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Original Paper

Geophysical Contributions to Hydrogeological Study in the Chemtou–Sidi Miskine Agricultural Sector (Northwestern Tunisia)

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This study presents an example of the use of geophysics for agricultural water management. Borehole data, gravity measurements and vertical electrical soundings were used to reconstruct a precise hydrogeological scheme of the Chemtou–Sidi Meskine area (Northwest of Tunisia) in order to assist exploitation and judicious management of the underground water resources for irrigation. The Chemtou–Sidi Meskine area belongs to Mejerda basin, the most important agricultural sector in Tunisia. It is characterized by the coexistence of alluvial and basement aquifers, which are very scare in this country. The computed gravity maps emphasize an E–W lineament separating Hairech metamorphic formations and Mejerda alluvial deposits. The apparent resistivity maps confirm the presence of this lineament. The interpreted vertical electrical soundings are correlated with lithological columns to give more accurate structural patterns. The resulting geoelectrical cross sections highlight a normal fault network that collapsed metamorphic aquifers, controlled the Quaternary alluvial aquifers thickness and created closed areas with high water salinity that is unfavorable for exploitation.

INTRODUCTION

Global warming will influence agriculture by the reduction in water availability for irrigation. It will consequently pose stress on food production systems that are under pressure to satisfy the food needs of a rapidly growing world population. Tunisia will be particularly affected by climate change because it is among the 17 most hydraulically stressed countries in the world (World Bank 2014). Moreover, its economy is heavily dependent on agriculture, and this provides 11% of the GDP and 18% of the country's labor force. Agriculture is the largest user of water in Tunisia; it consumes more than 85% of available water resources.

Water management practices, however, have the potential to create resilience to climate change and to enhance water and food securities. Hydrogeological modeling is an efficient practice for water tables protection and conservation (e.g., Jaworska-

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Szule 2009; Takhur 2016), but it requires sufficient details about groundwater quantity, quality and movements. Precise hydrogeological schema cannot be elaborated from boreholes because the cost will be prohibitive. Incorporation of geophysical measurements is a relevant solution to elaborate hydrogeological schema. This is realized in many of our researches (Guellala et al. 2005, 2009a, b, 2010a, b, 2011, 2012a, b, c, 2013, 2014, 2016; Guellala 2010, 2015), which concern different sectors of Tunisia (North Africa).

This study concerns the Chemtou–Sidi Miskine region within the Mejerda basin, the most important agricultural sector of Tunisia. It is the only region in Tunisia where metamorphic aquifers are present. This is the first hydrogeological study of the whole Chemtou–Sidi Miskine aquifer system including Quaternary alluvial reservoirs and ancient metamorphic reservoirs. At the Tunisian scale, this study is primarily a geophysical application for the characterization of metamorphic aquifers. In terms of methodology, the innovation of the present study consists of the application of two geophysical methods having different investigation depth and generally used separately in hydrogeological studies, namely: vertical electrical soundings (e.g., Gasmi 2002; Zouhri et al. 2004; Asfahani 2006; Gouasmia et al. 2006; Ben Lasmar et al. 2013, 2014) and gravity survey (e.g., Khattach et al. 2004; Najine et al. 2006). The aim of the combined application of these two geophysical methods in this study is to characterize two types of aquifers (alluvial and metamorphic) in order to determine favorable areas for exploitation of groundwater for irrigation.

GEOLOGICAL AND HYDROGEOLOGICAL CONTEXTS

The Mejerda average basin (Fig. 1a) is a molassic depression limiting thrust nappes in the north (Rouvier 1977). It is filled by Quaternary alluvial deposits composed of clays, gravels and sands (Gottis and Sainfeld 1955), comprising a multilayered aquifer system (Parsons Company 1967; Andrieux and Tablot 1972; Guellala et al. 2005).

The margins of the Mejerda average basin are geological outcrops with ages ranging from Permian–Triassic to Miocene–Pliocene. Among these outcrops, the Hairech massif (Fig. 1a) consists of metamorphic formations (Alouani and Tlig 1988).

