Journal of African Earth Sciences 205 (2023) 104996

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Influence of the Meso-Cenozoic tectonics on groundwater and surface water flows in the Skoura hydrogeological basin (folded Middle Atlas, Morocco)

Mohamed El Fartati [a], Saïd Hinaje [b], Driss Yaagoub [b,*], Bouhcine El Fellah Idrissi [c,d], Samir Amrani [b], Youssef Gharmane [b], Mohammed Laiche [b], Youssef Drissi [b], Tarik Tagma [a]

[a] Laboratoire Multidisciplinaire de Recherche et Innovation, Faculté Polydisciplinaire de Khouribga, Université Sultan Moulay Slimane, Khouribga, Morocco
[b] Laboratoire Systèmes Intelligents, Géoressources et Energies Renouvelables (SIGER), Université Sidi Mohammed Ben Abdellah, Faculté des Sciences et Techniques, B.P. 2202, Route d'Imouzzer, Fès, Morocco
[c] Equipe de recherche Innovation Pédagogique des SVT, Centre Regional des Métiers de L'Éducation et de La Formation, El Jadida, Morocco
[d] Laboratoire Géosciences Marines et Sciences du Sol, Université Chouaib Doukkali, Faculté des Sciences, El Jadida, Morocco

ARTICLE INFO

Handling Editor: DR Damien Delvaux

Keywords:
Hydrogeology
Aquifer
Brittle tectonics
Skoura basin
Middle Atlas
Morocco

ABSTRACT

The Skoura hydrogeological basin, part of the Folded Middle Atlas Mountain range, is located 30 km NE of Boulemane city and 50 km SE of Sefrou city. It is limited to the North and North-East by the Aichoun reliefs, to the West by the North Middle Atlas Fault (NMAF) and to the South by the Tichoukt ridge. It corresponds to a collapsed area resulting from polyphase tectonics succeeding from the Upper Miocene to present day. Its location between two major structural lines favors the accumulation and runoff of all precipitated water. This work aims to identify the geological structures which guide groundwater and surface water flows. The geological mapping and the measurements of the water points capturing the water table, have allowed to reconstitute the geodynamic evolution of this basin on one hand, and to identify the various aquifers containing the water table on the other hand. The Skoura water table circulates within four aquifer systems represented by Liassic carbonates, Bathonian sandstones, Vallesian lacustrine limestone and the Plio-Quaternary fluvio-lacustrine deposits. The impermeable substratum of each reservoir layer is respectively represented from bottom to top by Triassic-Liassic red claystones, Bathonian versicolored marls, Vallesian lacustrine claystones and Upper Miocene marls. The superposition of the piezometric map with the fracturing map shows that the groundwater flow axis is multidirectional. Groundwater flows along faults and fracture, following two main directions converging towards the Mdaz River. A first flow from SW to NE characterizing the upstream part of the hydrogeological basin and a second flow from West to East which covers its central part. Concerning surface water flows, they are guided by the submeridian and transverse faults, as well as by the two major faults (NMAF and the Tichoukt Fault) which have played a major role in the genesis and evolution of the Oued Mdaz valley.

1. Introduction

The Middle Atlas of Morocco is a NE-SW mountain range that belongs to the Atlas system, which is an intracontinental mountain range, extending over NW Africa across Morocco, Algeria, and Tunisia (Frizon de Lamotte et al., 2008). It is limited in the North by the South-Rifain corridor, in the South by the High Atlas and the High Moulouya, in the North-West by the Western Meseta and in the South-East by the Middle Moulouya (Fig. 1). Its structure corresponds to large NE-SW trending synclinal basins, parallel to narrow anticlinal ridges, faulted and sometimes intruded by gabbroic rocks (Termier, 1936; Colo, 1961; Fedan, 1988). The Middle Atlas is subdivided into two structural domains, separated by the NMAF (Colo, 1961; Duée et al., 1977; Fedan, 1988; Charrière, 1990; Hinaje, 2004) (Fig. 1). These are the Middle Atlas Causse or Tabular Middle Atlas to the NW and the Folded Middle Atlas to the SE. The Skoura hydrogeological basin lies within the folded Middle Atlas, is limited in the South and South-East by the Tichoukt ramp and in the North-West by the NMAF. It is filled with sedimentary sequences corresponding to the Dogger formations. These latter are unconformably overlain by Neogene and Quaternary series (Fig. 1). The genesis of this basin is mainly related to the succussion of several tectonic episodes occurring from the Upper Miocene to present (Hinaje, 2004; Hinaje

* Corresponding author.
E-mail address: yaagoub.driss@gmail.com (D. Yaagoub).

https://doi.org/10.1016/j.jafrearsci.2023.104996
Received 17 February 2023; Received in revised form 10 June 2023; Accepted 15 June 2023
Available online 16 June 2023
1464-343X/

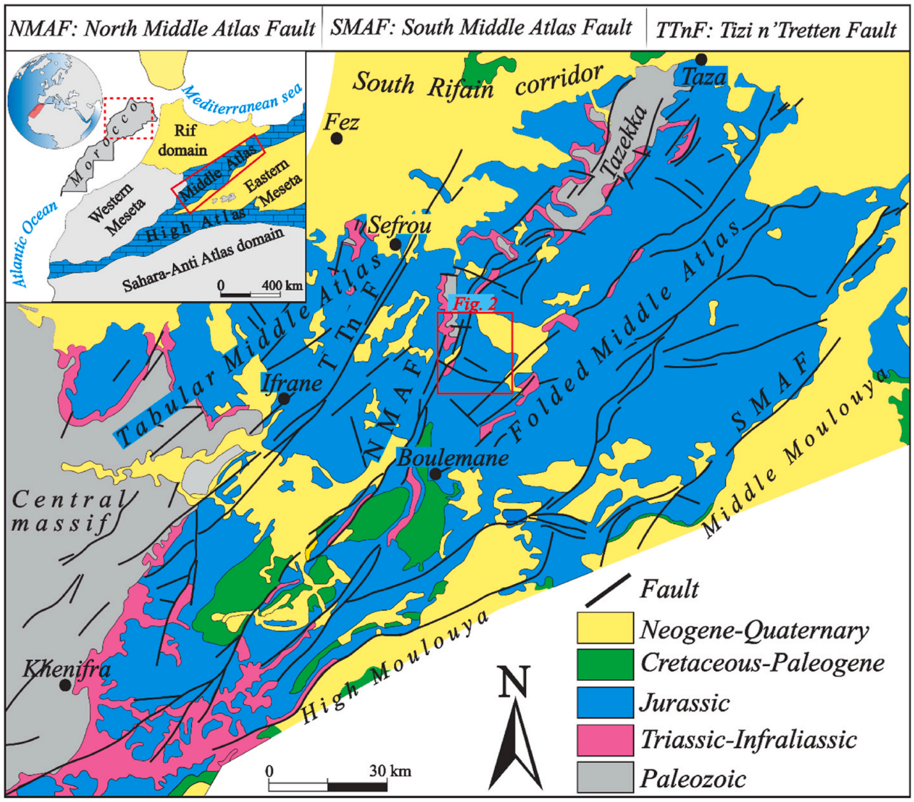

Fig. 1. Geographical location and general geological setting of the study area in the Middle Atlas, modified from the geological map of Morocco at 1/1,000,000 (Hollard et al., 1985).

et al., 2019; EL Fartati et al., 2019, 2021).

The faulted and fractured areas are considered as potential water reservoirs (e.g., Caine et al., 1996; Ohlmacher, 1999; Voeckler and Allen, 2012; Welch and Allen, 2014; EL Fartati et al., 2021; Allen and Nott, 2021). The relationship between fracturing and groundwater flow has not been previously approached in the Folded Middle Atlas. Some studies have mainly focused on hydrological modeling and flow assessment of a few water springs (Chapond, 1962; Chamayou et al., 1975; Amraoui, 2005; Msaddek et al., 2020; Qadem et al., 2022). Currently, due to periods of drought stress, groundwater is flowing along the unclogged planes of fractures and faults. Hence the importance of tectonic studies combined to hydrogeological and climatic investigations.

Since the groundwater flow is mostly guided by faults and fractures, their analysis is therefore necessary for any aquifer system (e.g., Levens et al., 1994; Bense and Person, 2006; Mayer et al., 2007; Burbey, 2008; Bense et al., 2008; El Fellah Idrissi, 2010; Folch and Mas-Pla, 2008; Bense et al., 2013; El Fartati et al., 2021). Moreover, the recent periods of droughts in Morocco, as well as the excessive exploitation of surface water in the Skoura hydrogeological basin makes it most likely that the groundwater and surface water flow mainly follows fractures and faults. On the other hand, the diversity of tectonic-sedimentary and lithostratigraphic features of the multi-layered aquifers has made complex hydrological systems. To characterize high water potential structures, a combination of lithostratigraphic, structural and piezometric analysis of the water table is necessary. The superimposition of the structural on the piezometric maps allowed to identify the aquifer extent and the spatial distribution of groundwater flows characterizing the Skoura hydrogeological basin.

The identification of fractures contributing to surface flows can be carried out using techniques based on geophysical data and/or morphometric analysis (e.g., Delaney et al., 1986; Chorowicz and Deffontaines, 1993; Dridri and Fedan, 2001). These techniques have allowed the identification of large fractures participating in the water flow (e.g., Chorowicz and Deffontaines, 1993; Pastor et al., 2015; Amine et al., 2020). However, it is necessary to combine field mapping and fracturing analysis with these techniques in order to affirm the role of brittle tectonics on the incision of valleys, as well as their genesis and their shape.

In this work, we adopted a multidisciplinary approach mainly based on field work (structural and stratigraphic cross-sections, mapping of brittle structures and structural analyses, and identification of water points capturing the water table). This study aims to identify the structural and hydrogeological characteristics of the Skoura basin and to highlight the importance of faults and fractures in the control and orientation of groundwater and surface water flows. The obtained results will allow to select favorable and unfavorable zones (potential structures) for the implantation of water catchment points (wells, boreholes), especially when there are insufficient rainfall periods. The exploration of water deposits associated with faulted structures also allows for the preservation of the water table by giving special attention to the good extraction of groundwater (example of the pumping test approach in order to report the critical and exploitation flow). The results of this multidisciplinary work are represented on a set of piezometric-structural maps, stratigraphic columns, geological cross-sections, fault rose diagrams, fault density distribution diagrams and conceptual water flow 3D models.

2. Geological setting

2.1. The Middle Atlas mountain range in the atlas system

The Middle Atlas mountain range is a NE-SW branch of the Atlas system (Middle Atlas and High Atlas chains) which extends obliquely across the mesetan domain (Fig. 1). The Atlas system is an intra-continental, autochthonous system, developed over a continental

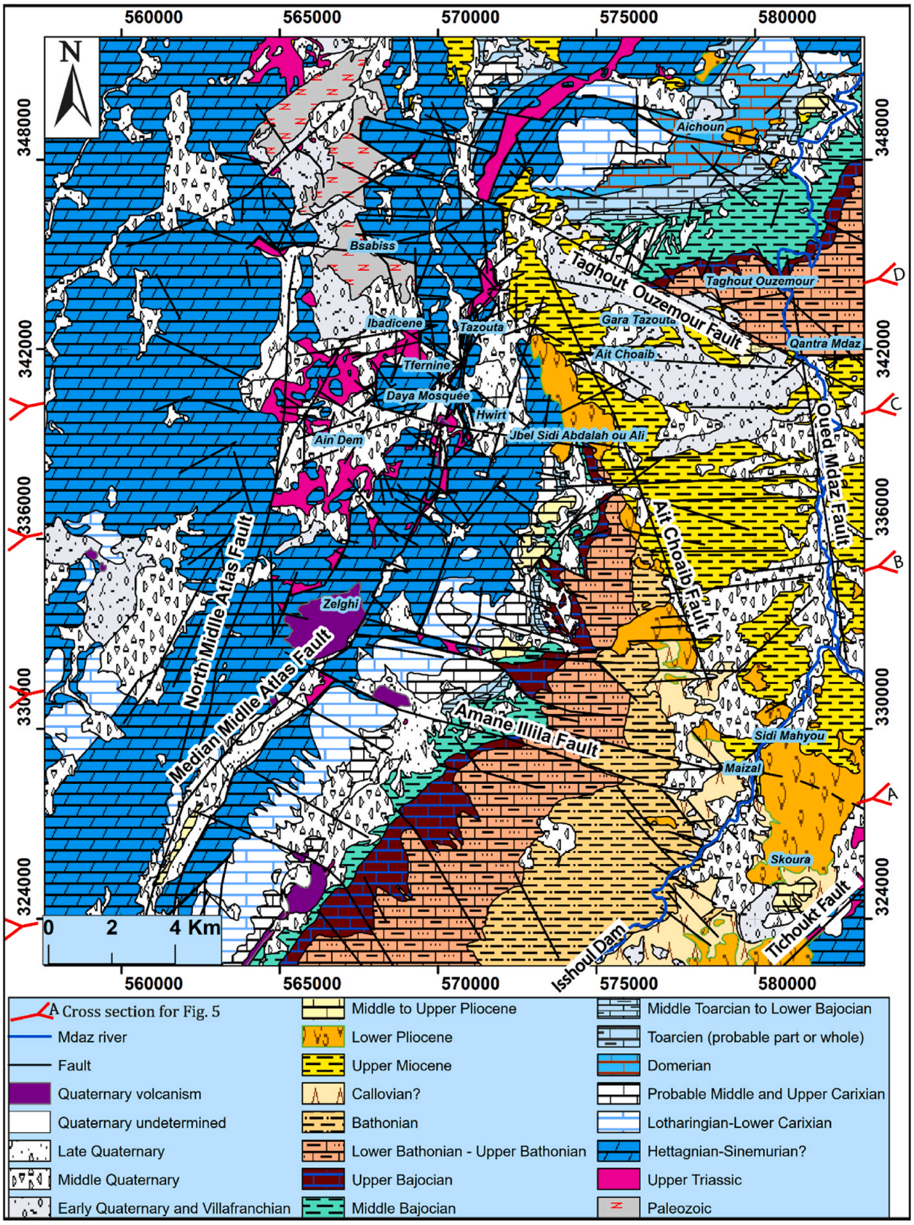

Fig. 2. Geological map of the study area (Charrière, 1989, modified).

