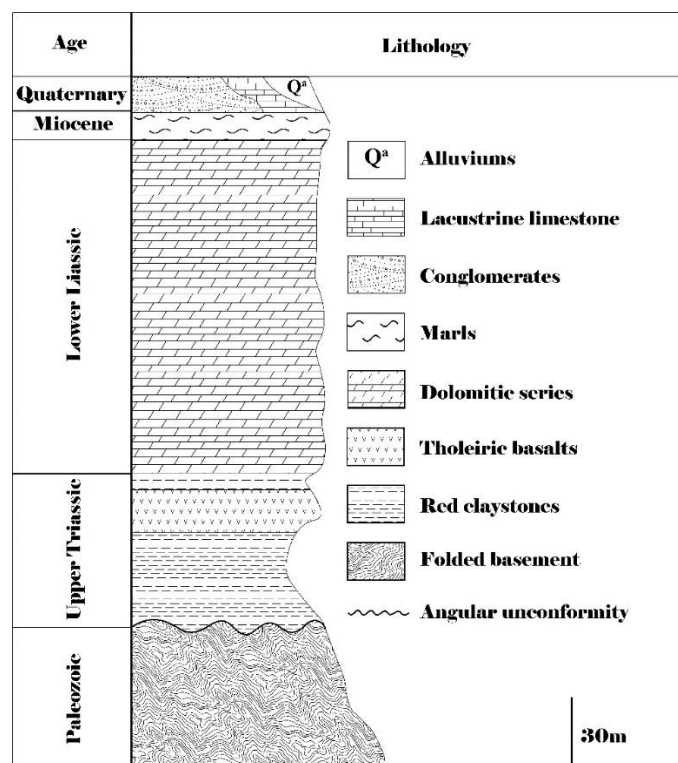


Fig. 4. Lithostratigraphic log of the Ribat El Kheir Plateau, modified from (El Fartati et al., 2021)

2.3. Materials and Methods

To conduct this hydrogeological study in the Ribat El-Kheir plateau, performed an analysis of tectonic fracturing, along with a piezometric mapping. Additionally, certain physicochemical parameters (electrical conductivity and pH) of the unconfined aquifer were measured. Based on piezometric level measurements from 60 water points (boreholes and springs), the construction of the piezometric map captures the aquifer as shown in Fig. 5 while ensuring the validity of the subsequent interpolations. This map represents the key synthesis of a hydrogeological study (Castany, 1982). The reliability of this map is determined by the density of measurement points and the used of kriging interpolation method used. The remaining parameters were measured in situ using a multifunction conductivity meter (Hanna Instruments) on water samples were collected from the springs, wells, and boreholes.