The Hairech series of sandstones and schists intercalated with metric dolomite underwent anchizonal metamorphism and are dated Triassic (Bolze 1954; Rouvier 1977; Perthuisot 1978) and Permian–Triassic (Burollet 1973; Alouani et al. 1991). An old borehole drilled at the northwestern flank of Jebel Hairech in 1954 shows that the thickness of these series is more than 900 m. The aquifer potential of the Hairech series has been confirmed by water borehole "Lihairech," which provides a significant flow rate of 50 l/s (CRDA Jendouba 2014).

The rocks overlying the Hairech series (Chemtou, Kef el Agueb, Sidi Abdallah, Sidi Assem and Koudiat Nouimia outcrops) are composed of marbles and dolomites, which were affected by metamorphism, are considered as Liassic (Jurassic) deposits (Durand Delga 1955; Gottis and Sainfeld 1955; Rouvier 1977; Alouani 1991). They are intensively fissured and karstified (Alouani and Tlig 1988; Alouani et al. 1997), and they constitute an important aquifer (Manâa 1986), which is being exploited in the different parts of the Jurassic massif.

METHODOLOGY AND RESULTS

Gravity Study

Gravity data from the Chemtou–Sidi Miskine area were obtained from the "Office National des Mines" (ONM) of Tunisia. Gravity measurements were taken using Scintrex CG3 gravity meter with approximately one measure station per square km. The gravity data were processed using Geosoft Mapping and Processing System (Geosoft/Oasis software). They were gridded using minimum curvature technique (Briggs 1974).

In this study, complete Bouguer anomaly, residual anomaly and enhanced horizontal gradient maps are realized. The residual anomaly, which expresses the response of the relatively shallow upper crustal structures, was obtained by subtracting the Bouguer anomaly from the regional field. Upward continuation, based on spectral filtering, was used to deduce the regional field (Blakely 1996; Jacobsen 1987; Jacoby and Smilde 2009). The enhanced horizontal gradient method helps to detect the main subsurface discontinuities (Fedi and Florio 2009; Amiri et al. 2011).

The map of geological outcrops was superimposed on the calculated gravity maps for interpreta-
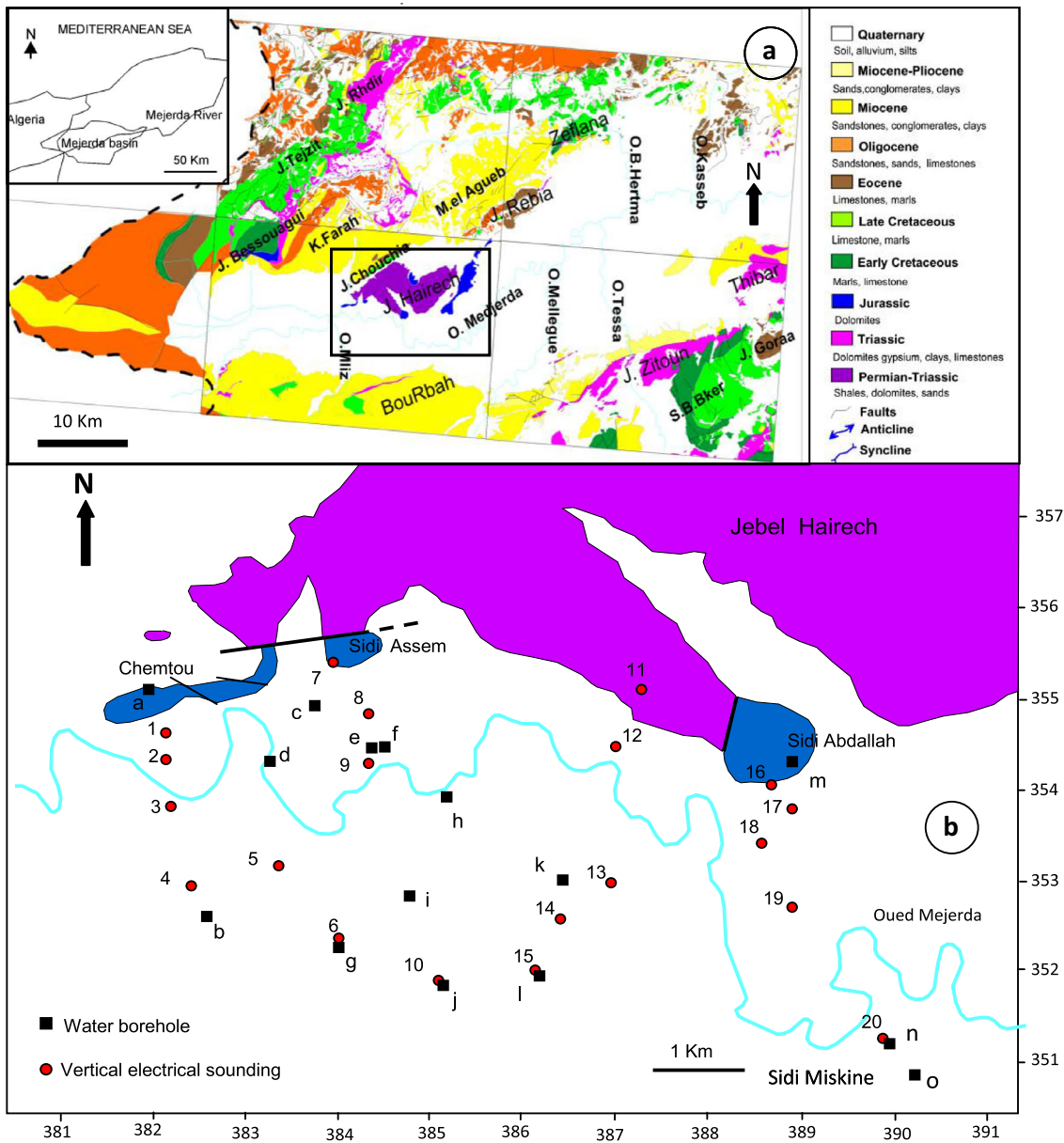
Figure 1. Study area location and data distribution. (**a**) Geological map of Mejerda average basin (adapted from Amiri (2012)). (**b**) Distribution of vertical electrical soundings and water boreholes.