basement (Frizon de Lamotte et al., 2008 with references therein). Its general structure corresponds to large syncline basins and anticline ridges with axes parallel to the directions of the two chains (e.g., Termier, 1936; Laville, 1985; Fedan, 1988; Ibouh, 2004; Hinaje, 2004). The geodynamic evolution of the Atlas system includes, roughly, two major periods (e.g., Fedan, 1988; Jacobshagen et al., 1988; Charrière, 1990; Hinaje, 2004; Frizon de Lamotte et al., 2008; Gouiza et al., 2010; Fekkak et al., 2018; Ellero et al., 2020; Lanari et al., 2020; Gharmane et al., 2021; Yaagoub et al., 2021a, 2021b, 2021c, 2022, 2023; Moussaid et al., 2023 with references therein): (i) the pre-orogenic period which lasts from the Triassic to the Late Cretaceous. It starts after the Variscan orogeny during the break-up of Pangea with several successive extensional episodes. This is responsible for the development of syn-rift and post rift basins filled with sedimentary series linked to the Tethys-Atlantic domain and volcanic floods of the Central Atlantic Magmatic Province (CAMP); (ii) the orogenic period which start from Late Cretaceous in the framework of the convergence between Africa and Iberia/Europe plates. This is responsible for the inversion of the pre-orogenic basins and the uplift of the Atlas young fold-and-thrust belts.

2.2. The Skoura hydrogeological basin

The Skoura hydrogeological basin, located in the transition zone between the Middle Atlas Causse and the Folded Middle Atlas (Fig. 1), is mainly dominated by Dogger terrain, unconformably overlain by Neogene and Quaternary formations. It is limited in the SE by the Tichoukt structural flat-ramp-flat system, which consists of Liassic carbonate formations. The subsidence of the Skoura basin during the Neogene is amplified by submeridian Middle-Late Quaternary normal faults which explains its current synform structure. The different lithological units characterizing the Skoura basin are arranged as follows (Fig. 2):

- The geological series represented by red claystones and salt, intercalated by a very fractured basaltic complex, which is entirely localized at the edge of the NMAF and at the Tichoukt fault ridge.

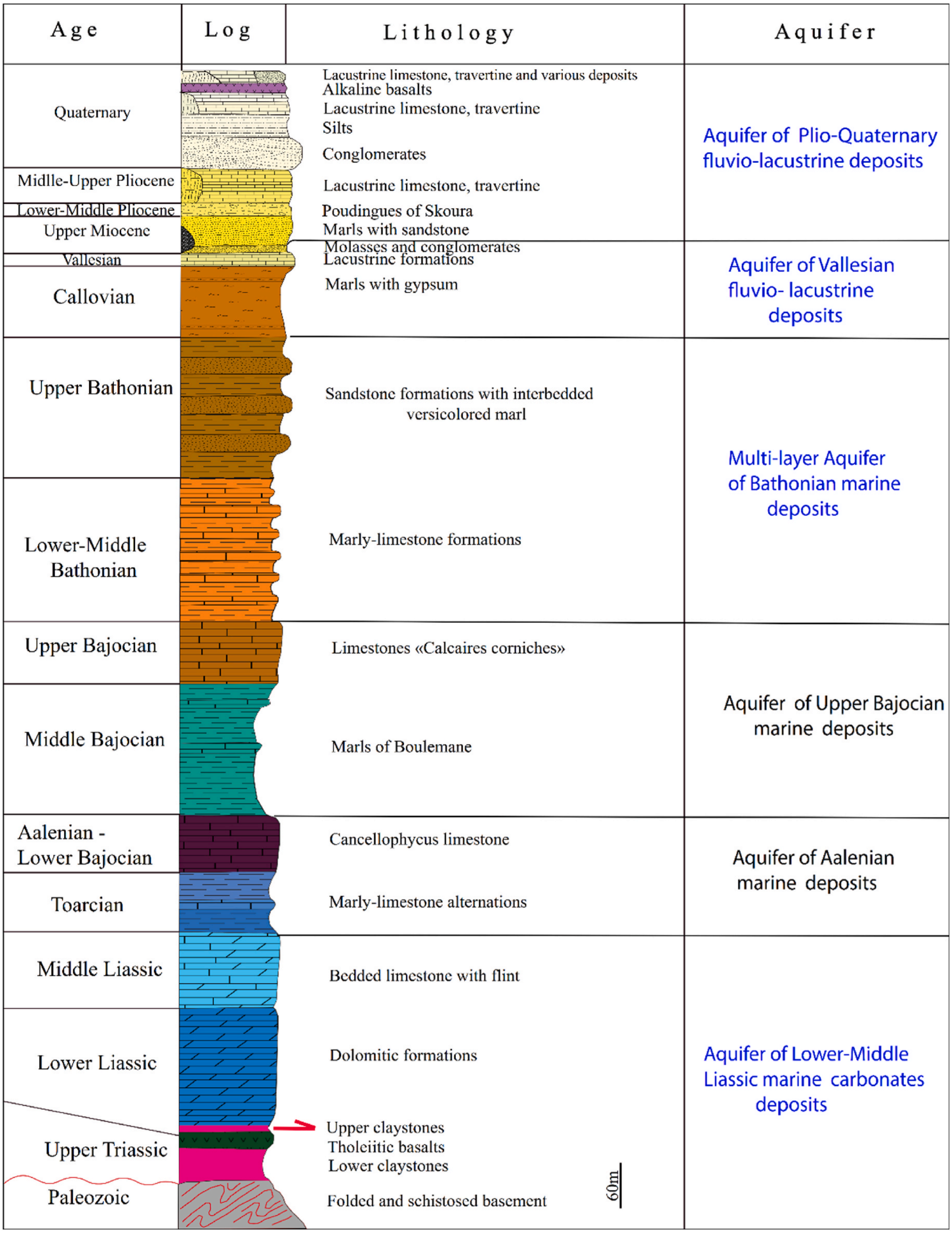

Fig. 3. Lithostratigraphic column showing the aquifers linked to the water table in the hydrogeological Skoura basin.

These claystones and basaltic formations are assigned to the Upper Triassic (Michard, 1976);

- The Liassic carbonate formations conformably deposited on the Triassic series and represented, from bottom to top, by Lower-Middle Liassic dolostones and limestones (Termier, 1936; Colo, 1961; Du Dresnay, 1979; Martin, 1981; Charrière, 1990; Sabaoui, 1998; Hinaje, 2004). They form the skeleton of the Tichoukt ridge to the south of the studied area;
- The Dogger is represented by the following formations:

-Boulemane marls outcropping to the NE in the Aichoun area and to the SW of the study area, overlain by Upper Bajocian limestones "calcaires corniches" (Fedan, 1988; Sabaoui, 1998; Charrière, 1990) (Fig. 2).

- Towards the "Mdaz pont" to the North, the Bathonian formations are represented by marl and sandstone alternations; -Towards the

Skoura village, especially in the Maizal area, the Skoura Callovian marls and gypsum constitutes the top of the Dogger series (Choubert and Faure-Muret, 1960–62; Fedan, 1988; Charrière, 1990) (Fig. 2);

- Malm, Cretaceous and Paleogene formations are lacking. During this period the Skoura area is considered as a structural paleohigh regarding the Atlantic-dependent Cretaceous and Paleogene transgressions (Fedan, 1988; Charroud, 1990);
- The Miocene formations are contained in the forward gulfs from the South Rifain strait to the Skoura basin (Daguin, 1927). To the NE of the Skoura basin, the Miocene series begins with the Ajdir Ahbari formation consisting of Vallesian calcilutites and white lacustrine limestones (Jaeger et al., 1973; Hinaje, 2004; EL Fartati, 2021) (Fig. 2). This lacustrine series is covered by Upper Miocene formations, represented by conglomerates at the bottom, surmounted by sandy marls with sandstone paleochannels (Charrière, 1990; Sabaoui, 1998; Hinaje, 2004; El Fartati, 2021);
- The Plio-Quaternary is characterized by fluvio-lacustrine, continental, travertine sequences and volcanic flows (Martin, 1981; Moukadiri, 1983; Harmand and Cantagrel, 1984; Fedan, 1988; El Azzab and El Wartiti, 1998; Sabaoui, 1998; Hinaje, 2004; EL Azzouzi et al., 2010; Hinaje et al., 2019; EL Fartati., 2021).

The genesis and the evolution of the Skoura hydrogeological basin is mainly related to the succession of several tectonic episodes from the Upper Miocene to the present (Hinaje, 2004; EL Fartati et al., 2019, 2021). These episodes are marked by five fault systems: (i) during the Upper Miocene, the Skoura basin underwent an NE-SW extensional episode responsible for the genesis of N120 to N140 grabens which receive marine sediments. Thes grabens are framed by NW-SE trending normal faults; (ii) during the Lower-Middle Pliocene, a major NW-SE compressional episode contributed to the uplift of the NE-SW Middle Atlas reliefs and the emplacement of the Lower-Middle Pliocene Skoura puddingstones formation; (iii) during the Middle-Upper Pliocene, ENE-WSW trending normal faults associated with a NNW-SSE extensional episode allowed the genesis of an ENE-WSW continental basin with fluvio-lacustrine sedimentation; (iv) the third normal fault system with NNE-SSW to NE-SW direction, assigned to the Early-Middle Quaternary, has accentuated the deepening of the Skoura basin by the creation of N15 to N45 trending grabens; (v) the last Middle-Late Quaternary fault system is represented by submeridian normal faults which are responsible for the current Skoura basin structure. These faults are due to an ENE-WSW extensional episode.

3. Methods

To carry out our study, we adopted an approach based on the collection and analysis of field data (i.e., piezometric, cartographic, and structural data). This approach consists of:

- Identifying the water points catching the water table with a Liassic, Dogger and Mio-Plio-Quaternary multilayer aquifer. The number of measurements carried out between springs and wells exceeded 200 water points. We executed a piezometric campaign during the summer period (June, July and August 2017), whose processing allowed to establish the piezometric map. This map is an important tool for hydrogeological studies (Castany, 1989);
- Carrying out structural measurements on fault slickensides (direction, dip, pitch of striae, …) affecting the different geological formations belonging to the Skoura hydrogeological basin. The age of these formations allowed to characterize and classify the tectonic episodes, and to establish a relative chronology of the deformation phases recorded in the study area. Other techniques are used to determine the timing of deformation such as the relationships between fault systems (cross-cutting, incompatibility of the movements of parallel faults, superposition of multiple generations of slickenlines, the presence of synsedimentary faults, …);
- Establishing structural cross-sections and stratigraphic columns in order to define the geological aquifers and the circulation patterns of groundwater and surface water;

The processing of the collected field data is carried out using the ARC-GIS software. The kriging interpolation method was used to establish the piezometric map of the Skoura water table. The superposition of this map on the fracturing map makes it possible to determine the direction of groundwater flow and also to geo-reference potential structures for the implantation of water wells and boreholes.

4. Results

4.1. Geological identification of the aquifer

The hydrogeological characterization of the water table in the Skoura basin is mainly based on a detailed geological study that aims to identify the different lithostratigraphic series found in the study area, and to inventory the different water points capturing the water table. Geological mapping and lithostratigraphic sections carried out in the field have made it possible to identify at least four aquifer systems of different importance, which communicate with each other laterally and vertically. Groundwater is stored in the following geological formations: (Fig. 3):

- The Lower-Middle Liassic dolostones and limestones, having as impermeable substratum the Triassic red claystones and being able to contain a water table and confined groundwater. This groundwater essentially characterizes the upstream part of the hydrogeological basin of Skoura corresponding to Jbel Tichoukt area;
- The Bathonian sandstones and limestones, with marl intercalations, which may contain several water tables recharged from surface infiltrations and/or through faults. Indeed, this formation favors the appearance of a multilayer aquifer where the water supply is done by exchanges with the other superimposed aquifers, by vertical upward or downward flows. Which corresponds to the ''drainance'' phenomenon as defined by Castany (1982);
- The Vallesian lacustrine limestones overlying lacustrine and palustrine clays of the same age. This lacustrine aquifer is very restricted and is covered by the Upper Miocene sandy marls;
- The alluvium superficial water table is stored in the Plio-Quaternary fluvio-lacustrine, travertines and alluvial fan deposits.