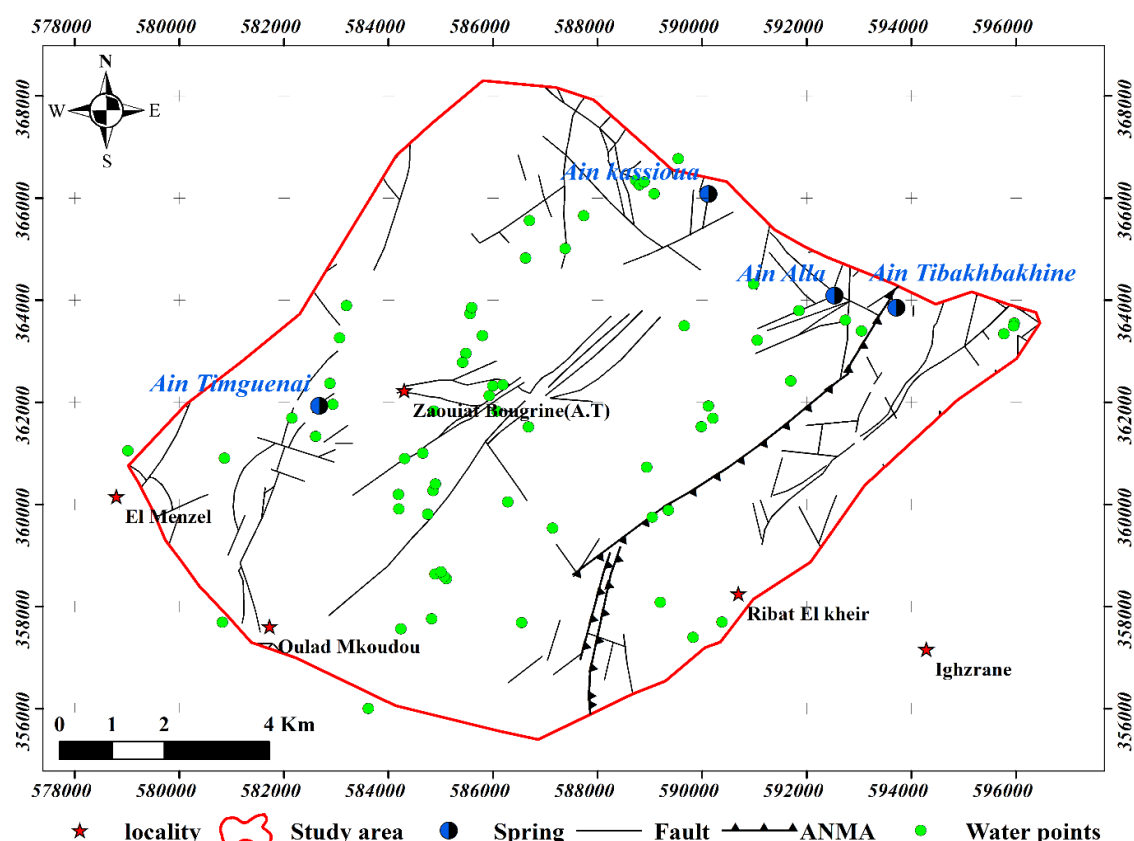


Fig. 5. Spatial distribution of water points in the Ribat El-Kheir aquifer

3. Results

Previous studies (Bouikbane et al., 2016; Allaoui et al., 2018; El Makrini et al., 2022; Tarik et al., 2023) have highlighted that the Middle Atlas Plateau is controlled by a complex fault network. The dominant fault system consists of Hercynian NE-SW oriented faults, which represent the primary structural framework of the region. These older faults are frequently intersected or displaced by younger fault systems, reflecting a polyphased tectonic evolution.

This structural complexity has led to the formation of tectonic blocks, which are either uplifted (horsts) or subsided (grabens) due to thrusting and extensional processes.

The fracture map (Fig. 6) was developed from fieldwork that involved tectonic data, geological profiles (Fig. 7), and structural assessments of the different geological formations. The overlaying of the

piezometric map on the fracture map as shown in Fig. 8 was helped for determining the direction of the groundwater flow.

The Ribat El-Kheir plateau is particularly affected by a complex fault network (Fig. 6), determining its genesis and current configuration. These faults are organized along two main directions:

NW-SE System: This system includes major faults, such as the North Middle Atlas Fault (NMAF), as well as faults located in the center of the plateau. These structures exhibit a significant vertical component, playing a crucial role in the current morphology of the plateau (Colo, 1961; Sabaoui, 1998).

NE-SW System: This system is particularly visible in the SW and NW parts of the plateau, reflecting a complex and differentiated structure of the geological Formations.