tion. Mainly, two gravity anomalies are distinguished from Bouguer (Fig. 2a) and residual maps (Fig. 2b). The positive anomaly (1) covers the metamorphic massifs (Hairech and Jurassic massifs). It is explained both by the high density of the formations characterizing these massifs and their anticlinal structure (Guellala et al. 2011b). It is worth noting that the area

of the positive anomaly exceeds the limits of the metamorphic formations drawn on the geological map. This indicates that these formations extend under the Mio-Plio-Quaternary cover. The negative anomaly (2), which marks the southern part of the map, is caused by the thick low-density Mio-Plio-Quaternary deposits that fill the Mejerda plain.
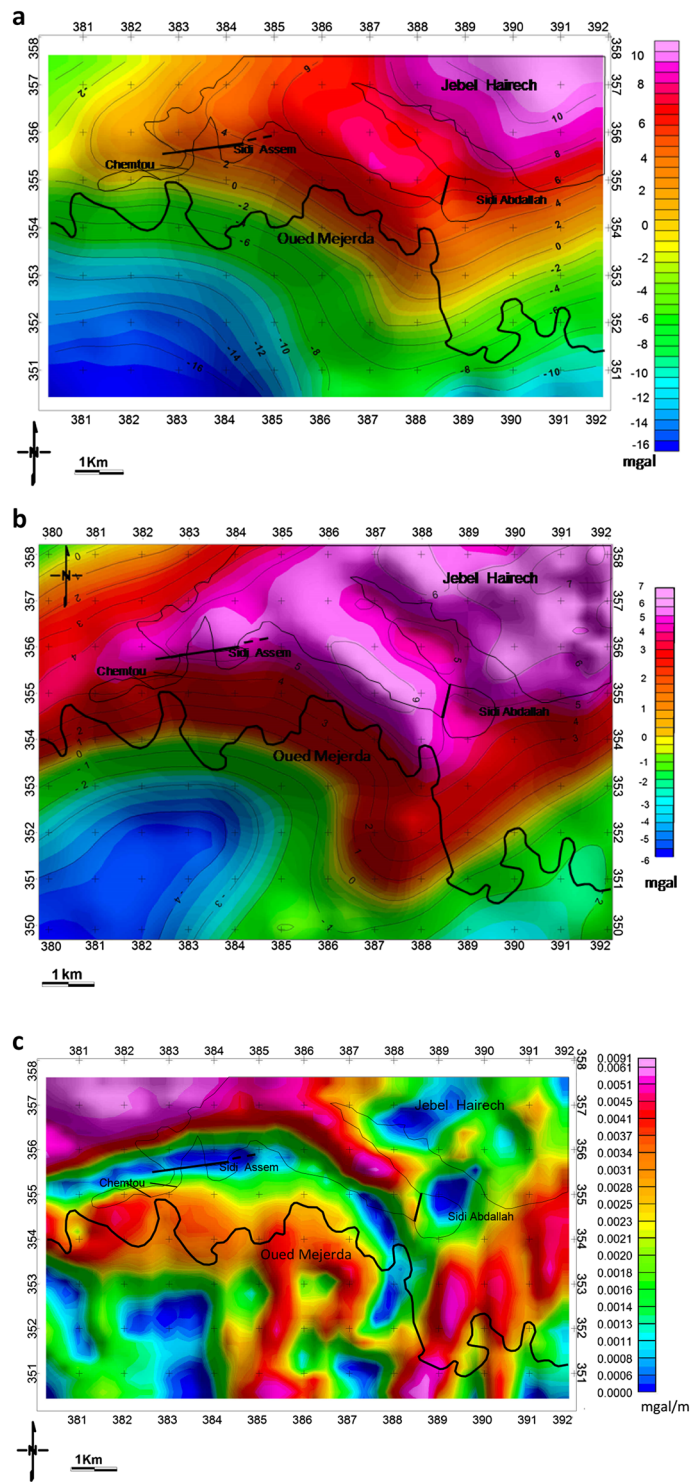
Figure 2. Gravity maps: (**a**) Bouguer anomaly; (**b**) Residual anomaly; (**c**) Enhanced horizontal gradient.