4.1.1. Liassic aquifer system

To the SE of the Skoura basin, along the Tichoukt ramp, the Liassic formations represent an important water reservoir largely contributing to the permanent flow of Oued Mdaz (Fig. 2). The texture of the carbonate rock and the fracturing caused by polyphase brittle tectonics play an important role in the circulation of groundwater and in the development of the various karst systems. All these factors contribute to the dissolution of the carbonate rock by causing the enlargement of the pores and the fractures (fissure, interstitial and karstification porosity).

The Liassic aquifer system has the capacity to contain a discontinuous water table framed by faults. The depth of the water table exceeds 200 m in some locations. However, at abnormal contacts, this depth weakens due to the thinning of the water-bearing layer. The water table with Liassic aquifer ensures in large part the drinking water supply for the population of Skoura and the neighboring areas. It emerges on the surface as many springs, such as the Tadout spring which emerges along a NW-SE transverse fault plane in Jbel Tichoukt.

4.1.2. Bathonian aquifer system

Parallel to the NMAF, the Bathonian series which particularly characterize the Skoura hydrological basin, outcrop with a very remarkable dip (of about 60°) towards the basin core (Fig. 2). They occupy a smaller

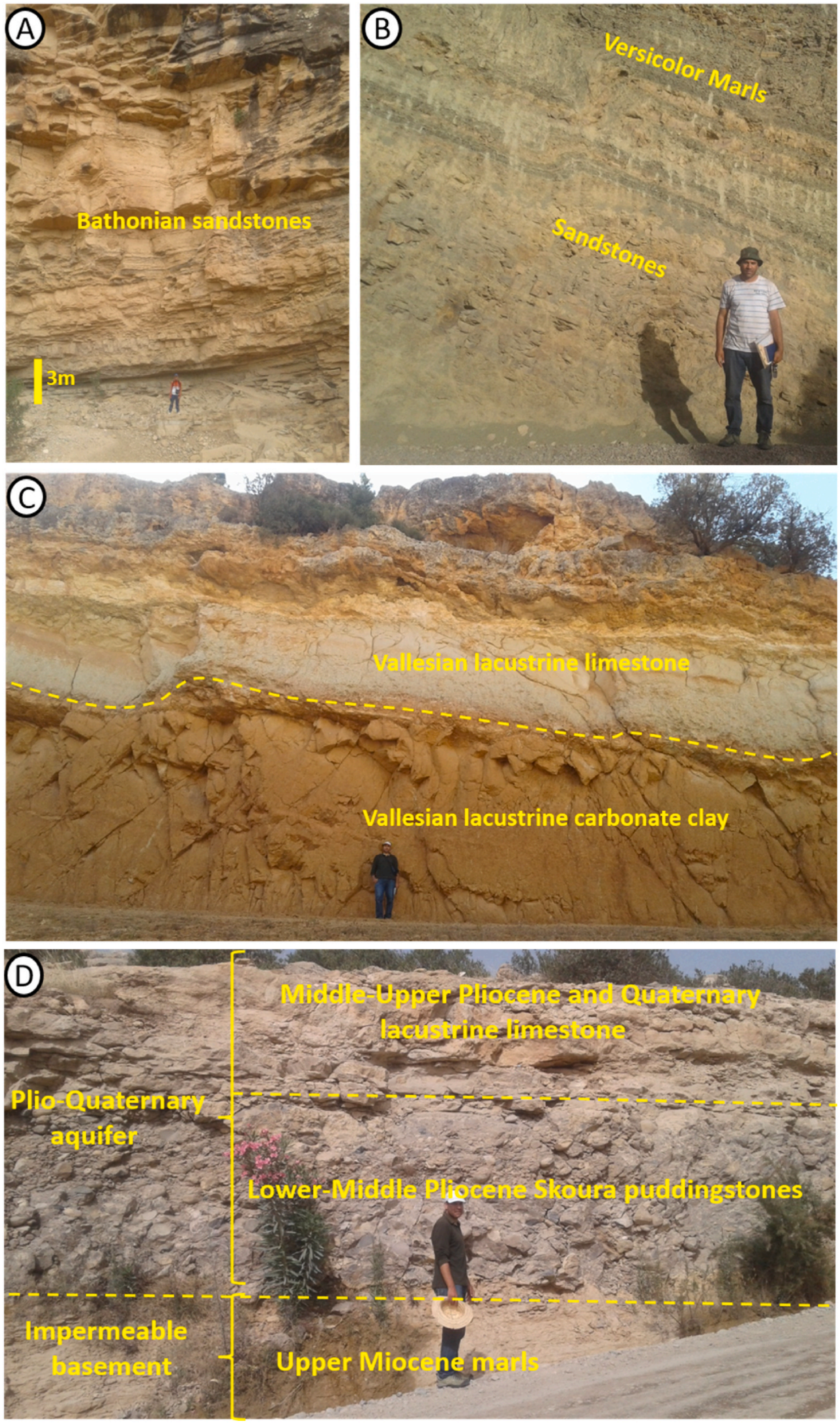

Fig. 4. Location of different types of aquifers in relation to the substratum characterizing the Skoura hydrogeological basin. A. Thick sandstone series constituting the Bathonian aquifer in the Oued Mdaz area. B. Bathonian marl and sandstone alternations west of Skoura village. C. Vallesian lacustrine limestones and its carbonate clay impermeable basement in Ajdir Ahbari area. D. Plio-Quaternary aquifer system and its Miocene impermeable basement in "Mdaz pont" area.

area in the NE of the basin than in the SW (Fig. 4B). They are represented by sandstones with versicolored marl intercalations, where the thickness can exceed 100m, especially near the "Mdaz pont" area (Fig. 4A). The area geological features allowed to identify a Bathonian aquifer containing a water table with an impermeable basement made up of versicolored marls. This multilayer aquifer system forms a good water reservoir for groundwater storage and circulation. The tilting of the reservoir layer towards the Oued Mdaz, accelerate the infiltration and drainage of groundwater. The water table roof within these outcropping formations is very close to the topographic surface. This water table

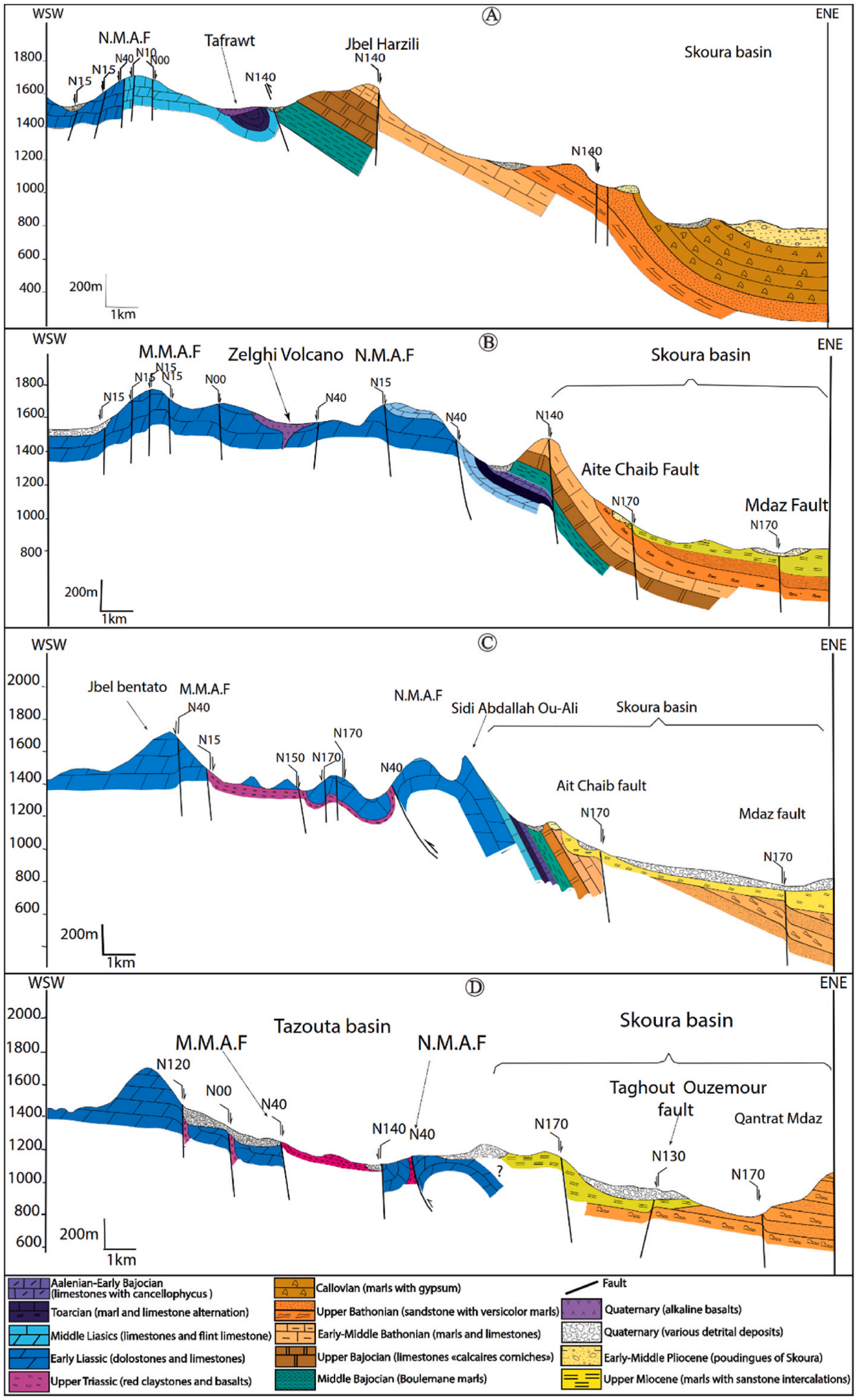

Fig. 5. Geological cross-sections showing the structure and geometry of the aquifers affected by NE-SW, NW-SE and N–S fault systems in the Skoura basin. (See location of the cross-sections in Fig. 2).

reappears on the surface, giving rise to springs such as Tarahrourte and Tannoute springs. Moreover, the alternation of sandstones and versicolored marls intersected by faults can generate vertical flows contributing to the appearance of multi-layered confined groundwater.

Towards the core of the Skoura basin, the Bathonian aquifer is buried under Neogene and Quaternary deposits, forming a confined groundwater (Fig. 2). Indeed, in addition to the tilting of this aquifer towards the center, the thickness of the cover made by the superimposed Neogene and Quaternary formations favors the presence of a deep confined groundwater flowing SE-wards.

The recharge of the water table traversing the Bathonian aquifer is clearly linked to the recharge of the Liassic aquifer located upstream, which subsequently influences the drainage of the Oued Mdaz. The wells catching this groundwater in the Bathonian aquifer as well as the emergent water sources ensure the drinking water supply for the population of Sidi Mahyou village and the irrigation of some agricultural

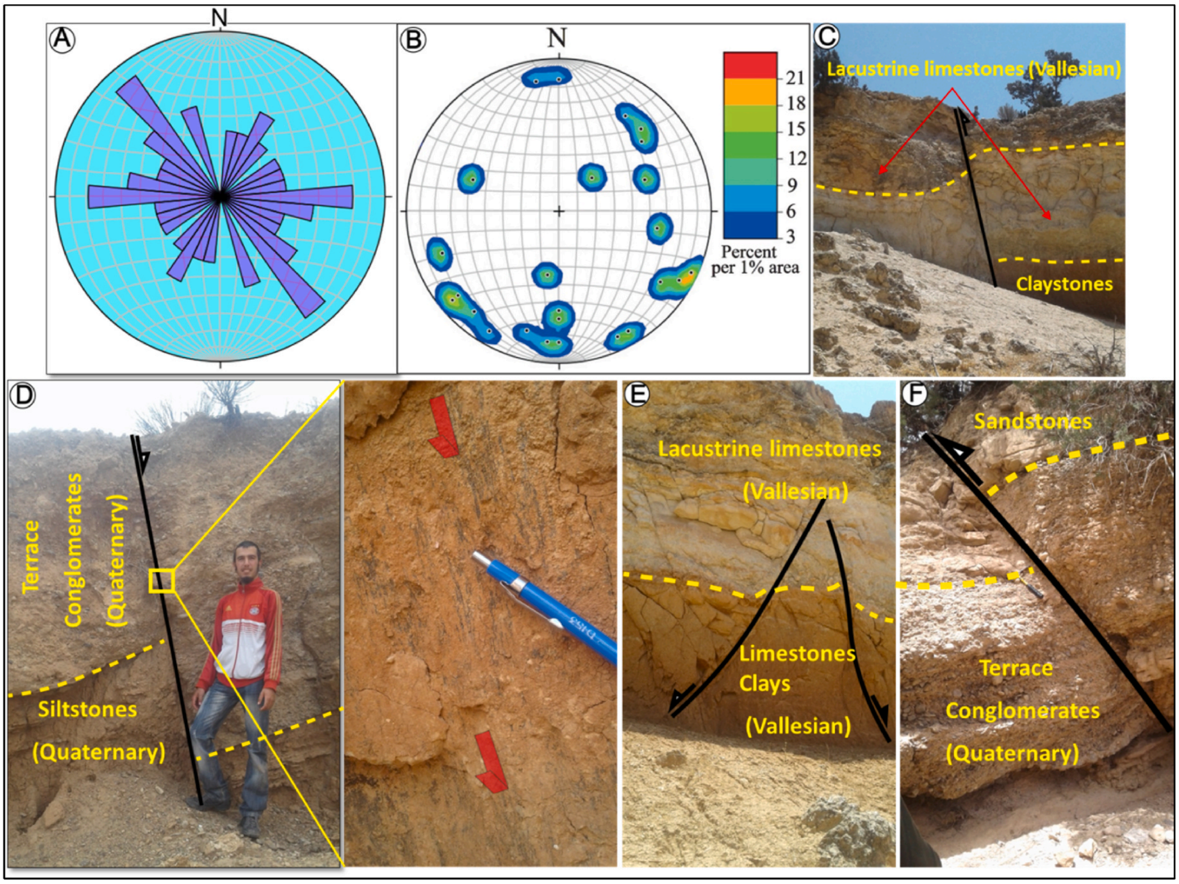

Fig. 6. Rose diagram of the faults cross-cutting the Skoura basin (A and B). C. Reverse fault cross-cutting the Vallesian formations. D. Normal fault affecting the Quaternary formations. E. Vallesian synsedimentary normal faults. F. Apparent reverse fault cross-cutting the Quaternary formations.

areas.