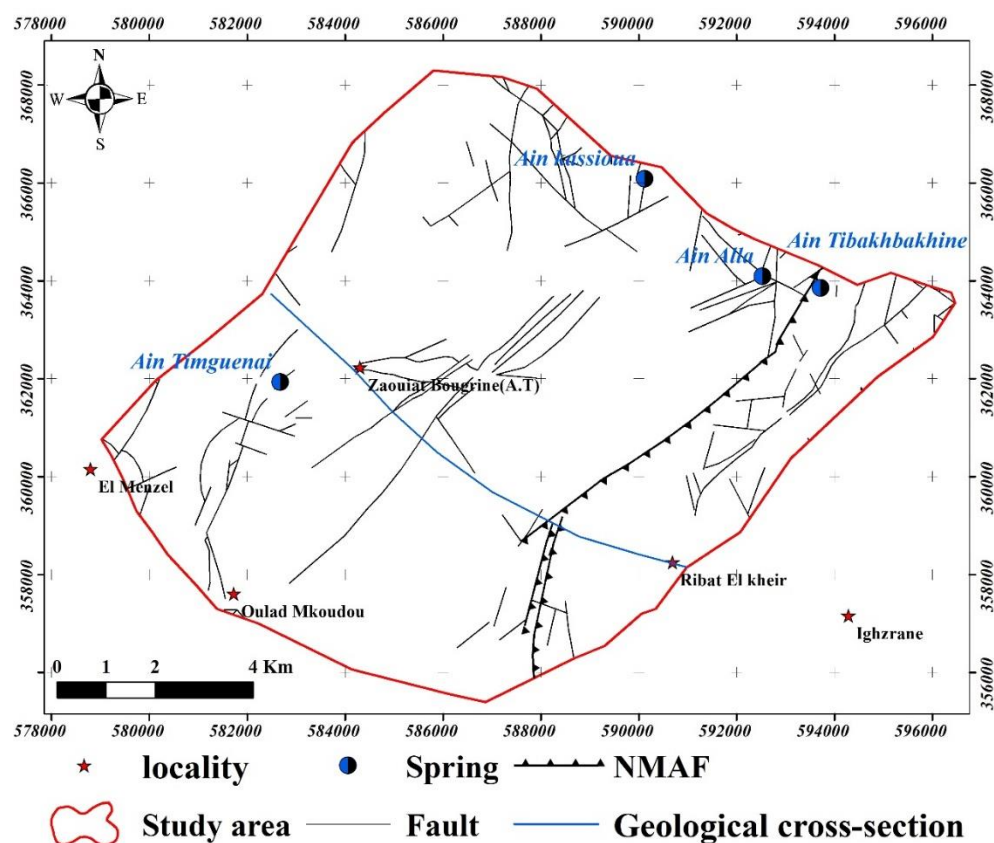


Fig. 6. Faults mapping in the Ribat El Khier plateau

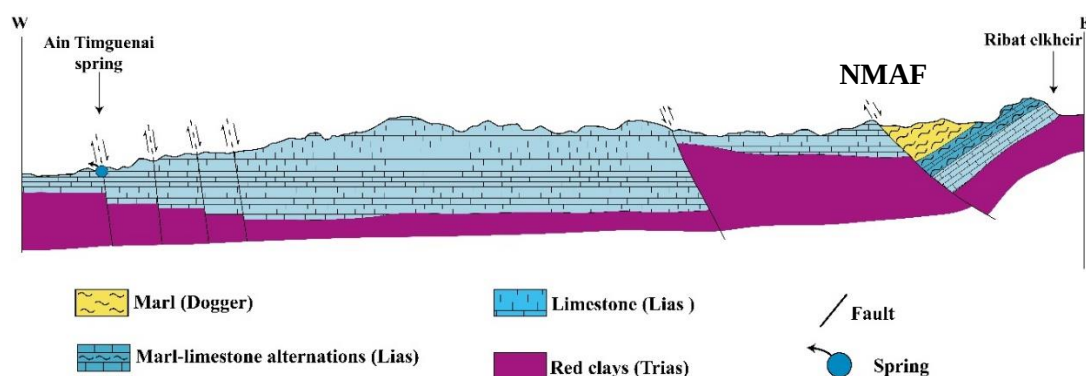


Fig. 7. Geological cross-section of the Ribat El-Kheir Plateau showing horsts and grabens were controlled by NE-SE faults

The piezometric map of the Ribat El-Kheir plateau reveals a significant variation in the piezometric level, ranging from 1100 m in the East to 850 m in the west, corresponding to an elevation between 1050 m and 800 m. The highest values are concentrated in the Eastern part of the plateau, while the lowest values are found in the west, near the village of Aïn Timguenai. This configuration indicates a general groundwater flow from East to West.

The detailed analysis of the map shows the flow direction in several stages:

From SW to NE: The flow initially follows the main faults, notably the North Middle Atlas Fault (NMAF).

NW-SE Re-orientation: faults-oriented NW-SE then modify the flow direction, leading to a preferential flow along this system.

Influence of the impermeable substratum: The Triassic red saline clays, which form an impermeable substratum for the Lias aquifer, facilitate the formation of numerous water springs along the plateau's edges. These springs are generally associated with drainage zones which controlled by the faults.

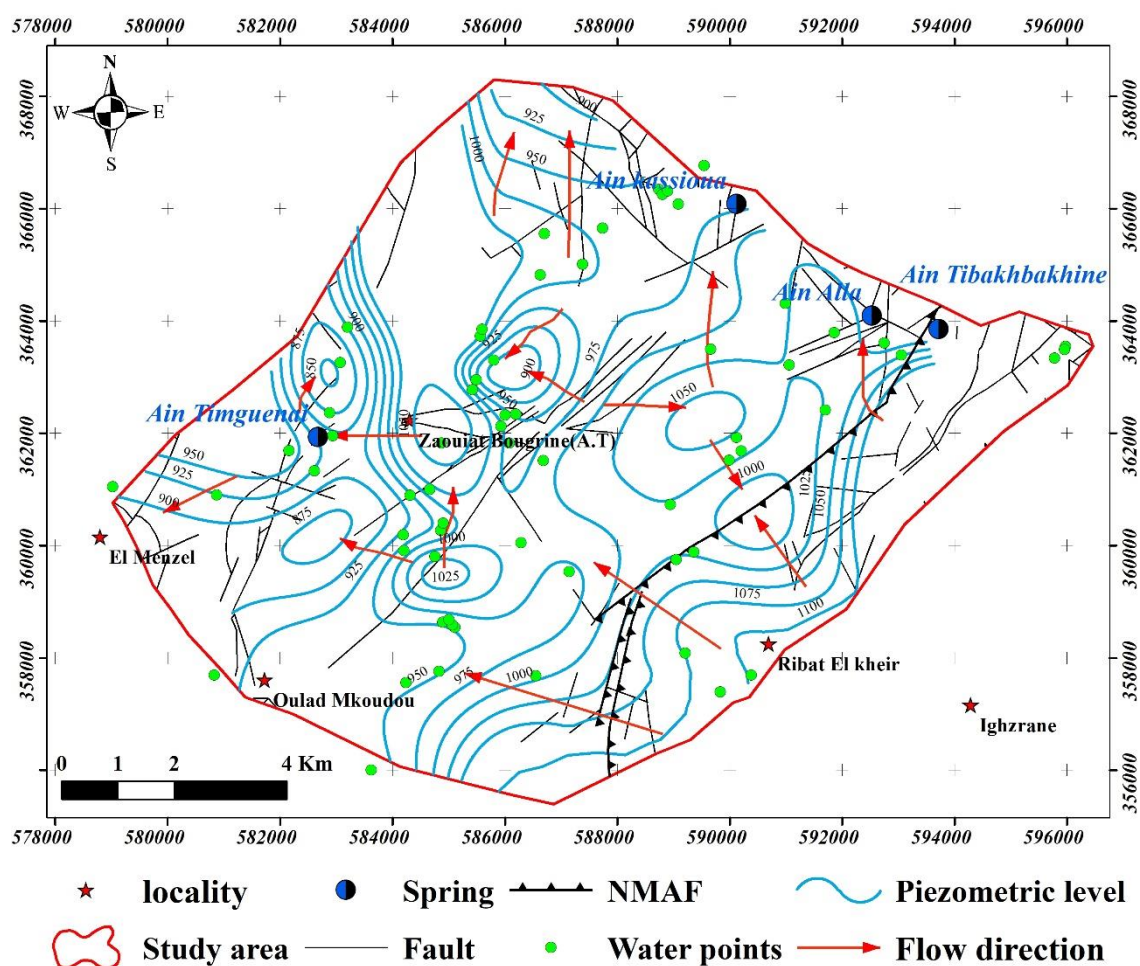


Fig. 8. Piezometric map of the Ribat El-Kheir plateau showing their water flow direction

pH is an essential parameter for assessing the acidity or alkalinity of water as well as its chemical equilibrium. Generally, drinking water has pH values between 7 and 8.5. Water with a pH below this range is considered acidic, while water with a pH above 8.5 is classified as alkaline.