The enhanced horizontal gradient map (Fig. 2c) shows an E–W-trending lineament with maximum amplitude at the south of Jebel Hairech. This lineament may be a structural discontinuity separating the metamorphic formations and Mejerda basin. However, it is difficult to draw exactly this discontinuity on the geological map.

Geoelectrical Study

Resistivity Mapping

Apparent resistivity data of 20 vertical electrical soundings (Fig. 1b), executed with the Schlumberger configuration for a maximum electrode spacing of 3000 m, were arranged and contoured in the form of maps that express a qualitative representation of resistivity distributions for various depths. The different maps (Fig. 3) show high-resistivity values for the Hairech series (155 Ohm m) reflecting the thickness of these series (sandstones, schist and dolomites), which exceeds 900 m. The maps reveal low-resistivity zone (<50 Ohm m) in the Mejerda basin filled by Mio-Plio-Quaternary deposits.

The vertical electrical soundings executed on the Jurassic massifs (Sidi Assem and Sidi Abdallah) express various responses for the different spacing between the current electrodes A and B. For A–B spacing of 100 m (Fig. 3a), a high resistivity of 220 Ohm m was measured at Sidi Abdallah, whereas Sidi Assem corresponds to a conductive zone (30 Ohm m). For A–B spacing of 300 m (Fig. 3b), high-resistivity contours (60–110 Ohm m) characterize the different Jurassic massifs. For A-B spacing of 800 m (Fig. 3c), the resistivity values fall to 25 Ohm m at Sidi Abdallah. For A–B spacing of 1500 m (Fig. 3d), both Sidi Assem and Sidi Abdallah show low-resistivity contours (<50 Ohm m). The observed resistivity changes indicate a variable depth of the Jurassic metamorphic layers.

