



Hydrogeologic Characterization of a Fault-Related Dome Using Outcrop, Borehole and Electrical Resistivity Data

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Geological structures introduce heterogeneity along deformed strata, which in turn exert a strong control on regional groundwater occurrences and water flow. We developed and applied procedures of structural, borehole and direct current resistivity (DCR) data to (1) figure out a reliable structural model of a fault-related dome, (2) visualize the relationship between structural complexity and aquifers geometry and (3) characterize the fault damage zones and its related sealing potentialities. The present approach was applied at the northern Eastern Desert, Egypt, considering its complex deformation history. To alleviate the uncertainties and artifacts in solving the DCR inverse problem, advanced and non-conventional inversion schemes were applied. Moreover, fault seal potentialities were assessed by applying the shale gouge ratio (SGR) estimation to predict the groundwater pathway flow. The main findings include: (a) The DCR measurements can be considered as a complementary tool to visualize the relationship between subsurface structures and aquifers geometry at highly deformed areas; (b) detailed surface structural data analysis combined with sophisticated inversion algorithms application can increase the reliability of the constructed geo-electrical cross sections for deep and large-scale geological surveys; and (c) the structural modeling of geological units and faults distribution contributes to clarify hydrogeological settings and aquifers connectivity. The approach can be readily applied elsewhere, as long as detailed structural analysis, geometric parameters and high-resolution DCR resistivity data are available.

KEY WORDS: Geologic structures, Electrical resistivity tomography (ERT), Aquifers connectivity, Fault zone characterization (FZC), Shale gouge ratio (SGR).

INTRODUCTION

Folds are one of the most frequent structures found in strained rocks; however, they represent a challenge for structural modeling because the geometry of folded surfaces cannot be figured out

from individual structural observations. The term “doubly plunging anticline” or “dome” is used for describing convex up structures with fold axis that is inclined in two directions. The development of domal structures can be distinguished from many probable mechanisms such as, post-impact uplift (Herrmann 2017), plutonism (Erkül et al. 2017), refolding (Benavente-Marín and Jabaloy-Sánchez 2017) and diapirism (e.g., Dewing et al. 2016). Recently, three possible mechanisms were suggested by Henaish (2018a) to form fault-related domes affecting sedimentary rocks, which are: (a) domes formed in strike-slip zones (Fig. 1a); (b) domes

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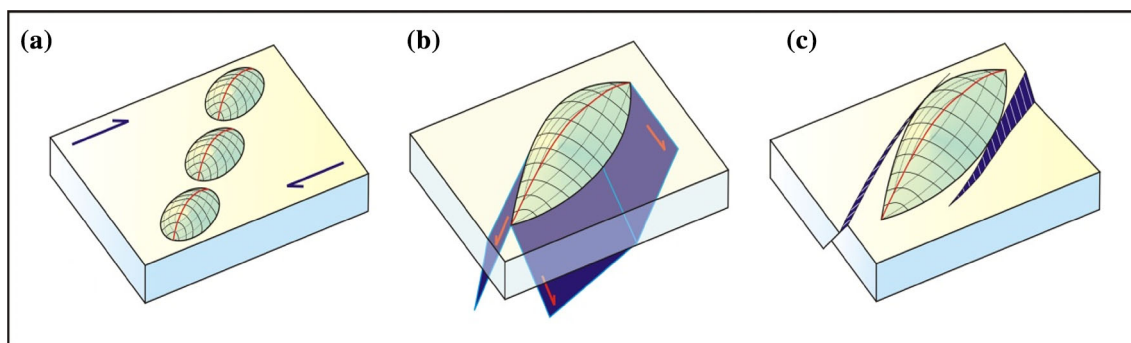


Figure 1. Different styles of fault-related domes (modified after, Henaish 2018a); (a) domes formed in strike-slip zones; (b) domes formed by drag along normal fault arrays and (c) domes formed at transfer zones of overlapped normal faults.

formed by drag along normal fault arrays (Fig. 1b); and (c) domes formed at transfer zones of the overlapped ends of normal faults (Fig. 1c).