In the Ribat El-Kheir aquifer, the pH distribution map (Fig. 9) indicates that the groundwater has values ranging from 6.19 to 7.83. Waters flowing through carbonate rocks exhibit a slightly alkaline pH, reflecting the influence of these Formations on the water's chemical composition. In contrast, waters in

contact with the Triassic clay-evaporitic and basaltic Formations show a slightly acidic pH (6.19–7). These characteristics are particularly pronounced at major faults, such as the North Middle Atlas Fault (NMAF), or in deep boreholes that reach the Triassic clays.

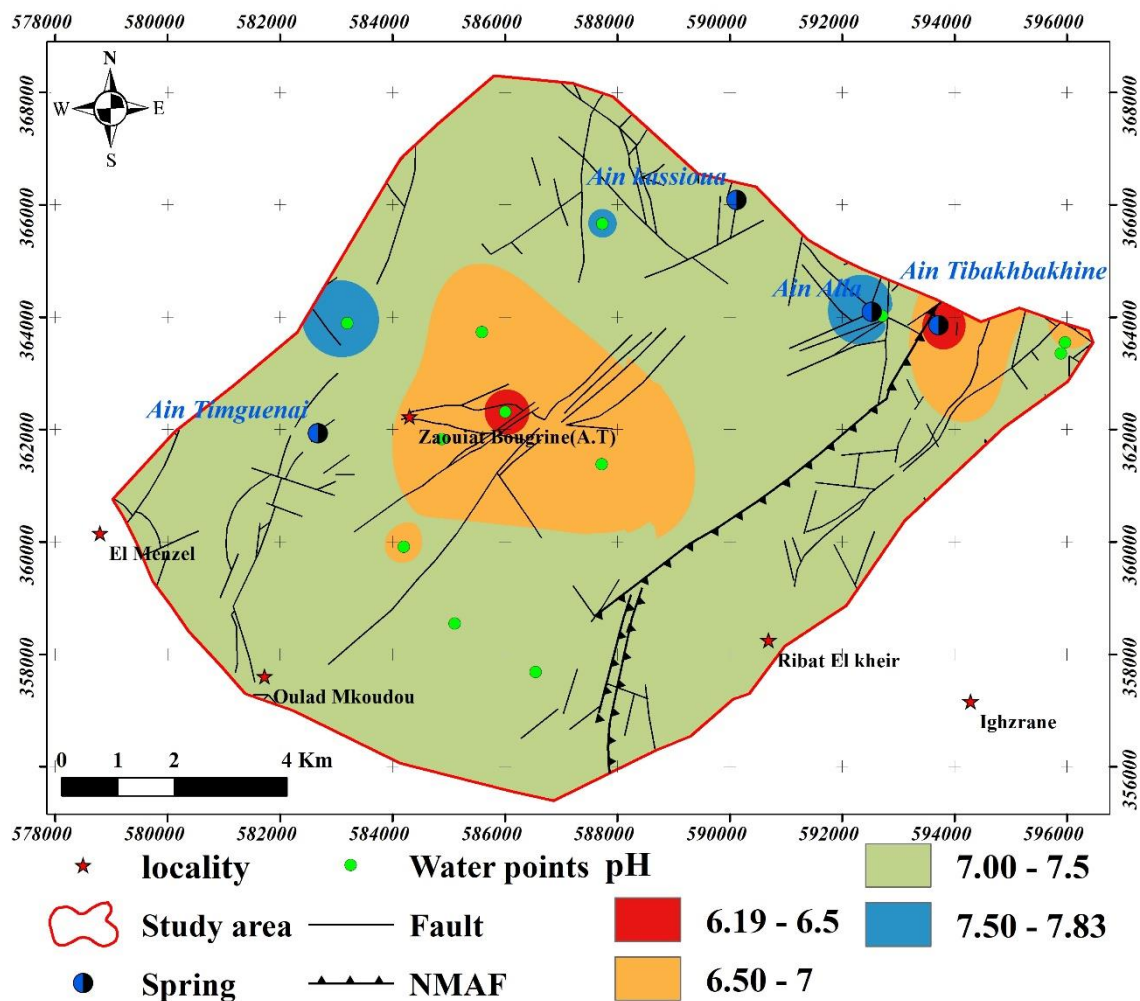


Fig. 9. Map of pH variation in the groundwater of the Ribat El-Kheir Plateau

Electrical conductivity (EC) is a numerical measure of a solution's ability to conduct an electric current, primarily influenced by the concentration of dissolved mineral salts, which are good conductors, in contrast to organic compounds, which are generally poor conductors. Standard (EC) is expressed in millisiemens per meter (mS/m) or microsiemens per centimeter ($\mu\text{S}/\text{cm}$) at a reference temperature of 25°C. Natural waters typically have values ranging from 50 to 1500 $\mu\text{S}/\text{cm}$.