4.1.3. Vallesian aquifer system

To the NE of the Skoura basin, near the Mdaz pont, the Vallesian deposits, which cover a relatively small area, are represented by a thick clay-carbonate layer surmounted by white lacustrine limestone layers (Figs. 3 and 4C). These lacustrine limestones are tilted to the SW due to the N130 Taghout-Ouzemour synsedimentary normal fault (Fig. 2). The fissure permeability and fracture intensity characterizing the aquifer provide a good water reservoir with impermeable substratum corresponding to Vallesian brown carbonate clays with calcareous nodules. The thickness of the limestone layer, not exceeding 10 m, in addition to the Miocene and Plio-Quaternary cover, reveal that the depth of this water table will be less important than that contained in the Liassic aquifer. In addition to the fracture intensity, the SW and SSW tilting of this limestone level influences the groundwater storage due to the increase of the infiltration coefficient and the decrease of the storage rate. All these hydrogeological factors increase the groundwater flow towards the South where the water table is deeper. This explains the absence of water points capturing the water table locally located within this aquifer. Towards the South, the Vallesian aquifer system is buried under the Upper Miocene marls (Fig. 2), and probably supplies the deep aquifer located to the South and the surface water of Oued Mdaz valley.

4.1.4. Plio-Quaternary aquifer system

The Skoura basin is characterized by the predominance of Plio-Quaternary fluvio-lacustrine and travertine deposits. It is represented, from bottom to top, by Lower-Middle Pliocene Skoura puddingstones, surmounted Middle-Upper Pliocene lacustrine limestones (Fig. 3). The Pliocene series are capped by Quaternary alluvial fan deposits, lacustrine limestones, and travertines (Figs. 3 and 4D).

Geological maps and cross-sections show a multi-layered alluvial aquifer. In the Skoura basin, this aquifer covers a large area. It contains a significant free water table, with an impermeable substrate represented by Upper Miocene marls (Fig. 3). The depth of the water table changes according to the thickness of the underlying formations and the thickness of the reservoir layers. It is directly supplied by rainwater or by groundwater through transverse faults from the uplifted areas containing the Liassic dolomitic aquifer.

The alluvial aquifer supplies numerous springs such as Ain Lghoul, Sidi Mahyou, Mghirta and Sidi Yahia springs. These springs emerging from faulted and/or lithostratigraphic contacts, mainly supply some villages with drinking water and the irrigation of some agricultural plots. It also contributes to the permanent flow of the Oued Mdaz.

4.2. Structural analysis of the Skoura hydrogeological basin

The structural and lithostratigraphic analyses enable highlighting the different geological structures affecting the study area. All these studies contribute on one hand to the characterization of the various aquifers by unraveling the relationship between them, and to identify the main water flow axes of the superficial water table on the other hand. Three major fault systems played an important role in the structuring of the study area and contribute to guiding groundwater and surface water flows. These are the NE-SW, N–S and NW-SE fault systems (Figs. 5 and 6).

4.2.1. NE-SW fault system

In the Skoura hydrogeological basin, two major NE-SW trending structural lines have contributed to the genesis and structuring of the

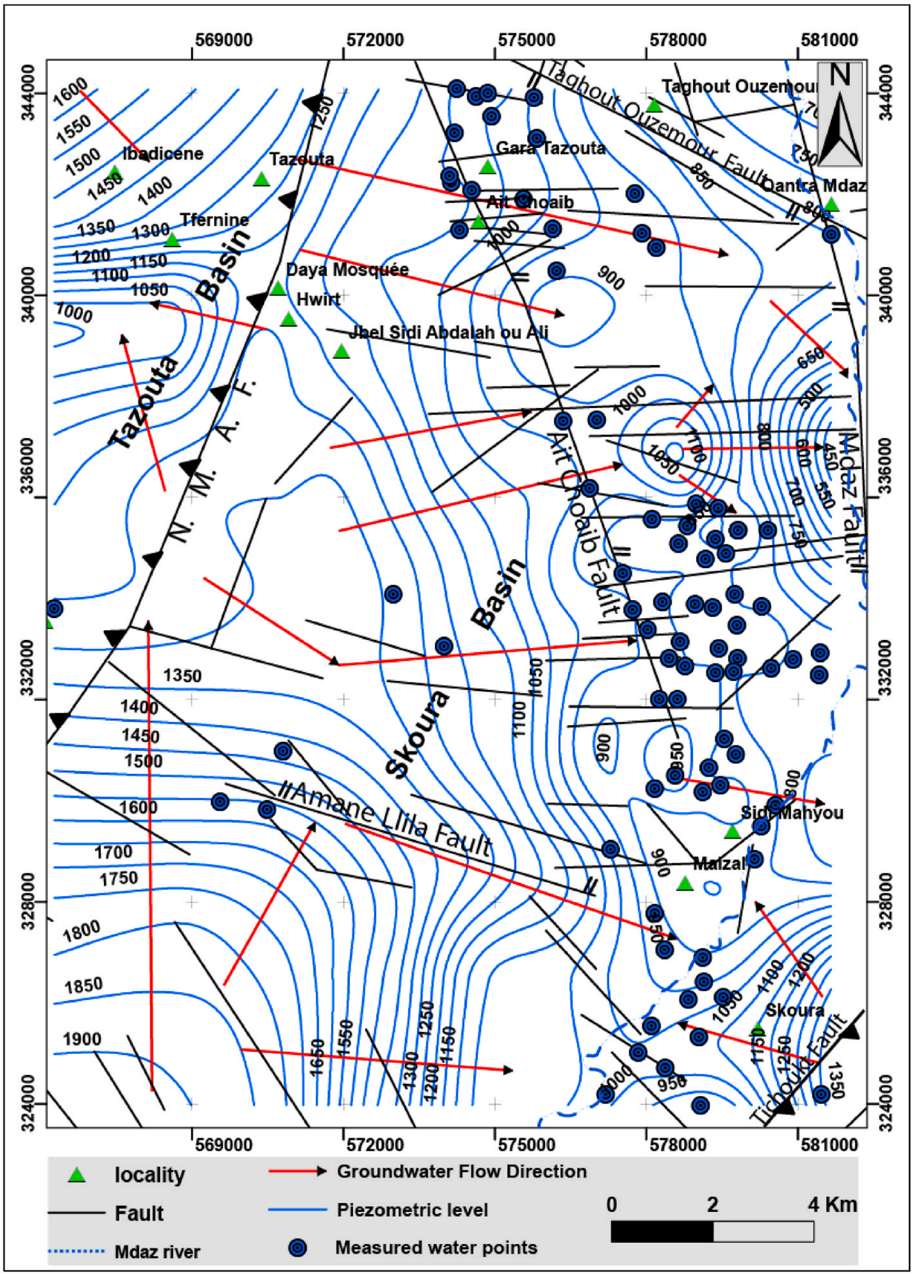

Fig. 7. Piezometric map of the Skoura water table (June, July and August 2017).

basin. These are the NMAF in the NW and the Tichoukt Fault in the SE (Fig. 5).

4.2.1.1. North Middle Atlas Fault (NMAF). The N30 to N70 NMAF marks the transition between the Folded Middle Atlas and the Oued Zraa-El Menzel area which is part of the Middle Atlas causse. It is cross-cut by a N80 to N140 fault network (Fig. 2). This fault zone materialized by reverse and thrust faults, is rooted SW of the village of the Tazouta in a single subvertical fault network, staking out Triassic claystones and basalts (Fig. 2). This structural barrier that separates the Tazouta Basin from the Skoura Basin played the role of a topographic paleohigh limiting the marine transgression during the Upper Miocene (Fig. 5).

4.2.1.2. Tichoukt Fault. The Tichoukt fault corresponds an NE-SW anticlinal ridge which extends over 30 km from Boulemane in the SW to Skoura village in the NE. This major fault constitutes the southern and southeastern limit of the Skoura Basin with a ramp anticline framework constituted by Liassic carbonate.

The major Tichoukt Fault corresponds to a N45 to N60 trending reverse to thrust fault, SE dipping and its plane is filled with Triassic claystones and basalts. The thrust series shows reversed Bathonian sandstones with versicolored marl intercalations and Bathonian-Callovian marl with gypsum. The reverse movement of this Fault zone is divided into two episodes assigned to the Vallesian and the Lower-Middle Pliocene (Hinaje, 2004). This is evidenced by the unconformity between the Vallesian deposits and the Bathonian layers, and the unconformity of the Pliocene deposits on the Miocene strata. This reverse movement affects all the ante-Miocene and Miocene series, and it doesn't affect the last terms of the Skoura puddingstones. This tectonic activity is the result of a N120 paroxysmal compression during the

Vallesian and NW-SE during the Lower-Middle Pliocene, materialized by N30 to N60 reverse and thrusts faults, associated with submeridian sinistral strike-slip faults and N80 to N110 dextral strike-slip faults (Hinaje, 2004).

4.2.2. N–S fault system

This fault system, which cross-cuts the Skoura basin, is represented by two main submeridian faults: (i) the Oued Mdaz fault in the East and (ii) the Ait Chaib fault in the West (Fig. 5). The first extends over a distance exceeding 10 km, parallel to the Oued Mdaz Valley. Its Middle-Late Quaternary normal movement caused the dislocation of the natural wall of the Oued Mdaz paleo-dam (Fig. 6D) (natural dam lake whose wall corresponds to a N130 normal fault) (El Fartati et al., 2019, 2021). For the Ait Chaib fault, which essentially caused the elevation of the Douar Aït Chaib plateau, is located near the NMAF, whose vertical slip exceeds 100 m. The tectonic compartmentalization in stepped blocks, produced by the normal movements of these faults, accentuated on one hand the subsidence of the basin by favouring the deposition of Quaternary sediments, and on the other hand, it allowed overflow of the superficial water table.

4.2.3. NW-SE fault system

Other structural lines have contributed to the structuring of the Skoura fluvio-lacustrine basin. These are NW-SE to WNW-ESE transverse faults such as the Taghout-Ouzemour fault and the Amane Ilila-Kandar fault (Fig. 6A and E).

4.2.4. Taghout-Ouzemour fault

It is a N130 trending fault, located north of the Skoura basin along the Jbel Ich-Ighanimene and Aichoun reliefs (Fig. 5D). This fault, with an important paleogeographic feature during the Vallesian and Middle-Upper Pliocene, played a major role in the installation of the Mdaz paleo-dam (El Fartati et al., 2019). Indeed, its Vallesian-Upper Tortonian-Messinian normal movement caused the tilting of the Bathonian strata towards the SW, favouring the emplacement of a paleo-dam lake (Hinaje, 2004; El Fartati et al., 2019, 2021). This one has known a lacustrine, marine and fluvio-lacustrine sedimentary trilogy; constituting the Neogene and Quaternary formations. The Taghout Ouzemour fault extends towards the NW, crossing the Tikharbichine and Bou Meriem areas until it is crossed by a segment of the NMAF. Near the "Mdaz pont" area, it is crossed by the N170 trending Mdaz fault (Fig. 6C and F).

4.2.4.1. Amane Ilila-Kandar fault. The N120 to N140 trending Amane Ilila-Kandar fault (Fig. 6A) (Hinaje, 2004), extends from the Kandar inlier to the Tichoukt Fault zone to the SE, crossing the Aman Ilila formations and the NMAF respectively (Fig. 2). South of the Skoura basin, this fault is locally hidden by Neogene and Quaternary deposits. Its last dextral strike-slip movement, during the Middle-Late Quaternary, has favored Jbel Zalghi strombolian volcanic activity (Hinaje et al., 2019) (Fig. 5B). Its first normal movement during the Upper Miocene is responsible for the outcrop of the Paleozoic basement in the Kandar inlier (Hinaje, 2004).