Worldwide, domal structures have an economic significance in controlling the occurrence of natural resources (e.g., oils and groundwater) due to the structural complexity associated with doming. Hence, domal structures are very attractive to the Earth science community. Indeed, most of the previous studies dealt with four-way dip closure structures (i.e., domes) from petroleum geology perspective (e.g., Dewing et al. 2016). In general, salt domes create excellent hydrocarbon traps that can be found in many regions all over the world (e.g., Gulf of Mexico region of North America, North German–North Sea area of Europe and Iraq–Iran–Arabian Peninsula of the Middle East). In addition, domes represent a significant structural target for mineral exploration (Manuel et al. 2017) where mineral deposits (e.g., Au and Ag) are evident with granitic and gneiss domes (e.g., Germany, South Africa and Egypt).

From structural geology perspective, basins and grabens are usually favorable for groundwater exploration (e.g., Abotalib et al. 2019). However, many groundwater resources were evident at domal structures at many localities around the world (e.g., Qin and Lu 2019). In fact, internal structural complexity of various types of domal structures should be taken in consideration when dealing with hydrogeological, environmental and engineering purposes (e.g., Bense et al. 2013). Recently, the relationship between structural complexity and groundwater flow has been studied using individual structural analysis along fault and fracture zones (e.g., Ladevèze et al. 2019).

From geological perspective, inadequate understanding of subsurface geology could lead to

unreliable structural model. Accordingly, nondestructive geophysical methods pose a valuable alternative that get better subsurface geology portrayal (e.g., Yilmaz and Koksoy 2017). Recently, modern integrative approaches of structural geology and geophysics are able to figure out the subsurface geology/structures information correlated with borehole and surface geological data on a range of spatial scales (e.g., El-Sawy et al. 2018). For example, direct current resistivity (DCR) surveys represent a considerable source of regional and deep geological information (e.g., Henaish and Attwa 2018). In addition, DCR data are suitable for subsurface structures delineation for large areas and for determining aquifer geometry (e.g., Attwa et al. 2009). DCR soundings have been widely used for demarcation of subsurface layer boundaries and water bearing formations (e.g., Benabdelouahab et al. 2019). Moreover, ERT (electrical resistivity tomography) is favored for imaging lateral heterogeneities and linear features (e.g., Attwa et al. 2016). Currently, ERT has been commonly used with success to (1) image the subsurface geological structures (e.g., Eleraki et al. 2010; El Bastawesy et al. 2019), (2) predict the geotechnical parameters at the field-scale and (3) deal with hydrogeophysical investigations (e.g., Attwa and Günther 2012; Misonou et al. 2013; Gupta et al. 2019).

In arid to semiarid regions of complex structural setting worldwide, freshwater supplies demand is on the rise due to growing new community projects with water resources paucity. The tectonic and structural setting of the northern part of the Egyptian Eastern Desert (EED) is very complex. In addition, such desert lands are considered as promising regions for new urbanism projects in Egypt (e.g., Cairo-Suez District “CSD,” Fig. 2a). Consequently, understanding groundwater system,

as a natural resource, is vital for sustainable development in such complex structure area. In the present study, we asked the following. (1) To what extent can an integrative approach, using outcrop, borehole and shallow geophysical data, is able to figure out the structural architecture of a highly deformed domal structure? (2) How can detailed structural mapping be vital to understand the role of structural elements in groundwater occurrences and/or aquifers connectivity in highly deformed areas? Within this work, we aimed to undertake the following tasks. (a) Develop and apply procedures to map a fault-related domal structure at northern EED considering its tectonic and structural setting. (b) Test the potential use of advanced conventional and non-conventional inversion approaches to reduce the uncertainty of inverse problem effects and reinforce the numerical geophysical modeling findings. (c) Characterize the fault damage zones using outcrop and ERT data. (d) Discuss the importance of our findings and the potential application for aquifer geometry characterization especially in arid to semiarid regions elsewhere especially in highly deformed areas.