The electrical conductivity distribution map across the plateau (Fig. 10) shows values ranging from 347 to 1791 $\mu\text{S}/\text{cm}$, indicating significant variability depending on the zones and geological formations. Waters with high conductivity are primarily located near boreholes reaching the Triassic red saline clays and at the Aïn Tibakhbakhine spring, situated near the Triassic outcrops. These high-conductivity areas reflect the influence of evaporitic formations rich in dissolved salts on the groundwater quality.

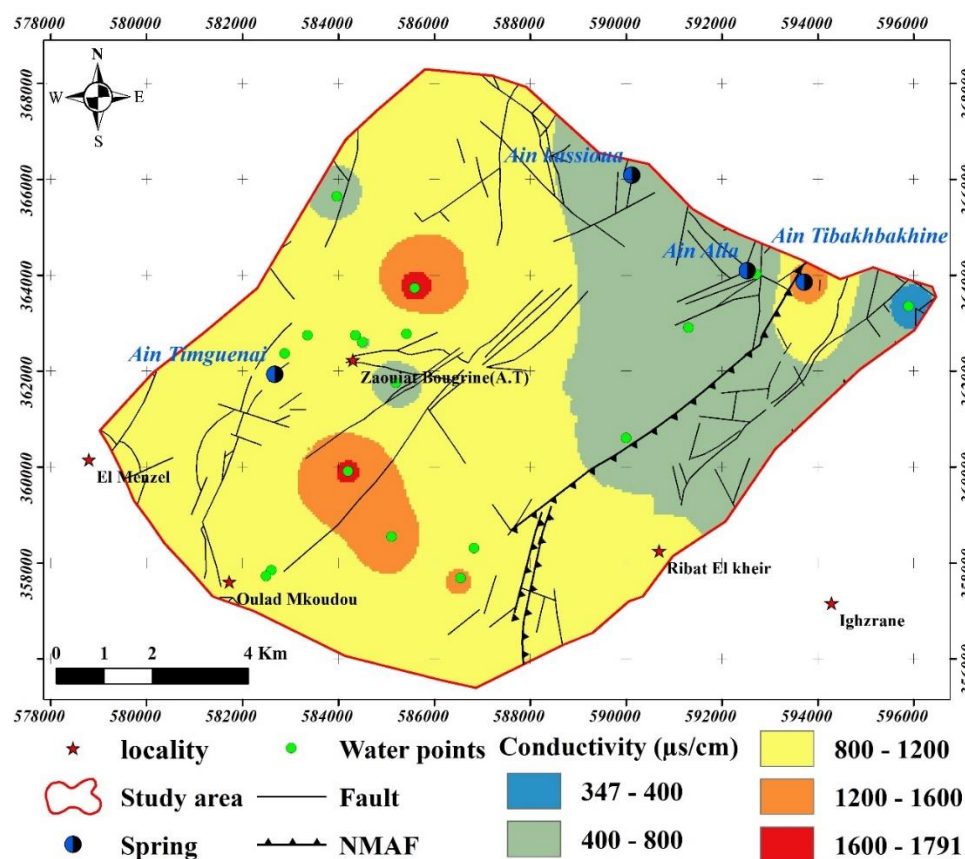


Fig. 10. Map of electrical conductivity variations in the groundwater of Ribat El Kheir

4. Discussion

The Ribat El Kheir plateau hosts a fractured aquifer in which faults play a crucial role, both in the productivity of the carbonate reservoir and in groundwater flow patterns. By integrating piezometric data with the fracture map, it was observed that the piezometric contour lines typically run parallel or at an angle to most of the fractures impacting the plateau. The isopies are aligned parallel to the main structural lineaments (Fig. 8) (Elhmaidi et al., 2012; Allaoui et al., 2018; Habiballah et al., 2022; Naouadir et al., 2023), such as the N45° faults that associated with the North Middle Atlas Fault (NMAF). In contrast, the groundwater flow seems to be primarily occurred at right angles or inclined to the planes of the N130°-oriented faults.

The results of the geological mapping indicate that the flow of the shallow aquifer in the Ribat El-Kheir region is directed from the elevated blocks towards the subsided blocks, particularly towards the Aïn Timguenai area. This dominant flow follows faults with a marked vertical component. These observations are consistent with previous studies on the El-Menzel Causse, where Naouadir et al. (2023) highlighted that the karstification and hydrogeological processes are largely guided by major fault systems, particularly those oriented NE-SW and NW-SE. Moreover, the morphogenesis of closed depressions in the Middle Atlas, as discussed by Naouadir et al. (2023), further supports the hypothesis that the tectonic controls and plays a key role in defining groundwater circulation pathways.

Additionally, the findings were aligned with previous research on the relationship between karst evolution and tectonics in the Middle Atlas (Naouadir et al., 2023). The study on the Causse of El Menzel emphasized that structural discontinuities serve as conduits for groundwater movement, a phenomenon similarly observed in the Ribat El-Kheir plateau. These results further confirm that the regional hydrogeology is significantly influenced by inherited tectonic structures, which dictate both aquifer recharge zones and groundwater discharge areas.