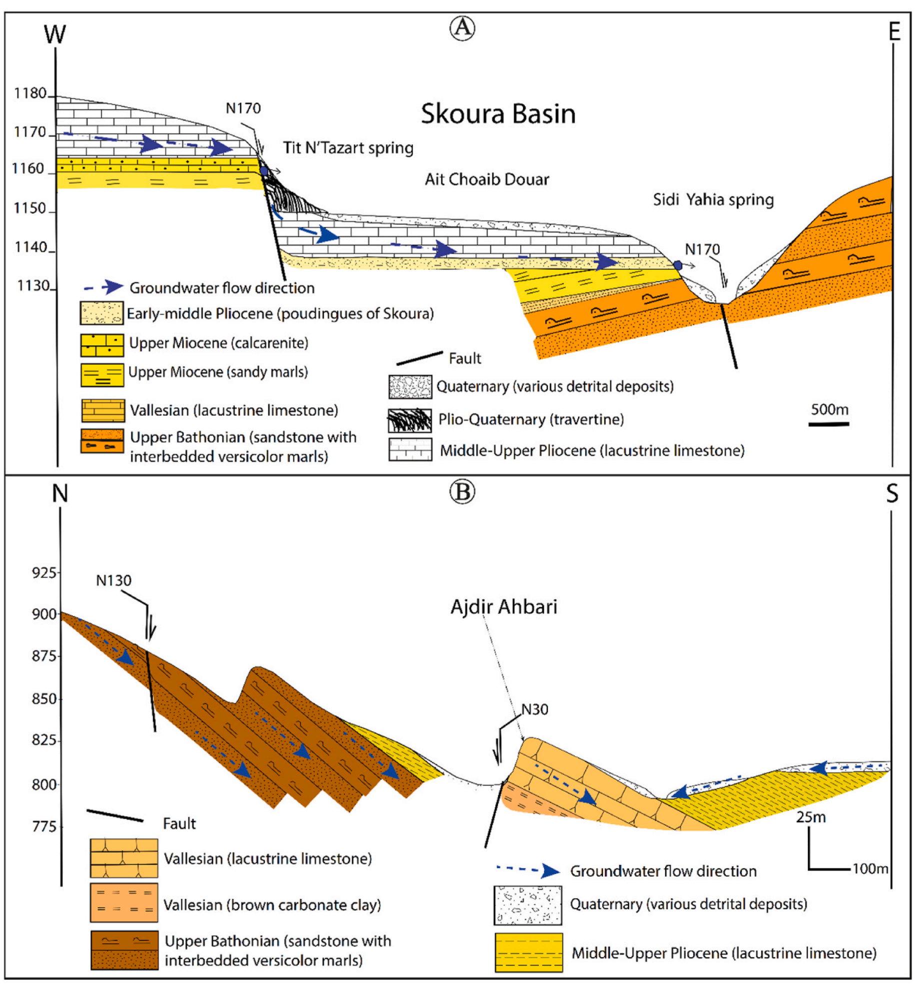

Fig. 8. Geological cross-sections showing the extension of the Vallesian, Bathonian and Plio-Quaternary aquifer with superimposed water table and confined groundwater.

4.3. Analysis of the piezometric map of the Skoura hydrogeological basin

It seems that the lithological diversity of aquifers directly influences groundwater flows and infiltration. It is therefore necessary to highlight the hydrodynamic behavior of the water table for each aquifer, their mutual relationship and their relationship with the Tazouta Liassic water table. The piezometric map we carried out during the summer of 2017, shows the main drainage axes of the superficial water table. Overall, the water table covering the Skoura basin flows towards Oued Mdaz following E-W and SW-NE direction (Fig. 7).

The hydrogeological basin of Skoura is limited to the west by the NMAF. Its thrust block located towards this basin shows the sedimentary series ranging from Lower Liassic to Quaternary with an eastward dip of the layers ranging from 20° to 75°. This geometry of the layers favors a groundwater and surface water flow towards the axis of the Skoura basin crossed by the N–S Oued Mdaz valley. The structural line traced by the NMAF divides the study area into two hydrogeological entities and constitutes a groundwater and surface water sharing zone (Fig. 7). Part of the water flows towards the West where it supplies the calcareous-dolomitic aquifer of the Tazouta basin and the other flows towards the East to supply the Skoura basin aquifers (Fig. 7).

According to the present study, the Skoura hydrogeological basin contains at least four aquifers. The aquifer layers are constituted successively by the Liassic carbonates, the Bathonian sandstones, the Vallesian lacustrine limestones and the Plio-Quaternary fluvio-lacustrine deposits. The study area is affected by a fault network which played a preponderant role in water infiltration and drainage by ensuring inter- and intra-aquifer supply. The Skoura water table, whose recharge corresponds to the accumulated rainfall of the Oued Mdaz watershed, is also supplied from the Tazouta Liassic water table and Tichoukt ridge through the NW-SE, ENE-WSW and N–S trending fault planes.

The value of the hydraulic gradient calculated at the Tichoukt ridge is 15% and 24% to the east of the basin (catchment area) (Fig. 7). These two values indicate a relatively rapid flow. On the other hand, at Ait Chaib, the hydraulic gradient does not exceed 6% which reflects a very slow flow (Fig. 7). It may be due to the presence of clay or sand formations that fill the interstices and pores of the reservoir rock.

4.3.1. Behavior of the water table in the liassic aquifer

The analysis of the piezometric map of the Skoura basin shows that the isopiezes present a concentric and tight shape; which confirms a fast and converging water flow towards the Oued Mdaz valley (Fig. 7). The main flow is generally from the SE to the NW. The important thickness of the Liassic formations which form the water reservoir, ensures on one hand the sustainability of the Oued Mdaz and on the other hand the supply to the Skoura village in drinking water. This Liassic groundwater emerges at the surface giving numerous water springs, among the most important is the Tadout spring.

The recharge of this water table is normally provided by direct infiltration of rainwater and also from snowmelt water. By its position and altitude, the Jbel Tichoukt ramp is considered as one of the most important water recharge areas in the Middle Atlas, because it favors both the supply of the Skoura Liassic water table and constitutes a dividing line between the groundwater flows that are made towards the North and the NE towards the Skoura subsident zone and SE flows towards the El Mers syncline.

4.3.2. Behavior of the water table in the bathonian aquifer

In the SW part of the Skoura hydrogeological basin (Fig. 7), the piezometric curves show a convexity towards the NE with a decrease of the piezometric levels, which we interpret as a flow of the water table towards the subsiding zone of the basin located towards the NE. Also, the map shows a piezometric protuberance or dome (elliptic curve with divergent current liners) with current lines diverging towards the surrounding areas. This indicates the existence of a supply zone by faults, which ensures the water providing of the Plio-Quaternary water table and then the Oued Mdaz the Oued Mdaz. We conclude that the water table contained in the Bathonian sandstones in southwestern part of the basin flows in all directions (S–N, SW-NE and W-E). Indeed, at the contact of the structural line of Amane Ilila, the flow diverges towards Oued Mdaz following the N120 fault plane. Consequently, the W-E direction flow towards the Oued Mdaz valley favors the emergence of numerous water springs such as the Tanhrourte spring and the Tannoute spring. However, to the NE of the basin, the isopieze curves are parallel to the Taghout Ouzemour fault; this shows a W-E flow direction (Fig. 7). This flow converges towards the Oued Mdaz following the plane of this fault. The dip of the Bathonian aquifers towards the South, also favors the supply of the deep Liassic water table located south of the basin (Fig. 8B).

The recharge of the water table in the Bathonian aquifer is either ensured from direct infiltration of precipitation water, or from groundwater coming from the SW and NW. These come from the discharge of the Liassic aquifer of the Middle Atlas Causse along the NMAF. Noting that the recharge of the water table in the Bathonian aquifer is more important in the SW than in the NE. These infiltrations are due to the conductive combination and the connection between the Bathonian and Liassic aquifer systems. The propagation of the water table flow directly converges towards the Oued Mdaz valley.

4.3.3. Behavior of the water table in the Ajdir Ahbari Vallesian aquifer

The lack of water points capturing the water table in Ajdir Ahbari Vallesian aquifer, did not allow to complete the establishment of the piezometric map. Based on the piezometric map (Fig. 7), we observe the same isopieze pattern as that of the Bathonian aquifer. The water table flow converges towards the plane of the N130 Taghout Ouzemour fault supplying the Oued Mdaz. This fault played a major role in the formation of the Vallesian and Miocene sedimentary basins, as well as in structuring the aquifer geometry (El Fartati et al., 2019). The water flows in this aquifer are controlled by the dip of the limestone layers towards the SW and SSW, converging the waters towards the collapsed area of the Skoura basin. The combination of these two tectonic-lithostratigraphic factors contributes to a general water flow towards the Oued Mdaz valley. However, a part of the water flowing towards the SW, favors the recharge of the deep Vallesian water table (Fig. 8B). The water table contained in this aquifer is not exposed on the surface because of the limited extension of the Vallesian limestone and the dip of this layer which is buried under the Miocene deposits. It is directly supplied by infiltration of rainwater and by intercommunication between the different aquifers.

4.3.4. Behavior of the water table in the Plio-Quaternary aquifer

The analysis of the piezometric map of the Skoura basin allowed to conclude that the piezometric curves are relatively parallel to the major tectonic faults (Fig. 7). Thus, the high spacing of these curves reflects very low flows from NW to SE and also from W to E. These flows converge towards the Oued Mdaz valley where they emerge at the surface, giving numerous water springs or resurgences. These appear through the crossing of some faults with various directions; for example, the N170 Mdaz fault and the N160 Ait Chaib fault. These faults respectively contribute to the emergence of the Sidi Yahia spring and the Tit N'Tazart spring (Fig. 8A).

The recharge of this Plio-Quaternary water table is either directly from the infiltration of rainwater and snowmelt, or vertically and laterally from the Liassic water table of the Tazouta and Skoura basins. Lateral supplies occur along N80 to N130 normal fault planes. These faults are responsible for the transport and draining of the dolomitic reservoir of the Tazouta Liassic water table towards the Skoura Plio-Quaternary aquifer, also manifested by numerous resurgences.

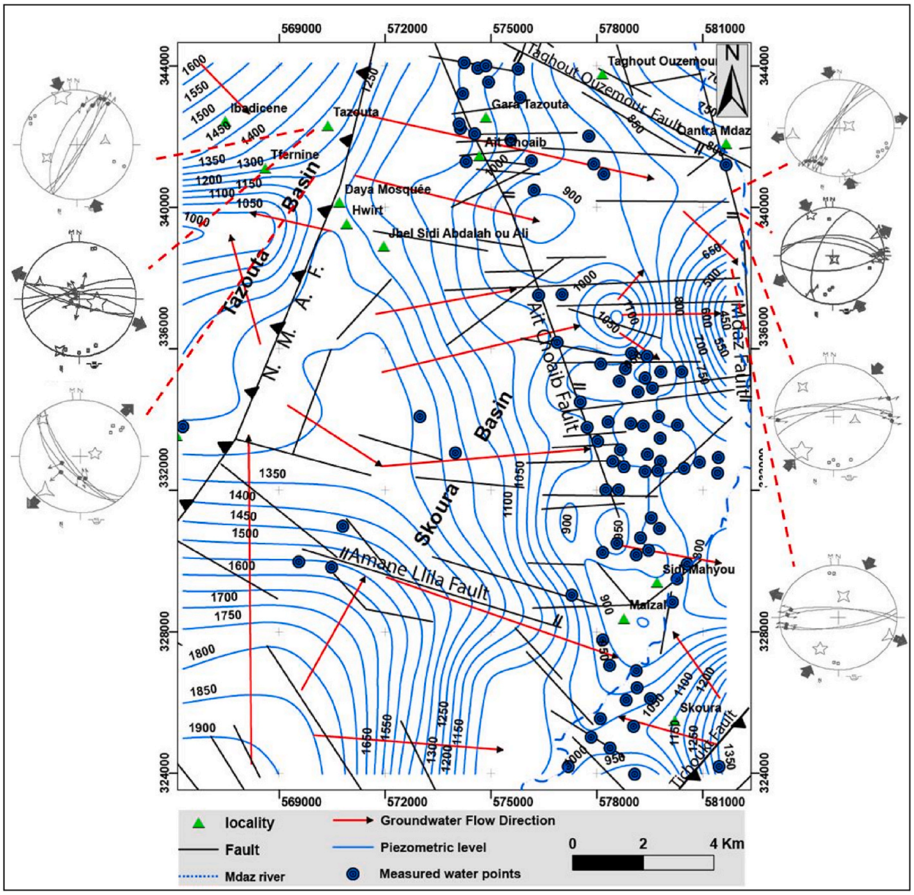

Fig. 9. Piezometric map of Skoura basin (June, July and August 2017) superimposed to fracturing map and associated Neogene and Quaternary tectonic episodes (paleostress axes) affecting the study area.

5. Discussion and synthesis

5.1. Influence of the brittle tectonics on the groundwater circulation in the Skoura hydrogeological basin

The Skoura hydrogeological basin corresponds to a subsiding area since the Miocene, where the sea has transgressed from the NW to the SE along a NW-SE trending gulf. This basin has four aquifer layers that can contain water table and confined groundwaters. These aquifers are represented by Liassic carbonate formations, Bathonian sandstones, Vallesian lacustrine limestones and the Plio-Quaternary fluvio-lacustrine deposits. The water table where we carried out our piezometric measurements and where springs and wells emerge is directly supplied by rainfall and indirectly through faults. It is characterized by multidirectional flows controlled by unclogged fractures and faults (Fig. 9).