STUDY SITE, REGIONAL GEOLOGY AND HYDROGEOLOGICAL SETTING

Tectonically, the northern EED represents a part of the unstable shelf units, which occupy the greater part of northern Egypt (Fig. 2a). It is mainly controlled by three tectonic events related to the movements involving the African, Arabian and Eurasian plates. These tectonic events include the deformation during the Late Cretaceous time where reactivation of E-W deep-seated faults was established. In addition, the northern EED was affected by deformation during Miocene and post-Miocene times, where NW–SE normal faults are evident due to the opening of the Gulf of Suez rift. A zigzag fault pattern is observable along the northern EED due to linkage of E–W to NW–SE faults. This fault pattern was responsible for shaping most of the exposed structural blocks along the CSD. Two major subdivisions can figure out the nature of geological structures at CSD. The northern CSD extends northerly to Cairo–Ismailia Road (Fig. 2a), and it is characterized by the presence of faults and gentle folds. Conversely, the southern part of CSD shows many high mountain ridges and several tilted fault blocks.

Several studies dealt with surface mapping of geologic structures at CSD using outcrop data (e.g., Moustafa and Abd-Allah 1991; Henaish 2018a, b) or space-borne optical and radar dataset (e.g., Hammam et al. 2018). Recently, regional structural mapping of CSD was presented using structural, geological and geophysical data (e.g., Attwa and Henaish 2018). The main implications of such previous structural studies along CSD were related to tectonic evolution of CSD, and/or environmental and geotechnical studies of the foundation rocks. On the other hand, the detailed structural mapping of a specific structural feature and/or the relation between the regional structures and aquifers geometry have not been investigated along CSD using surface and subsurface data. In addition, the near-surface structures and shallow aquifer distributions should be characterized using precise subsurface data integrated with detailed surface structural mapping.

Structurally, many fault-related domes are well exposed at CSD affecting sedimentary rocks in several localities (e.g., Gebel Oweibed, Gebel Nasuri, Gebel Homaira, Gebel Gharrah, Gebel Um Raqm and Gebel Hamza, Fig. 2a). The investigated area is represented by Gebel Hamza which is a fault-related dome that belongs to the northern CSD (Fig. 2a and b). Recently, a new urban area has been planned to be established around Gebel Hamza. Consequently, the development requires an in-depth evaluation of the structural setting and aquifer system, for which information about faults and aquifers geometry is needed in the first stage.

The lithostratigraphic setting of Gebel Hamza area (Fig. 2c) is represented by five main rock units. The oldest rock unit is represented by the Wadi Hof Formation (Farag and Ismail 1959), which has been defined from the observed boreholes comprising limestone with shale interbeds. The outcrop is represented by the Oligocene rocks of Gebel Ahmar Formation (Shukri 1954) that are composed of varicolored sandstone and argillaceous sandstone with basalt fragments, which was associated with volcanism of the Oligo-Miocene rifting. The Gebel Ahmar Formation is overlain unconformably by the marine Miocene rocks (Shukri and Akmal 1953), which consists of sandstone intercalated with shale beds. In addition, sandy limestone outcrops with local extension can be observed at the easternmost part of Gebel Hamza. The marine Miocene sediments are overlain by the sands and gravels which are argillaceous in parts of the non-marine Miocene unit (Shukri and Akmal 1953). Quaternary sands