In general, the flow of water follows a preferential direction towards the West as shown in Fig. 8. The orientation of this axis matches that of the submeridional faults, which crosscut faults trending from N80° to N130°. These findings corroborate previous studies on the Middle Atlas karst system, which demonstrate the structural control exerted by superimposed tectonics on groundwater movement (Naouadir et al., 2023). The integration of these structural and hydrochemical analyses reinforces the importance of fracture systems in defining aquifer dynamics and highlights the need for further detailed investigations into fault-related hydrogeological processes in the region.

4.1. Local Hydrogeological Context

4.1.1. Ain Timguenai spring

The Ain Timguenai spring (Fig. 11) is the most important on the Ribat El-Kheir plateau. Located to the SW of the village of Zaouiat Bougrine, it plays a key role in supplying drinking water and irrigating certain agricultural areas. This spring emerges within the Lias carbonate formations, specifically on a normal fault oriented N45°, at the interface with the impervious red clays of the Upper Trias. This spring has dried up due to the decline in its piezometric level.

The normal faulting raises the Triassic clays, creating an impermeable barrier that promotes the emergence of water. The water supply to this spring is sourced from two types of flow: longitudinal flow along the N45° fault plane and transverse flow from the adjacent horsts.

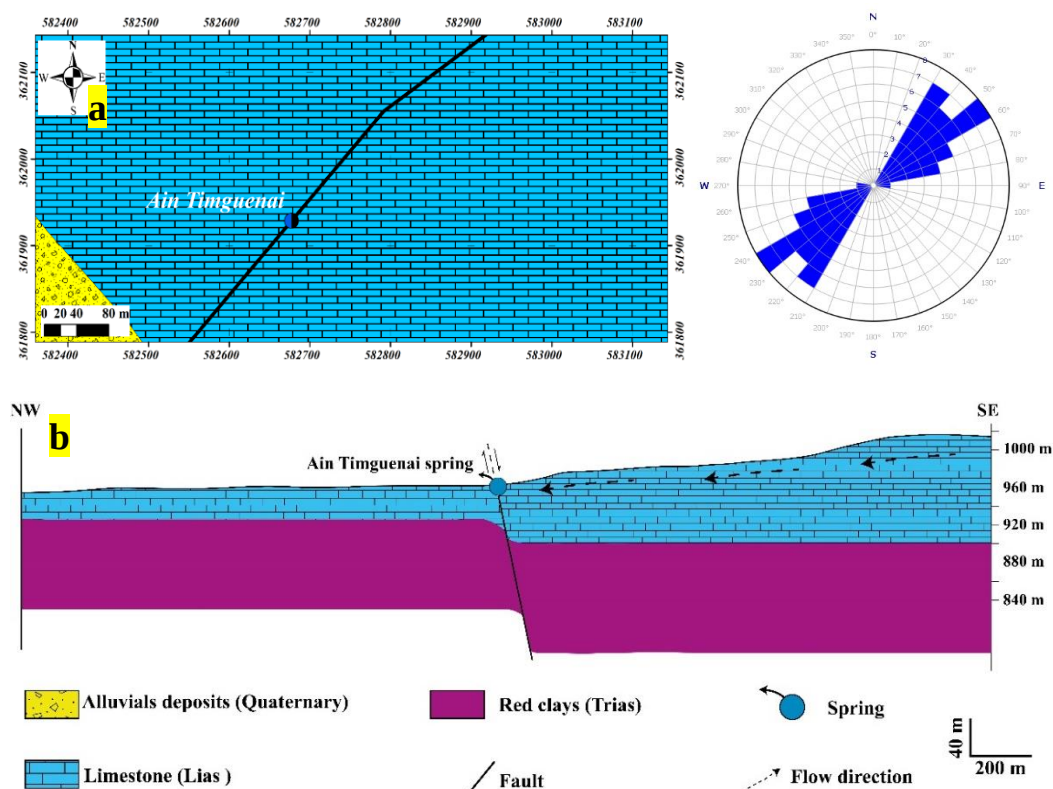


Fig. 11. Ain Timguenai hydrogeological model: (a) geological maps; (b) NW-SE geological cross section

4.1.2. Ain Kassioua spring

The Ain Kassioua spring (Fig. 12) is situated to the South of the village of Kassioua, along a near N-S oriented reverse fault. This fault brings the limestone Aquifer into contact with the impermeable red clays, thereby facilitating the emergence of the spring.

In the northern part of the plateau, the water from the Lias aquifer splits into two main flows: one heading towards the Ain Kassioua spring and the other towards the Ain Alla spring. These two springs are located in an area corresponding to the two SW-NE oriented grabens. This tectonic configuration promotes the collection of groundwater and its resurgence at the two mentioned springs. The fracture analysis at this station shows a dominant NE-SW direction, followed by a secondary NW-SE direction of lesser importance.