It is interesting to note the packed E–W resistivity contours between the metamorphic formations (Hairech and Jurassic series) and Mio-Plio-Quaternary deposits. These reflect lateral resistivity discontinuities that may indicate faults.
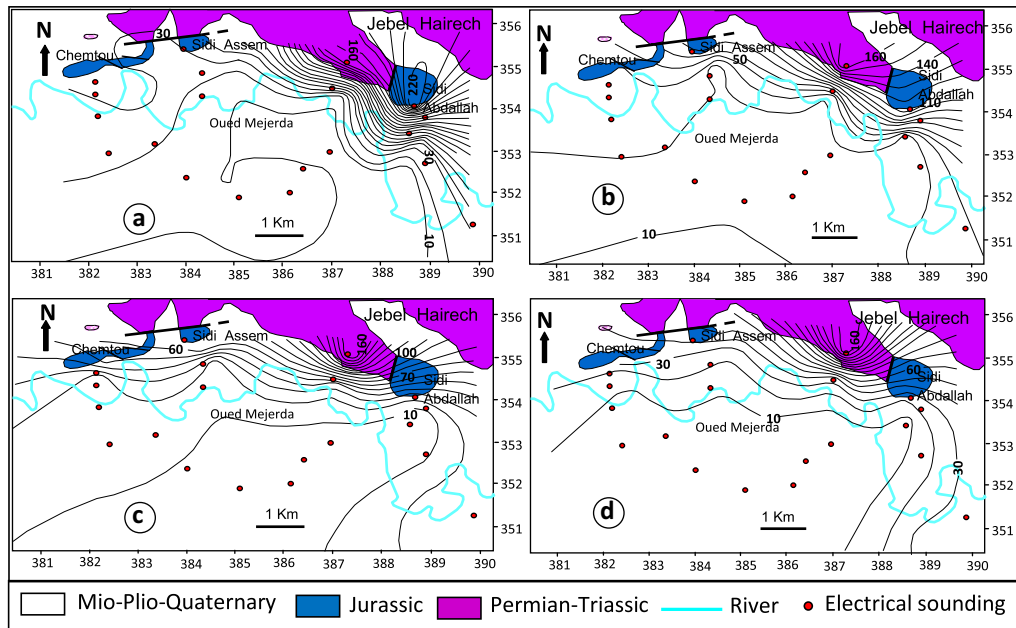
Figure 3. Apparent resistivity maps derived using different spacing between the current electrodes A and B (denoted as A–B spacing): (**a**) 100 m; (**b**) 300 m; (**c**) 800 m; (**d**) 1000 m.

Vertical Electrical Soundings Calibration

Existing boreholes and parametric soundings allowed electrical data calibration. Geological data incorporation is crucial to control the inversion results and to reconstruct the precise picture of sub-surface geology.

VES11 on Jebel Hairech shows a specific resistivity of 155 Ohm m for the Hairech series (Fig. 4a). For the Liassic dolomites and marbles, the values deduced from VES 1, VES 7 and VES 8 at the foot of the Sidi Assem and Chemtou massifs, range from 80 to 100 Ohm m (Fig. 4b).

VES 6, VES 10, VES 15 and VES 20, respectively, calibrated with the lithological columns of boreholes g, j, l and n, show low- to moderate-re-

sistivity values (6–50 Ohm m) for the Mio-Plio-Quaternary series (Fig. 4c).

The relationship between resistivity and facies obtained from their calibration enabled the interpretation of the rest of the VES data. Determination of initial geoelectrical models (thicknesses and resistivities) was manually achieved using theoretical master curves and auxiliary point charts. The models were subsequently refined using the WINSEV program (Jenny and Borreguerro 1993).