The cartographic studies we have carried out enable highlighting three major fault systems responsible for the genesis and evolution of the Skoura hydrogeological basin. These faults directly influence the groundwater and surface water flows. They strike in the NE-SW, NW-SE, and N–S directions. Their polyphase movements favor the flow of groundwater and surface water from the raised blocks to the collapsed blocks. They thus ensure a centripetal flow towards the basin center.

In the entire Skoura basin, the piezometric curves are relatively parallel to the main structural lines: the NMAF, the Amane Ililla Fault, the Tichoukt Fault, the Ait Chaib Fault, the Taghout Ouzemour Fault and the Oued Mdaz Fault (Fig. 9). Groundwater flows are generally perpendicular to the plane of these faults and also along them. The general water table is done through the tectonic compartmentalization in stepped blocks. This compartmentalization is only the result of a succession of Neogene and Quaternary extensional and compressional tectonic episodes. These episodes gave rise to N120 to N140, N70 to N90, N30 to N45 and N160 to N10 neoformed faults, as well as the reactivation of inherited faults. The superposition in time of these faults contributed, on one hand to the subsidence of the Skoura basin by favoring the emplacement of fluvio-lacustrine deposits, and on the other hand the geometric shape of water reservoirs. Indeed, the cumulative normal movements of all these faults towards the basin center; such as Taghout Ouzemour fault, Oued Mdaz fault, Ait Chaib fault and Aman Ilila fault; favor water flow towards the Oued Mdaz valley (Fig. 8A).

In the upstream part of the Skoura hydrogeological basin (Fig. 9), the water table flow is multidirectional. Thus, in the Jbel Tichoukt foothills, the groundwater flow is from SE to NW, perpendicular to the thrust Tichoukt Fault. This flow is driven by N130 and N160 trending normal fault planes. On the other hand, to the SW of the study area, it is also oriented towards the basin center, but in this case from NW to SE, following the Amane Ilila fault plane. In the SW part of the piezometric map, there is another type of flow which is from South to North and from SW to NE, perpendicular to the N130 normal fault.

Towards the center of the Skoura basin (Fig. 9), there is a radical change in the water table flow direction which is now towards the E and the ENE following the Oued Mdaz valley. This change is mainly related to tectonic compartmentalization into stepped blocks related to the normal movements of Middle-Late Quaternary submeridian faults. The shape of the isopiezes is consistent with the faulted basin structures; especially, the Aït Chaib normal fault, whose vertical slip towards the center of the basin exceeds 100 m (Fig. 8A). Along the passage zone of this fault, water flow occurs perpendicular to the fault plane, in association with the Upper Miocene N130 synsedimentary normal faults (Fig. 10A). The intersection of the N170 and N130 fault systems causes the drainage and resurgence of the free water table located in the Liassic

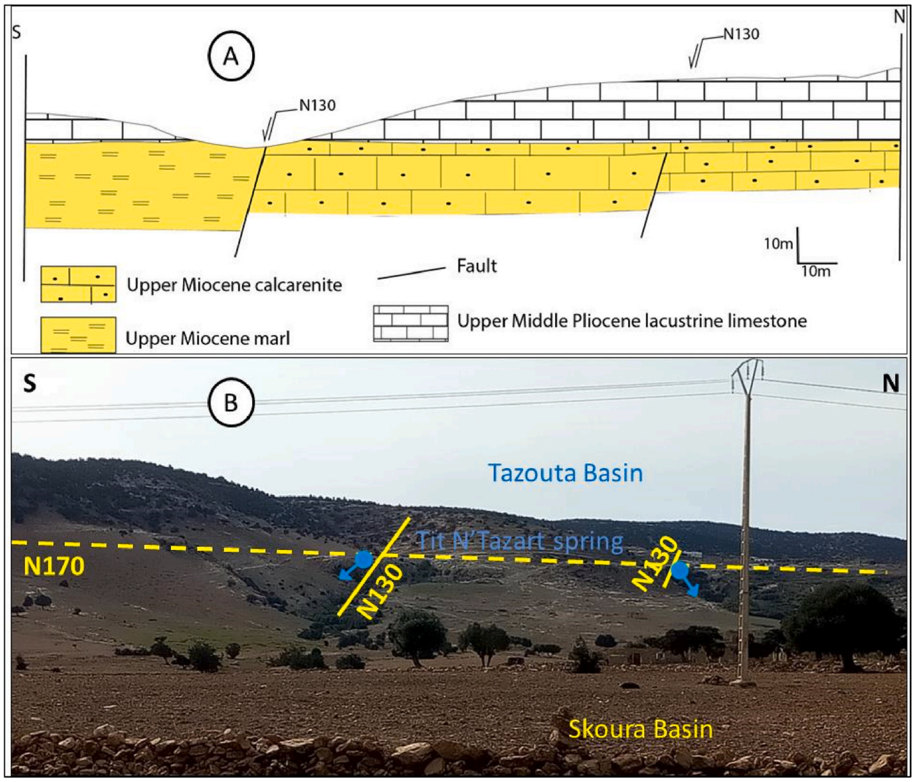

Fig. 10. Structural cross-section and field photo showing the Upper Miocene NW-SE synsedimentary faults which guide the groundwater flow direction from the Tazouta hydrogeological basin to the Skoura basin.

aquifer (Fig. 10B). These resurgences occur along the N120 to N140 fault planes, after a circulation of water through the Lower Liassic, Vallesian, Upper Miocene and Plio-Quaternary layers. We note several such springs such as the Tit N'Tazart, Sidi Yahia and Tiflwin springs. Through these transverse faults, the Tazouta Liassic water table supplies the Skoura superficial water table and the Oued Mdaz drainage (Fig. 8A and 10A and B).

Based on our field work, the majority of boreholes and wells capturing the Skoura water table coincide with fault zones, especially N80 and N160 trending faults. A similar study at the eastern edge of the Okanagan Basin in British Columbia and Canada confirms that wells capturing the Plio-Quaternary aquifer are coincident with the passage of NW-SE to N–S trending faults. These results were confirmed by geophysical and isotopic studies (Allen and Nott, 2021). Moreover, the studies carried out in eastern Morocco by Jilali and Zarhloule (2015) confirm that fractured Jurassic aquifers provide storage and orientation of groundwater flows. In addition to our study carried out in the Tazouta hydrogeological basin (EL Fartati et al., 2021) part of the Middle Atlas Causse, other studies were carried out in the Causse of Sefrou and Almis Guigou-Timahdit area by El Fellah Idrissi (2010), Amrani (2016) and Amrani et al. (2022) and provided similar results highlighting the hydrogeological importance of fractured aquifers.

In the north-east of the Causse of Martel (South of Brive, France), Marchet (1991) shows that there is a significant relationship between structural lineaments and the orientation of karstic drainage networks. In the Parisian basin, Rodet (1991) also mentioned the influence of fault lines which block the flow channeling along their axis. The development of the fracture network is not always solely responsible for the groundwater circulation, but also the water-rock interaction allows the extension of the latter by the effect of dissolution, and also has an important role in the process of water flow (Astruc and Simon-Coinçon, 1992). Consequently, there is a direct relationship between fracturing and groundwater flow as well as the development of karst systems (Renault et al., 1992).

5.2. Genesis of the hydrographic network of the Oued Mdaz and its influence on the surface water flows

The genesis of hydrographic valleys is essentially caused by the combination of two main geological factors; the watershed lithological nature and the fracturing density. Fractured ground is susceptible to rapid weathering and erosion (Whipple et al., 2013; Scott and Wohl, 2018). Because of the fissures, the surface water easily flows out causing their widening and extension by dissolution. Crushed fault zones can guide and reorient the flow direction of a stream. Thus, the contribution of fracturing in the genesis and development of a watercourse is concretely expressed by drainage anomalies.

The Oued Mdaz valley originates from the Isshoul dam in the SW, in parallel with the Tichoukt ridge (Fig. 2). At this point, the valley spreads over a distance of 14 km along the axis of the Skoura synform graben, whose flow direction is oriented NE-SW (Fig. 11). It perpendicularly cross-cuts the NW-SE synsedimentary Miocene faults planes which contributed to the subsidence of the basin. The main valley of Oued Mdaz has played and still plays a dual role corresponding to the erosion and transport of sediments downstream following the weakness zones due to multiple fault movements. In Sidi Mahyou village, the valley is reoriented at the contact of a N15 fault plane, then returns to its original direction which is sub-parallel to the Tichoukt ridge (Fig. 11). After approximately 6 km near Maizal area, the Oued Mdaz valley changes direction at the contact of a submeridian fault and then takes an almost N–S direction (Fig. 11). The direction change point corresponds to the tectonic node between the Oued Mdaz submeridian fault and N40 fault. Throughout the main valley of Oued Mdaz, which follows a network of submeridian faults, cross-cutting with Neogene faults appear. The incision of the valley is accentuated by the incompetence of predominantly Dogger and Neogene marl deposits. The fracturing map (Fig. 11) of the Skoura basin shows that most of the faults are not randomly distributed, but are related to well-defined tectonic episodes. These faults are organized in three major systems that we have described before. Due to

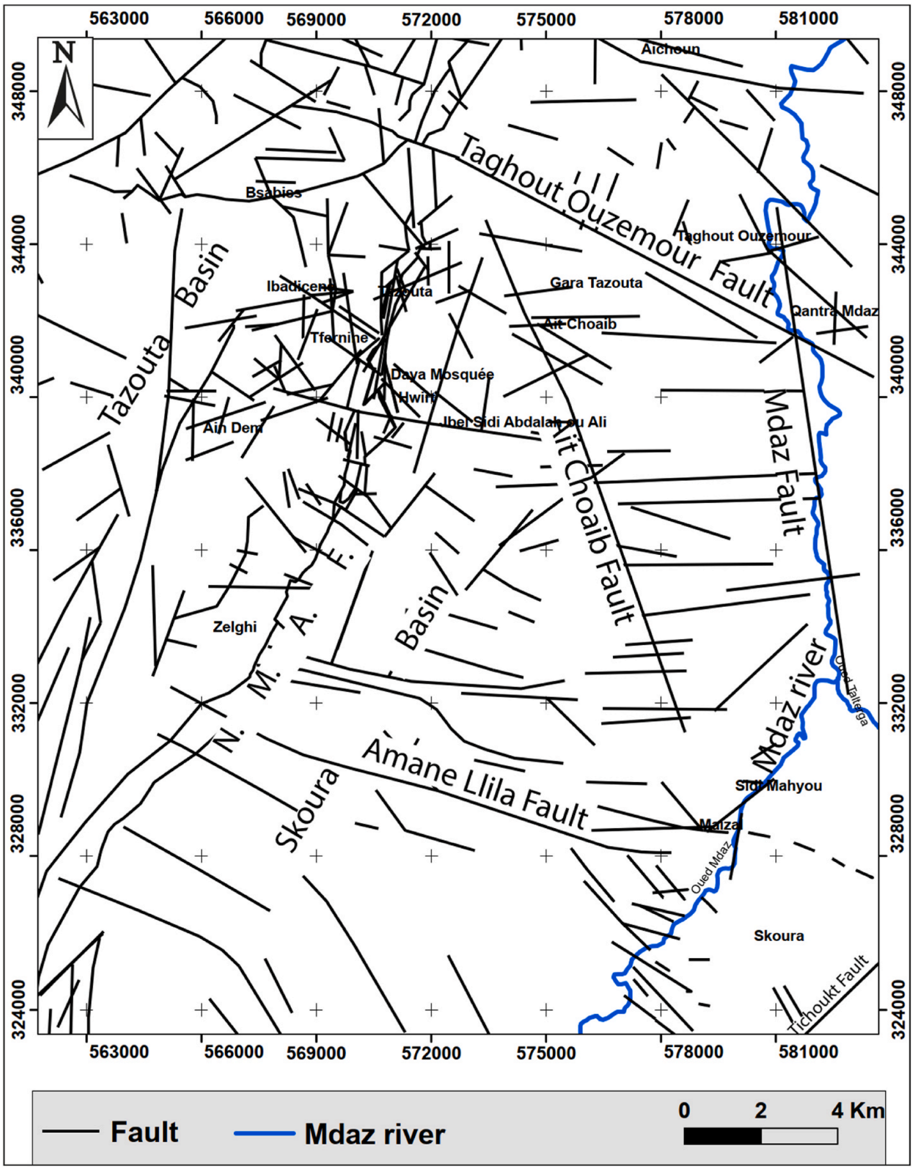

Fig. 11. Relationship between fracturing and the geometry of the hydrographic line of the Oued Mdaz valley (Skoura basin).

the large variations of fracture directions and density, the structuring of the Oued Mdaz valley is complex and linked to two main fault systems: the Upper Miocene N130 synsedimentary normal faults and the Middle-Late Quaternary submeridian normal faults.

Similar studies have been carried out in the Middle Atlas, the Prerif, the High Plateaux and the South Rifian corridor by Dridri and Fedan (2001), Pastor et al. (2015) and Amine et al. (2020), mainly based on morphometric analysis and notches network analysis applied to the Sebou and Inaouène hydrographic network; allowed the identification of the direction of the preferential axes to the surface water flows. In several studies, the data statistical processing shows the predominance of the N–S and NE-SW directions compared to other directions (El Fellah, 1983; El Fjiji et al., 1985; Charrière, 1990; Deffontaines et al., 1992).