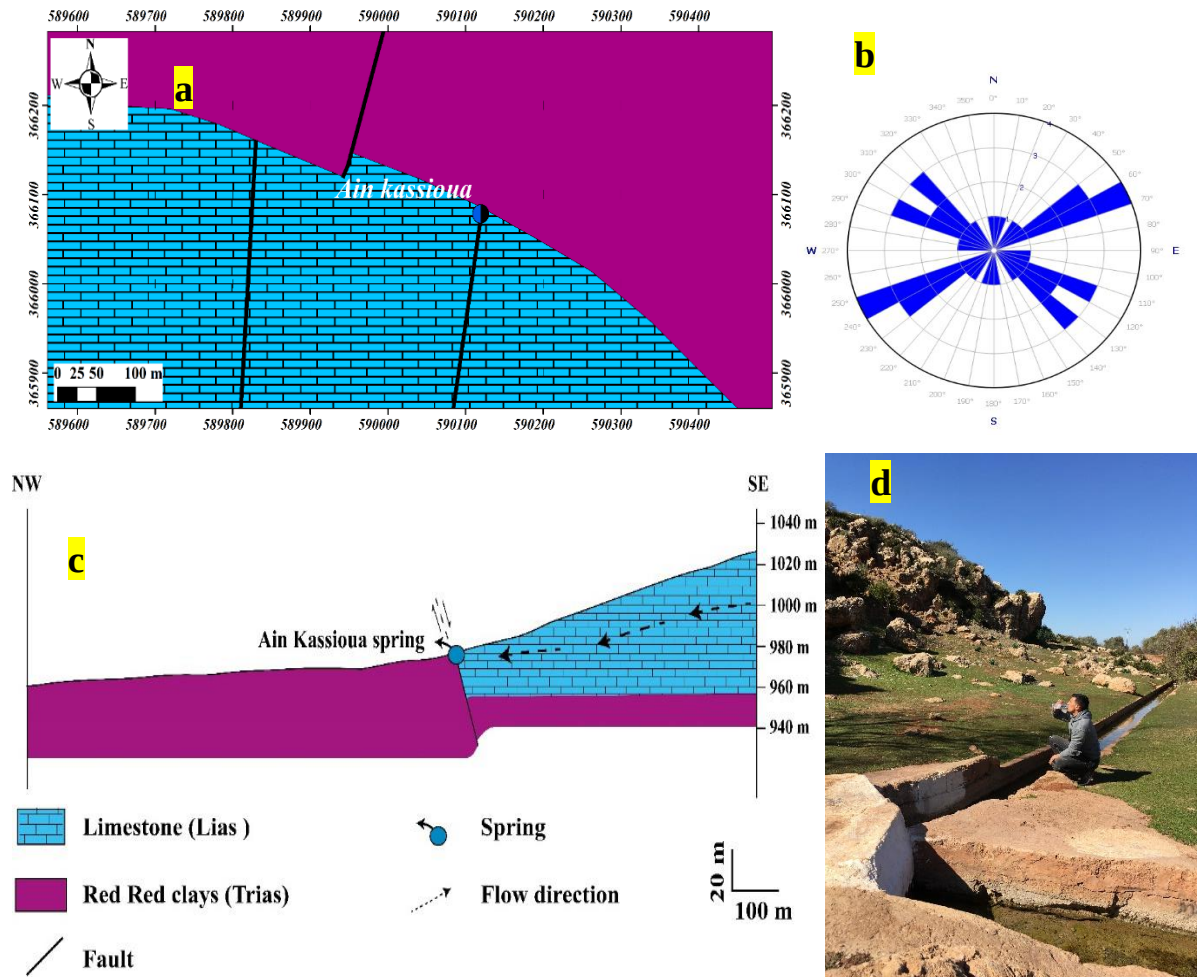


Fig. 12. Ain Kassioua hydrogeological model: (a) geological maps; (b) rose diagram; (c) NW-SE geological cross section; (d) picture taken during field work

4.1.3. Ain Alla spring

The Ain Alla Spring (Fig. 13), located on the northern flank of the Ribat El Kheir plateau, is situated at the junction between an earlier NE-SW oriented reverse fault and a later NW-SE oriented fault. The fracture analysis at this station reveals a dominant NW-SE to N-S direction, followed by a secondary, less significant NE-SW direction. The presence of these fault structures significantly influences groundwater flow by creating preferential pathways that enhance permeability along their orientations. The dominant NW-SE to N-S fractures likely serve as the primary conduits for groundwater movement, directing flow along these axes. Meanwhile, the secondary NE-SW fractures may contribute to localized variations in flow direction, potentially facilitating cross-flow or minor diversions. The interaction of these fault systems likely governs the discharge dynamics of the Ain Alla Spring, where groundwater is funneled along structural weaknesses and emerges at the surface.