Geoelectrical Cross Sections

The geoelectrical cross sections integrating the lithological columns and the interpreted VES data
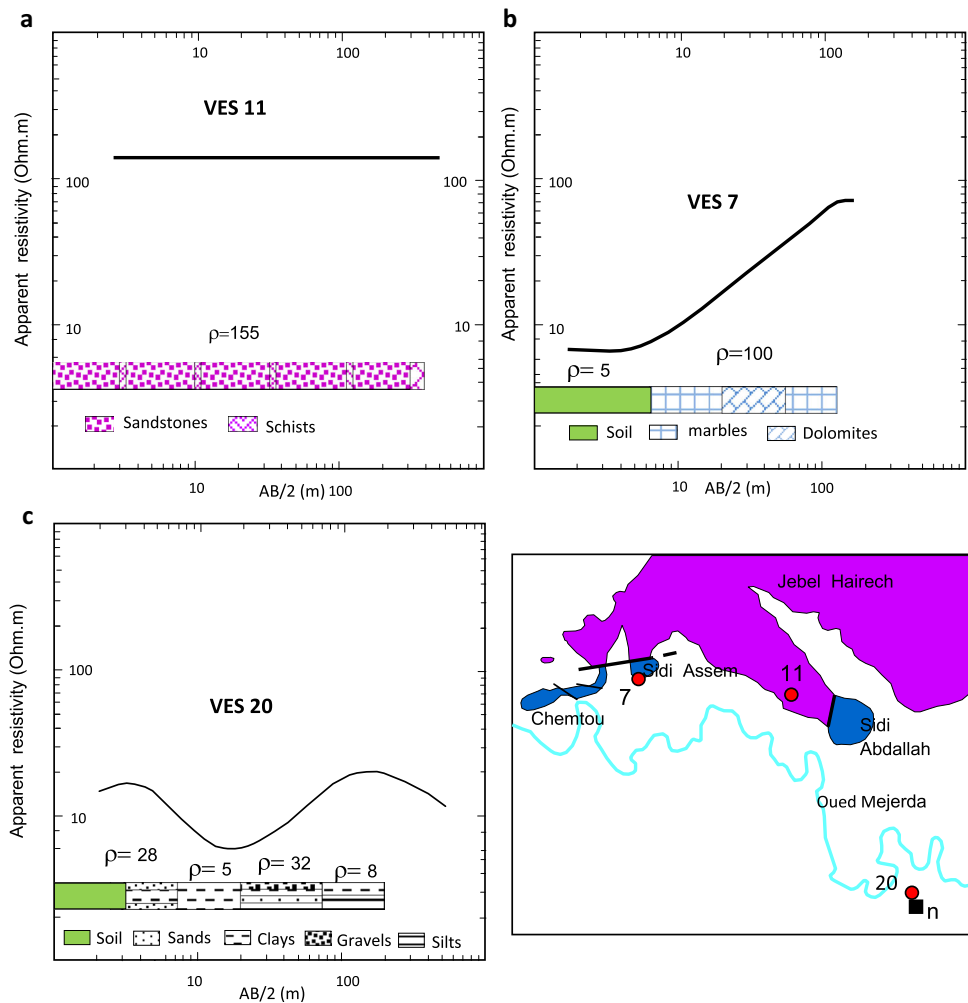
Figure 4. Electrical identification of geological series: (**a**) Hairech series; (**b**) Jurassic deposits; (**c**) Mio-Plio-Quaternary deposits. Resistivity (ρ) values are in Ohm m.

provided information about the aquifer system geometry. Four geoelectrical cross sections were established along NE–SW and NW–SE directions.

Cross section I (Fig. 5a): The resistive zone of 105 Ohm m beneath VES 1 expresses the continuity of the Chemtou Jurassic aquifer, which is underlain by a conductive layer (20 Ohm m) that can be correlated with Triassic rocks made of clay, dolomite and gypsum. Toward the S, the resistive layers beneath VES 3, VES 4 and VES 5 are diagnostic of alluvial aquifers. The difference between the geoelectrical models obtained from the neighboring electrical soundings VES 2 and VES 3 reflects lateral resistivity discontinuity that may indicate a fault separating Jurassic and Quaternary aquifers.

Cross section II (Fig. 5b): The Jurassic deposits outcropping at Sidi Assem massif are recognized at 160 m depth, underneath Quaternary alluvial deposits at the massif foot in borehole «c». Further away at 700 m, the borehole «e» reaches the Jurassic top at 135 m indicating that borehole «c» is located in a depression area and may be a result of normal faults controlling the thicknesses of the Quaternary deposits and their Jurassic substratum. Ten meters to the borehole «e», the borehole «f» shows 200 m of Quaternary deposits suggesting the presence of another normal fault between the aforesaid boreholes.

Cross section III (Fig. 5c): The electrical sounding 11 reveals the specific resistivity of the Hairech series (155 Ohm m). Nearby, VES 12 shows mainly three layers: The first resistive layer of 35 Ohm m is the continuity of the Quaternary aquifer recognized at borehole «k». Relying on the juxtaposed cross section, the second layer that exposes a response of 70 Ohm m is correlated with the Jurassic aquifer. The third layer is conductive with a value of 20 Ohm m and may correspond to Triassic deposits. The sudden resistivity change between VES 11 and VES 12 suggests a tectonic contact between the Hairech and Jurassic aquifers.

Cross section IV (Fig. 5d): Except for borehole «m» that exhibits 145 m of Jurassic series, boreholes «n» and «o» and electrical soundings 16, 17, 18, 19 and 20 in this cross section show Mio-Plio-Quaternary deposits and their electric responses. The Quaternary series include permeable layers that express an average resistivity of 30 Ohm m. The Mio-Pliocene series, essentially composed of marls and clays, is characterized by a low-resistivity value of (<10 Ohm m). The geoelectrical discontinuity between borehole «m» and VES 16 matches with the limit of the Sidi Abdallah Jurassic massif and may

indicate a fault. The remarkable reduction in the thickness of the Quaternary deposits in this cross section reflects the Mio-Pliocene substratum uplift toward the eastern part of the study area.