Overall, the obtained results in this work presents a qualitative study examining how the structural framework of the Skoura hydrogeological basin controls its hydrological-hydrogeological system. This was combining piezometric measurements, geological mapping and structural analysis. We therefore conclude that the groundwater flow is multidirectional, driven by SW- and W-trending faults. Whereas surface water is channeled through N–S structures and other major faults. However, we cannot deny that some uncontrollable factors could introduce some uncertainties regarding the interpretations derived from the established piezometric map. These factors mainly involve:

(i) the construction of the piezometric map is mainly based on the water points in the eastern part of the basin where boreholes and wells are concentrated. Unfortunately, in the western part, water points capturing the water table are very rare or totally missing;
(ii) the measurement period which extends over the three months of the summer period (June Jully and August). During this period, a decrease in water table is probably expected going from June to August. Moreover, during other periods of the year, the piezometric level is also strongly influenced by winter fluctuations due to snow and rainfall recharge. The main reason why we chose the summer period was the ease of access to water points, which was not possible during the winter. Moreover, we think that the piezometry is relatively static during the summer period compared to the winter fluctuations and thanks to the non-excessive exploitation of the water table in the Skoura area.

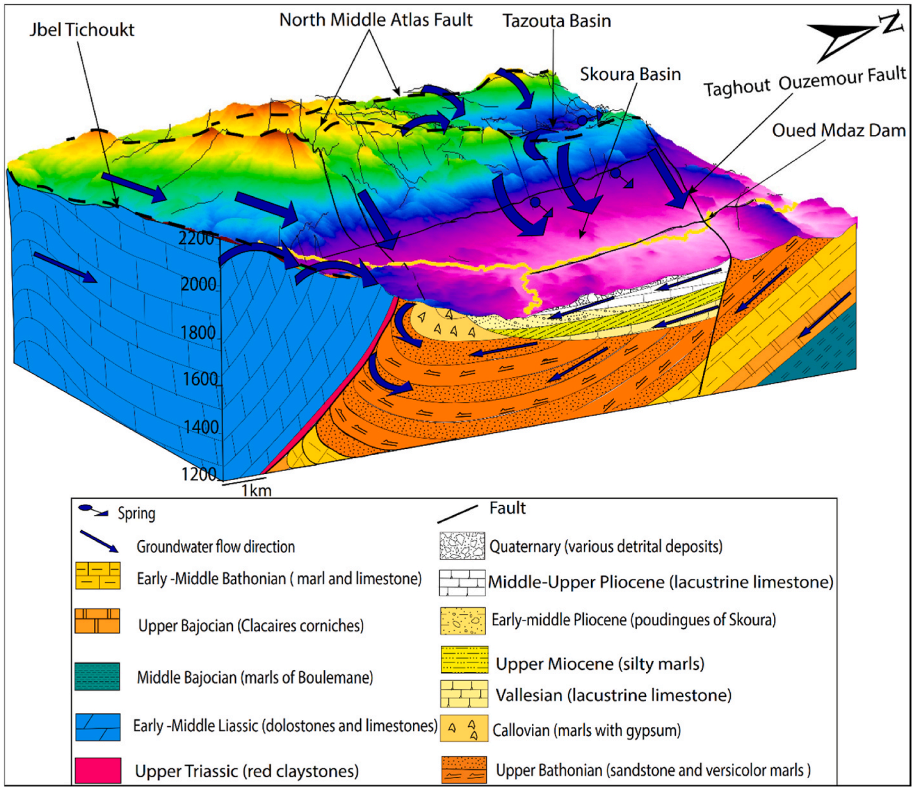

Fig. 12. Block diagram illustrating the groundwater and surface water flow in the Skoura hydrogeological basin.

6. Conclusion

The genesis and evolution of the Skoura hydrogeological basin is linked to several Neogene and Quaternary extensional and compressional tectonic episodes. These tectonic phases determining different fracture and fault systems which play an important role in the spatial distribution of groundwater and surface water flows. The circulations revealed by the water table piezometric map are generally compatible with the directions of the submeridian faults (Fig. 12).

In the Skoura hydrogeological basin, the direction of groundwater flow is multidirectional (Fig. 12). In the Skoura watershed, at Jbel Tichoukt area, water circulates from the Liassic aquifer to the Plio-Quaternary aquifer. The groundwater converges towards the center of the basin following the of the N130 fault planes. Moreover, the confined groundwater in the Bathonian layers located to the SW and W, flows along the planes of the same N130 fault system, but in the NW-SE direction towards the Oued Mdaz, crossing the Plio-Quaternary aquifer.

In the median part of the basin, the preferential axis of the surface water flow is parallel to the planes of the Upper Miocene N130 synsedimentary faults. This reflects a general flow towards the Oued Mdaz. These tectonic structures constitute a network of water transfer between the Middle Atlas Causse and the Folded Middle Atlas. Concerning surface water flows, they are guided by the submeridian and transverse faults, as well as by the two major faults (NMAF and the Tichoukt Fault) which have played a major role in the genesis and evolution of the Oued Mdaz valley. In addition to the importance of these tectonic structures, the nature of the geological terrain and the type of surface flow characterizing the study area have also contributed to the genesis and development of the perennial valley of the Oued Mdaz.

With the decrease of the groundwater piezometric level in Skoura, the results of our study clearly show that the direction of groundwater flow is compatible with the transverse and submeridian tectonic structures. They are qualified as the main potential water deposit areas with the current drought in Morocco.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

We are grateful to the Editor-in-Chief Dr. Damien Delvaux who welcomed our manuscript for publication. We are greatly acknowledged to Dr. Mohamed Gouiza (University of California, Davis, USA) and an anonymous reviewer for their helpful remarks and constructive corrections which contributed to improve the original version of this paper.

References

Allen, D.M., Nott, A.H., 2021. How important are those fracture zones? Scale dependent characteristics revealed through field studies and an integrated hydrological model of a mountain headwater catchment. Front. Water 3, 767399. https://doi.org/10.3389/frwa.2021.767399.

Amine, A., El Ouardi, H., Zebari, M., El Makrini, H., 2020. Active tectonics in the Moulay Idriss Massif (South Rifian ridges, NW Morocco): new insights from geomorphic indices and drainage pattern analysis. J. Afr. Earth Sci., 103833 https://doi.org/10.1016/j.jafrearsci.2020.103833.

Amrani, S., 2016. Hydrodynamisme, hydrochimie et vulnérabilité de la nappe d'eau superficielle et leur relation avec la tectonique cassante dans la zone effondrée Timahdite Almis Guigou (Moyen Atlas, Maroc). Thèse de Doctorat National, Université Sidi Mohamed Ben Abdellah, Fès, Maroc, p. 178.

Amrani, S., Hinaje, S., El Fartati, M., Gharmane, Y., Yaagoub, D., 2022. Assessment of groundwater quality for drinking and irrigation in the Timahdite–Almis Guigou area (Middle Atlas, Morocco). Appl. Water Sci. 12, 82. https://doi.org/10.1007/s13201-022-01609-3.

Amraoui, F., 2005. Contribution à la connaissance des aquifères karstiques : cas du Lias de la plaine du Sais et du Causse Moyen Atlasique tabulaire (Maroc). Thèse de Doctorat d'Etat ès-Sciences, Université Hassan II, Casablanca, Maroc, p. 237.

Astruc, J.G., Simon-Coinçon, R., 1992. Enregistrement de l'évolution climatique et tectonique par les paleokarsts (exemple du Quercy et de ses marges). In: Karst et évolutions climatiques. Presse univ., Bordeaux, pp. 497–508.

Bense, V.F., Gleeson, T., Loveless, S.E., Bour, O., Scibek, J., 2013. Fault zone hydrogeology. Earth Sci. Rev. 127, 171–192. https://doi.org/10.1016/j.earscirev.2013.09.008.

Bense, V.F., Person, M.A., 2006. Faults as conduit- barriers systems to fluid flow in siliciclastic sedimentary aquifers. Water Resour. Res. 42 (W0542) https://doi.org/10.1029/2005WR004480.

Bense, V.F., Person, M.A., Chaudhary, K., You, Y., Cremer, N., Simon, S., 2008. Thermal anomalies as indicator of preferential flow along faults in an unconsolidated sedimentary aquifer system. Geophys. Res. Lett. 35 https://doi.org/10.1029/2008GL036017.

Burbey, T.J., 2008. The influence of geologic structures on deformation due to groundwater withdrawal. Ground Water 46, 202–211. https://doi.org/10.1111/j.1745-6584.2007.00395.x.

Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. Geology 24, 1025–1028. https://doi.org/10.1130/0091-7613(1996)024<1025:FZAAPS>2.3.CO, 2.

Castany, G., 1982. Principes et méthodes de l'hydrogéologie. Bordas, Paris, p. 233.

Castany, G., 1989. Prospection et exploitation des eaux souterraines. édition Dunod, Paris, p. 711.

Chamayou, J., Combe, M., Gentier, B., Leclerc, C., 1975. Le bassin de Meknès-Fès et le couloir de Fès-Taza, (in ressources en eau du Maroc, plaines et bassins du Maroc atlantique). Notes et Mém. Serv. Géol. Maroc. 231, 41–71.

Chapond, G., 1962. La nappe captive profonde du bassin de Fès-Meknès. Inéd. arch. MTPC/DH/DRE, Rapp, p. 16.

Charrière, A., 1989. Carte géologique au 1/100.000, feuille de Sefrou. Notes et Mém. Serv . Géol. Maroc. 354.

Charrière, A., 1990. Héritage hercynien et évolution géodynamique alpine d'une chaîne intracontinentale : le Moyen Atlas au SE de Fès (Maroc). Thèse de Doctorat d'Etat ès-Sciences, Université Paul Sabatier, Toulouse, France, p. 589.

Charroud, M., 1990. Evolution géodynamique de la partie Sud-Ouest du Moyen Atlas durant le passage Jurassique-Crétacé. le Crétacé et le Paléogène : un exemple d'évolution intraplaque. Thèse 3ème cycle 234. Université Mohamed V, Rabat, Maroc.

Chorowicz, J., Deffontaines, B., 1993. Transfer faults and pull-apart model in the rhinegraben from analysis of multisource data. J. Geophys. Res. Solid Earth 98, 14339–14351. https://doi.org/10.1029/93JB00190.

Choubert, G., Et Faure-Muret, A., 1960-62. Evolution du domaine atlasique marocain depuis les temps paléozoïques. In: Livre Mém. P. Fallot Mém. H. Sér, pp. 447–527 soc. geol. Fr. t1.

Colo, G., 1961. Contribution à l'étude du Jurassique du Moyen Atlas septentrional. Notes et Mém. serv. Géol. Maroc. n° 139, 226.

Daguin, F., 1927. Contribution à l'étude géologique de la région prérifaine (Maroc Occidental). Notes et Mém. Serv. Géol. Maroc. n° 1, 334.

Deffontaines, B., Chotin, P., Ait Brahim, L., Rozanov, M., 1992. Investigation of active faults in Morocco using morphometric methods and drainage pattern analysis. Geol. Rundsch. 81, 199–210. https://doi.org/10.1007/BF01764549.

Delaney, P.T., Pollard, D.D., Ziony, J.I., Mckee, E.H., 1986. Field relations between dikes and joints: emplacement processes and paleostress analysis. J. Geophys. Res. Solid Earth 91, 4920–4938. https://doi.org/10.1029/JB091iB05p04920.

Dridri, A., Fedan, B., 2001. Rôle du contrôle structural dans la mise en place du réseau hydrographique de Sebou et Inaouène entre Fès et Oued Amlil (Maroc). Bulletin de l'Institut scientifique Rabat, section Science de la Terre 23, 67–77.

Du Dresnay, R., 1979. Sédiments Jurassiques du domaine des chaînes atlasiques du Maroc. Symposium sédim, 1. Jurassique W européen. A. S. F. Publ. sp., pp. 345–365

Duée, G., Hervouet, Y., Laville, E., Lucas, P., Robillard, D., 1977. L'accident nord moyen-atlasique dans la région de Boulemane (Maroc) : une zone de coulissement synsédimentaire. Ann. Soc. Géol. Nord, t XCVIII, 145–162.

El Azzab, D., El Wartiti, 1998. Paléomagnétisme des laves plio-quaternaires du Moyen Atlas: rotations récentes. C. R. Ac. Sci. Paris. 327, 509–512. https://doi.org/10.1016/S1251-8050(99)80031-7.

El Azzouzi, M.H., Maury, R.C., Bellon, H., Youbi, N., Cotten, J., Kharbouch, F., 2010. Petrology and K-Ar chronology of the neogene-Quaternary Middle Atlas basaltic province, Morocco. Bull. Soc. Geol. Fr. 181 (3), 243–257. https://doi.org/10.2113/gssgfbull.181.3.243.

El Fartati, M., 2021. Influence de la tectonique cassante méso-cénozoïque sur les Caractéristiques structuro-hydrogéologiques et géodynamiques des bassins de Tazouta et de Skoura (Moyen Atlas, Maroc). Thèse de Doctorat National, Université Sidi Mohamed Ben Abdellah, Fès, Maroc, p. 232.

El Fartati, M., Hinaje, S., Amrani, S., Gharmane, Y., Yaagoub, D., 2019. Le Bassin de Skoura-Tazouta (Moyen Atlas, Maroc): Un Exemple de Paléo-Barrage D'âge Néogène-Quaternaire d'origine Tectonique et à Remplissage Fluvio-Lacustre et Travertineux. Eur. Sci. J. 15, 339–361.