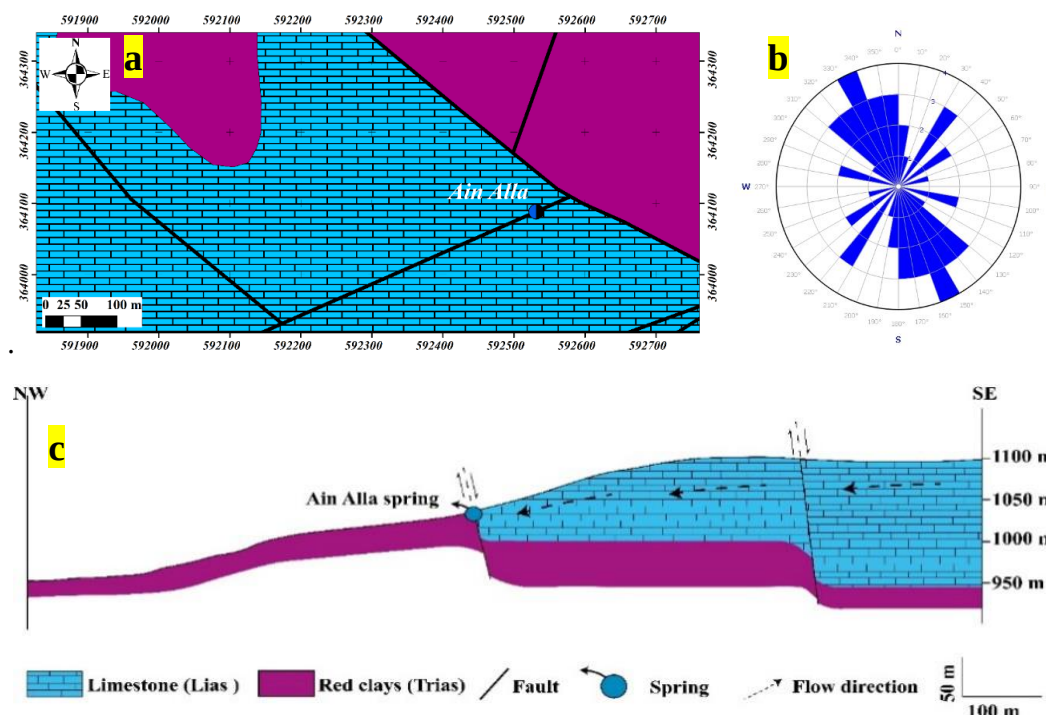


Fig. 13. Ain Alla hydrogeological model: (a) geological maps; (b) rose diagram; (c) NW-SE geological cross section

4.1.4. Ain Tibakhbakhine spring

The Ain Tibakhbakhine spring (Fig. 14), located east of the North Middle Atlas Fault (ANMA), emerges from a normal fault where Triassic clays meet Paleozoic schists. Unlike Ain Timguenai and Ain Kassioua, it has a deep origin, evidenced by its high CO_2 content, which suggests a connection to a deeper, possibly geothermal system. There is no hydraulic connection between Ain Tibakhbakhine and the Ribat el Kheir aquifer. A forthcoming study utilizing isotopic analysis will provide further insights into the origin of Ain Tibakhbakhine springs.

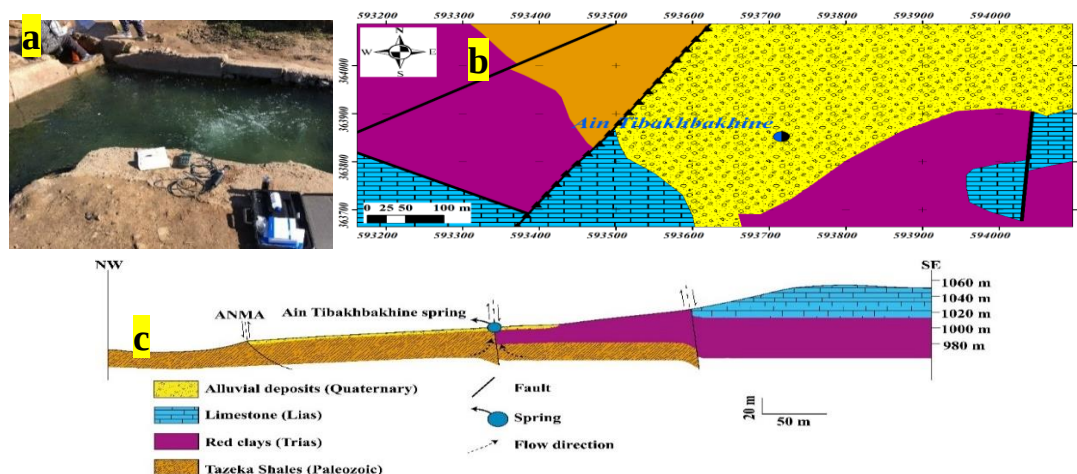


Fig. 14. Ain Tibakhbakhine hydrogeological model: (a) picture taken during field work; (b) geological maps; (c) NW-SE geological cross section

5. Conclusions

The Ribat El Kheir plateau, located in the northern Middle Atlas Causses, is distinguished by its karstic limestone Formations, which are intensely fractured, forming a major aquifer. This fracturing

facilitates both the infiltration of surface waters and their circulation within the underground reservoirs. Structural analysis has revealed a complex network of faults grouped into two main systems: NE-SW system, representing the major Hercynian faults, often intersected by later structures following the NW-SE system, significantly influencing the orientation of groundwater flow. These faults not only control the morphology of the plateau but also the dynamics of the groundwater flow. The piezometric study revealed a general flow of water from East to the West, influenced by the orientation of the tectonic structures and the presence of an impermeable substrata that composed of Triassic red saline clays. Maps of physical parameters revealed as (pH and electrical conductivity) highlighted significant variability related to water-rock interactions and local geological conditions. The slightly acidic pH of water interacting with basaltic and Triassic Formations contrasts with the slightly alkaline pH of water flowing through carbonate rocks. Similarly, high electrical conductivity values in certain areas reflect the influence of saline clays and evaporitic Formations from the Triassic. Finally, the analysis of the relationship between fracturing and water sources were confirmed the predominant role of faults in the emergence and orientation of flows. Sources such as Ain Timguenai, Ain Kassioua, and Ain Alla illustrate the direct influence of tectonic structures on the hydrogeological dynamics.

Acknowledgments

The author would like to express sincere gratitude to the Centre National pour la Recherche Scientifique et Technique (CNRST) for their financial support through a monthly scholarship. This funding has been instrumental in carrying out this research.

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