DISCUSSION AND CONCLUSIONS

Interpolation between the different geoelectrical cross sections allowed the construction of a structural map (Fig. 6) that exposes the different tectonic features characterizing the Chemtou–Sidi Meskine area. Moreover, this map gives precision to the pattern deduced from gravity maps. It exposes raised (R1 and R2) and subsided (D1 and D2) compartments separated by E–W faults. The fault (Fa) delineates the northern limit of the Jurassic aquifer outcrops that correspond to the raised compartment "R1." The inferred geoelectrical models show that this fault extends toward the E, under Quaternary cover. In the depression "D1," the Jurassic aquifer, collapsed through the faults (Fb) and (Fc), constitutes the substratum of a thick Quaternary series. Toward the S, in the horst structure "R2," this series shows remarkable thinning and their Jurassic substratum is relatively elevated. Its maximum thickness is encountered in the deepest compartment "D2" generated by (Fd) faulting. Therefore, the resulting structural map reveals that important extensive tectonic structures exist in the subsurface and control the geometry of Chemtou–Sidi Meskine aquifer system. These structures may be attributed to the recent Quaternary extension well proved at the Mejerda molassic borders (Rouvier 1977; Ben Ayed 1986; Gueddiche et al. 1992; Ould Bagga et al. 2006).