El Fartati, M., Hinaje, S., Chaouni, A., Yaagoub, D., Amrani, S., Gharmane, Y., 2021. Hydrogeology of the Tazouta basin and its relationship with the Neogene Quaternary brittle tectonics (folded Middle Atlas, Morocco). Arabian J. Geosci. 14, 2060. https://doi.org/10.1007/s12517-021-08453-w.

El Fellah Idrissi, B., 2010. Influence de la tectonique cassante sur les caractéristiques hydrogéologiques des aquifères triasico-liasiques et apport de l'hydrochimie à l'étude des eaux souterraines dans le Moyen Atlas septentrional (causse de Sefrou et de l'Anoucer). Thèse de Doctorat National, Université Sidi Mohamed Ben Abdellah, Fès, Maroc, p. 212.

El Fellah, B., 1983. Contribution à l'étude morphologique du couloir de Taza. Bulletin de l'Institut scientifique Rabat, section Science de la Terre 7, 51–63.

El Fjiji, H., Chafiki, D., Boukdiri, A., 1985. Prospection par sondages électrique des formations liasiques: Couloir Fès Taza, Bir Tam Tam - Oued Amlil. Rapport inédit, Direction de la recherche et de la planification de l'eau (Rabat).

Ellero, A., Malusà, M.G., Ottria, G., Ouanaimi, H., Froitzheim, N., 2020. Transpressional structuring of the high Atlas belt, Morocco. J. Struct. Geol. 135 https://doi.org/10.1016/j.jsg.2020.104021.

Fedan, B., 1988. Evolution géodynamique d'un bassin intraplaque sur décrochements : (Moyen-Atlas, Maroc) durant le Méso-Cénozoïque. Thèse de Doctorat d'Etat ès-Sciences, Université Mohammed V, Rabat, Maroc, p. 338.

Fekkak, A., Ouanaimi, H., Michard, A., Soulaimani, A., Ettachfini, E.M., Berrada, I., El Arabi, H., Lagnaoui, A., Saddiqi, O., 2018. Thick-skinned tectonics in a Late Cretaceous Neogene intracontinental belt (High Atlas Mountains, Morocco): the flat-ramp fault control on basement shortening and cover folding. J. Afr. Earth Sci. 140, 169–188. https://doi.org/10.1016/j.jafrearsci.2018.01.008.

Folch, A., Mas-Pla, J., 2008. Hydrogeological interactions between fault zones and alluvial aquifers in regional flows systems. Hydrol. Process. 22, 3476–3487. https://doi.org/10.1002/hyp.6956.

Frizon de Lamotte, D., Zizi, M., Missenard, Y., Hafid, M., El Azzouzi, M., Charrière, A., Maury, R.C., Taki, Z., Benammi, M., Michard, A., 2008. The Atlas system. In: Michard, A., Saddiqi, O., Chalouan, A., Frizon de Lamotte, D. (Eds.), Continental Evolution: the Geology of Morocco. Springer-Verlag, Heidelberg, pp. 133–202.

Gharmane, Y., Hinaje, S., Amrani, S., Elkourchia, A.F., EL Fartati, M., Yaagoub, D., 2021. Analysis of fracturing and installation of hydrothermal vein mineralization in the Mesozoic cover of the Tazekka Paleozoic inlier, Morocco. Arabian J. Geosci. 14 https://doi.org/10.1007/s12517-021-07692-1.

Gouiza, M., Bertotti, G., Hafid, M., Cloetingh, S., 2010. Kinematic and thermal evolution of the Moroccan rifted continental margin: Doukkala-High Atlas transect. Tectonics 29. https://doi.org/10.1029/2009TC002464.

Harmand, C., Cantagrel, J.M., 1984. Le volcanisme alcalin tertiaire et quaternaire du Moyen-Atlas (Maroc) : chronologie K/Ar et cadre géodynamique. J. Afr. Earth Sci. 2, 51–55. https://doi.org/10.1016/0899-5362(84)90019-8.

Hinaje, S., 2004. Tectonique cassante et paléochamps de contraintes dans le moyen atlas et le haut atlas central (Midelt-Errachidia) depuis le trias jusqu'à l'actuel. Thèse de doctorat d'Etat ès-Sciences, Université Mohamed V, Rabat, Maroc, p. 393.

Hinaje, S., El Fartati, M., Yaagoub, D., Amrani, S., Gharmane, Y., El Fellah Idrissi, B., 2019. Paleocontraintes et Contexte Tectonique de Mise en Place du Volcanisme Alcalin Neogene et Quaternaire du Moyen Atlas (Maroc). Eur. Sci. J. 15, 448–466.

Hollard, H., Coubert, G., Bronner, G., Marchand, J., Sougy, J., 1985. Carte géologique du Maroc au 1/1.000.000. Notes et Mém. Serv. Géol. Maroc. n° 260.

Ibouh, H., 2004. Du rift avorté au bassin sur décrochement, contrôles tectonique et sédimentaire pendant le Jurassique (Haut-Atlas centro-oriental, Maroc). Thèse de doctorat d'Etat ès-Sciences, Université Cadi Ayyad, Marrakech, Maroc, p. 224.

Jacobshagen, V., Brede, R., Hamptman, M., Heinitz, W., et Zylka, R., 1988. Structure and post paleozoïc evolution of the central High-Atlas. In: « Lectures Notes in Earth Sciences », , 26815, p. 245. « the Atlas System of Morocco Studies on its Geodynamic Evolution », Jacobshagen.

Jaeger, J.J., Michaux, J., David, B., 1973. Biochronologie du Miocène moyen et supérieur continental du Maghreb. C. R. Ac. Sci. Paris. t. 277, 2477–2480.

Jilali, A., Zarhloule, Y., 2015. Structural control of the hydrogeology in Figuig Oasis in the eastern high Atlas of Morocco. Proc. Geologists' Assoc. 126, 232–243. https://doi.org/10.1016/j.pgeola.2014.12.003.

Lanari, R., Faccenna, C., Fellin, M.G., Abderrahim, E., Nahid, A., Medina, F., Youbi, N., 2020. Tectonic evolution of the Western High Atlas of Morocco: oblique convergence, reactivation and transpression. Tectonics 39. https://doi.org/10.1029/2019TC005563.

Laville, E., 1985. Evolution sédimentaire, tectonique et magmatique du bassin Jurassique du Haut-Atlas, Maroc : Modèle en relais multiples de décrochements. Thèse de doctorat d'Etat ès-Sciences, Université de Longuedoc-Roussillon, Montpellier, France, p. 168.

Levens, R.L., Williams, R.E., Ralston, D.R., 1994. Hydrogeologic role of geologic structures. Part 1: paradigm. J. Hydrol. 156, 227–243. https://doi.org/10.1016/0022-1694(94)90079-5.

Marchet, P., 1991. Approche de la structure et de l'évolution des systèmes aquifères karstiques par l'analyse de leur fonctionnement. Application au NW du Causse de Martel (Quercy, France). Thèse de Doctorat d'Etat ès-Sciences, Université Paul Sabatier, Toulouse, France, p. 297.

Martin, J., 1981. Le moyen Atlas central, étude géomorphologique. Notes et Mém. Serv. Géol. Maroc. n° 258, 445.

Mayer, A., May, W., Lukkarila, C., Diehl, J., 2007. Estimation of fault-zone conductance by calibration of a regional groundwater flow model: Desert Hot Springs, California. Hydrogeol. J. 15, 1093–1106. https://doi.org/10.1007/s10040-007-0158-0.

Michard, A., 1976. Elément de géologie marocaine. Notes et Mém. Serv. Géol. Maroc. 252, 408.

Moukadiri, A., 1983. Les enclaves ultrabasiques associées aux basaltes alcalins dans le district volcanique d'Azrou-Timahdit (Moyen-Atlas, Maroc). Thèse 3ème cycle, Université Clermont Auvergne. Clermont-Ferrand, France, p. 150.

Moussaid, B., El-Ouardi, H., Casas-Sainz, A.M., Pocoví, A., Román-Berdiel, T., Oliva-Urcia, B., Ruiz-Martínez, V.C., Villalaín, J.J., 2023. Tectonic Evolution of the Moroccan High Atlas: A Paleomagnetic Perspective. Springer Geology. Springer, Cham. https://doi.org/10.1007/978-3-031-16693-8_1.

Msaddek, M., Kimbowa, G., El Garouani, A., 2020. Hydrological modeling of Upper Oum Er-Rabia basin (Morocco), comparative study of the event-based and Continuous-process HEC-HMS model methods. CWEEE 9, 159–184. https://doi.org/10.4236/cweee.2020.94011.

Ohlmacher, G.C., 1999. Structural domains and their potential impact on recharge to intermontane-basin aquifers. Environ. Eng. Geosci. 1, 61–71. https://doi.org/10.2113/gseegeosci.V.1.61.

Pastor, A., Babault, J., Owen, L.A., Teixell, A., Arboleya, M.L., 2015. Extracting dynamic topography from river profiles and cosmogenic nuclide geochronology in the Middle Atlas and the High Plateaus of Morocco. Tectonophysics 663, 95–109. https://doi.org/10.1016/j.tecto.2015.06.007.

Qadem, Z., Khalid, O., Qadem, A., Lasri, M., 2022. L'impact de La Sècheresse sur les Réservoirs Souterrains dans le plateau de Saïs, Maroc. Geomaghreb 16, 22–33.

Renault, P., Simon-Coincon, R., Astruc, J.G., 1992. Problèmes des causses du Quercyin : Karst et évolutions climatiques. Presse umv, Bordeaux, pp. 469–496.

Rodet, J., 1991. La craie et ses karsts. Thèse de doctorat d'Etat ès-Sciences, Université Aix-Marseille II, Marseille, France, p. 560.

Sabaoui, A., 1998. Rôles des inversions dans l'évolution méso-cénozoïque du Moyen-Atlas Septentrional (Maroc). L'exemple de la transversale El Menzel – Ribat Al Khayr – Bou Iblane 410. Thèse de doctorat d'Etat ès-Sciences, Université Mohamed V, Rabat, Maroc.

Scott, D.N., Wohl, E.E., 2018. Bedrock fracture influences on geomorphic process and form across process domains and Scales. Earth Surf. Process. Landforms. https://doi.org/10.1002/esp.4473.

Termier, H., 1936. Etude géologique sur le Maroc central et le Moyen Atlas septentrional. Notes et Mém. Serv. Géol. Maroc. n° 33, 1566.

Voeckler, H., Allen, D.M., 2012. Estimating regional-scale fractured bedrock hydraulic conductivity using discrete fracture network (DFN) modeling. Hydrogeol. J. 20 (6), 1081–1100. https://doi.org/10.1007/s10040-012-0858-y.

Welch, L.A., Allen, D.M., 2014. Hydraulic conductivity characteristics in mountains and implications for conceptualizing bedrock groundwater flow. Hydrogeol. J. 22 (5), 1003–1026. https://doi.org/10.1007/s10040-014-1121-5.

Whipple, K.X., DiBiase, R.A., Crosby, B.T., 2013. 9.28 bedrock Rivers. Treatise on Geomorphology 550–573. https://doi.org/10.1016/B978-0-12-374739-6.00254-2.

Yaagoub, D., Hinaje, S., El Fartati, M., Atif, Y., Elabouyi, M., Gharmane, Y., Amrani, S., 2023. Implication of the Triassic-Liassic rifting and Pangea breakup on the geodynamic, tectonic and mineralogical evolution of the Zeida Pb-Zn, Ba deposit (Upper Moulouya, Morocco). Rend. Fis. Acc. Lincei. https://doi.org/10.1007/s12210-023-01151-7.

Yaagoub, D., Hinaje, S., El Fartati, M., Gharmane, Y., 2021b. Analysis of tectonic fracturing in the Mibladen ore deposit (Upper Moulouya, Morocco) and its impact on the Pb–Ba mineralization emplacement. Rend. Fis. Acc. Lincei. 32, 325–342. https://doi.org/10.1007/s12210-021-00995-1.

Yaagoub, D., Hinaje, S., El Fartati, M., Gharmane, Y., Amrani, S., 2022. Cenozoic tectono-sedimentary evolution of the Upper Moulouya continental basins (Moroccan Atlas system): insights from lithostratigraphy, structural analysis and paleostress reconstruction. J. Afr. Earth Sci. 196, 104690 https://doi.org/10.1016/j.jafrearsci.2022.104690.

Yaagoub, D., Hinaje, S., El Fartati, M., Gharmane, Y., Ouhssaine, A., 2021c. Role of Triassic tectonics in the emplacement and distribution of hydrothermal mineralizations in the Aouli mining district (Upper Moulouya, Morocco). J. Iber. Geol. 47, 577–597. https://doi.org/10.1007/s41513-021-00171-2.

Yaagoub, D., Hinaje, S., El Ouaragli, B., El Fartati, M., Gharmane, Y., Amrani, S., Ouhssaine, A., Elabouyi, M., 2021a. Reconstruction of Mesozoic paleostress associated with the tectono-sedimentary evolution of the basins bordering the Aouli inlier (Upper Moulouya, Morocco). Arabian J. Geosci. 14, 706. https://doi.org/10.1007/s12517-021-07065-8.