Besides influencing the aquifer system geometry, tectonic deformations had significantly impacted the hydrochemical characteristics of the aquifer by generating a great variation of water salinity, which constitutes an important parameter for crop yield and soil productivity preservation. In the subsided compartment "D1," the salinity of the Quaternary aquifer measured in borehole «c», reaches 6 g/l. It reduced to 1.6 g/l in borehole «e» located in the raised zone "R2." This reflects a lack of connection between the depression "D1" and the neighboring extensive structures. "D1," limited by faults (Fb) and (Fc), corresponds to an isolated hydrogeological entity that contains salt water unsuitable for irrigation. "R2" and "D2" compartments show similar water salinities (1.2–1.8 g/l) indicating that the fault
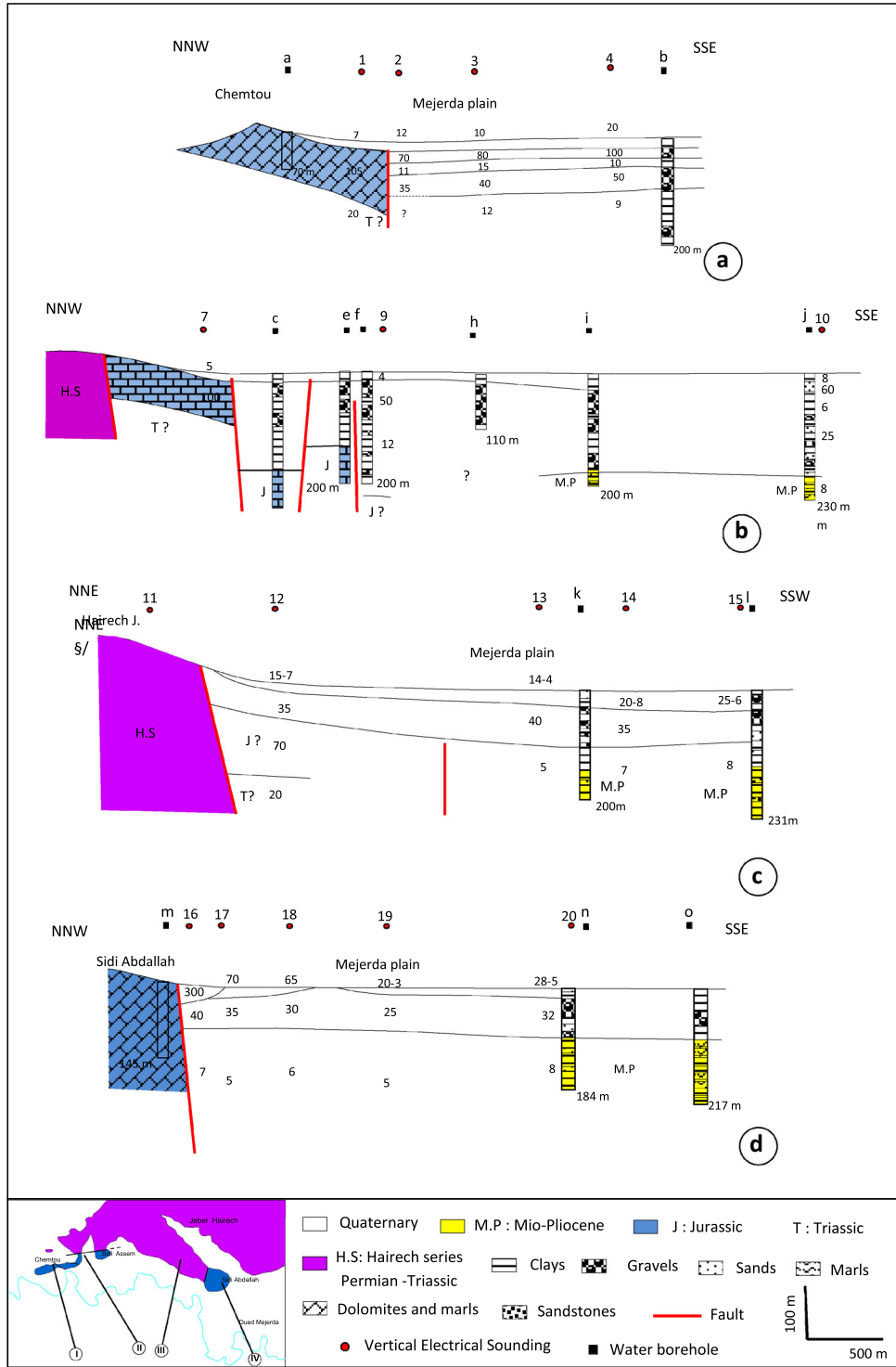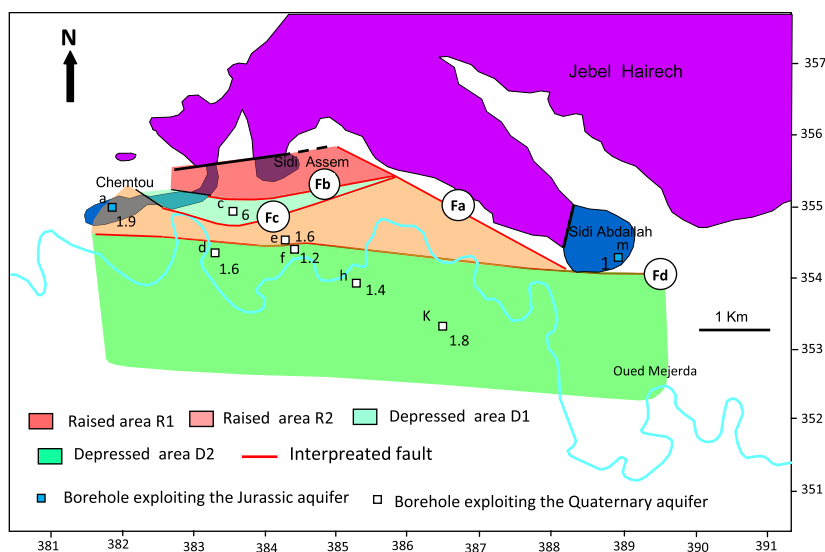
Figure 5. Geoelectrical cross sections: (**a**) I; (**b**) II; (**c**) III; (**d**) IV.

Figure 6. Reconstituted aquifer system geometry and its implication on the distribution of water salinity values.

(Fd) affects the Quaternary aquifers without influencing the communication between the reservoirs. The Jurassic aquifer, which largely outcrops, benefits from natural recharge by inducing a high water quality. In fact, the boreholes «**a**» and «**m**» exploiting this aquifer show water salinities of 1.9 and 1 g/l, respectively, (Fig. 6). In "R2" structure, the Jurassic and Quaternary aquifers present comparable salinities of 1.9 and 1.6 g/l, respectively, suggesting a common recharge source.

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