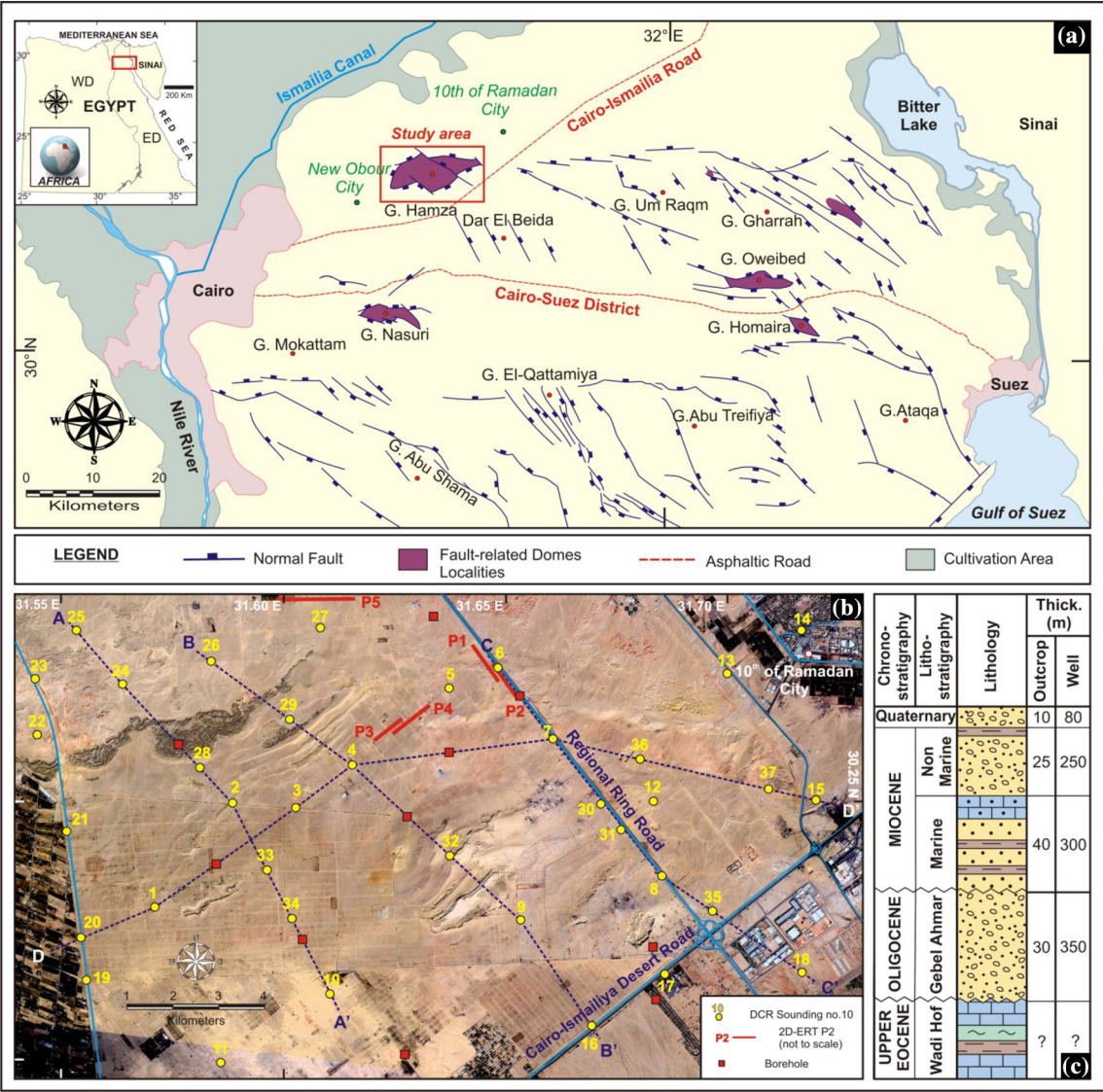


Figure 2. (a) Simplified structural map of Cairo-Suez District (CSD) and locations of fault-related domes (modified after Attwa and Henaish 2018; Henaish 2018a, b), ED: Eastern Desert; WD: Western Desert. (b) Google Earth satellite image (© 2018 DigitalGlobe) showing the location of the study area and the distribution of geophysical measurements and observed boreholes. (c) Composite stratigraphic section of the area under investigation.

and gravels are well exposed at the southern part of the area overlying the non-marine Miocene rock unit.

Recently, integration of remote sensing (RS) and geographic information systems (GIS) has been widely used to understand the hydrogeological systems across vast areas of arid and semiarid regions (e.g., El Bastawesy et al. 2019). To study the geomorphic characteristics of the CSD, a Shuttle Radar Topography Mission digital elevation model (SRTM

DEM) with resolution of 90 m at the equator (from USGS, the United States Geological Survey) was used to delineate the main basins from the available raster dataset. The DEM was processed using ArcGIS 10.1 to create a grid, in which the flow direction, flow accumulation and stream definition were computed. The result was ten basins (Fig. 3a) representing the Wadi systems along CSD. Notably, most of these basins discharge water to Ismailia Canal. In addition, faulting is controlling the formation of such

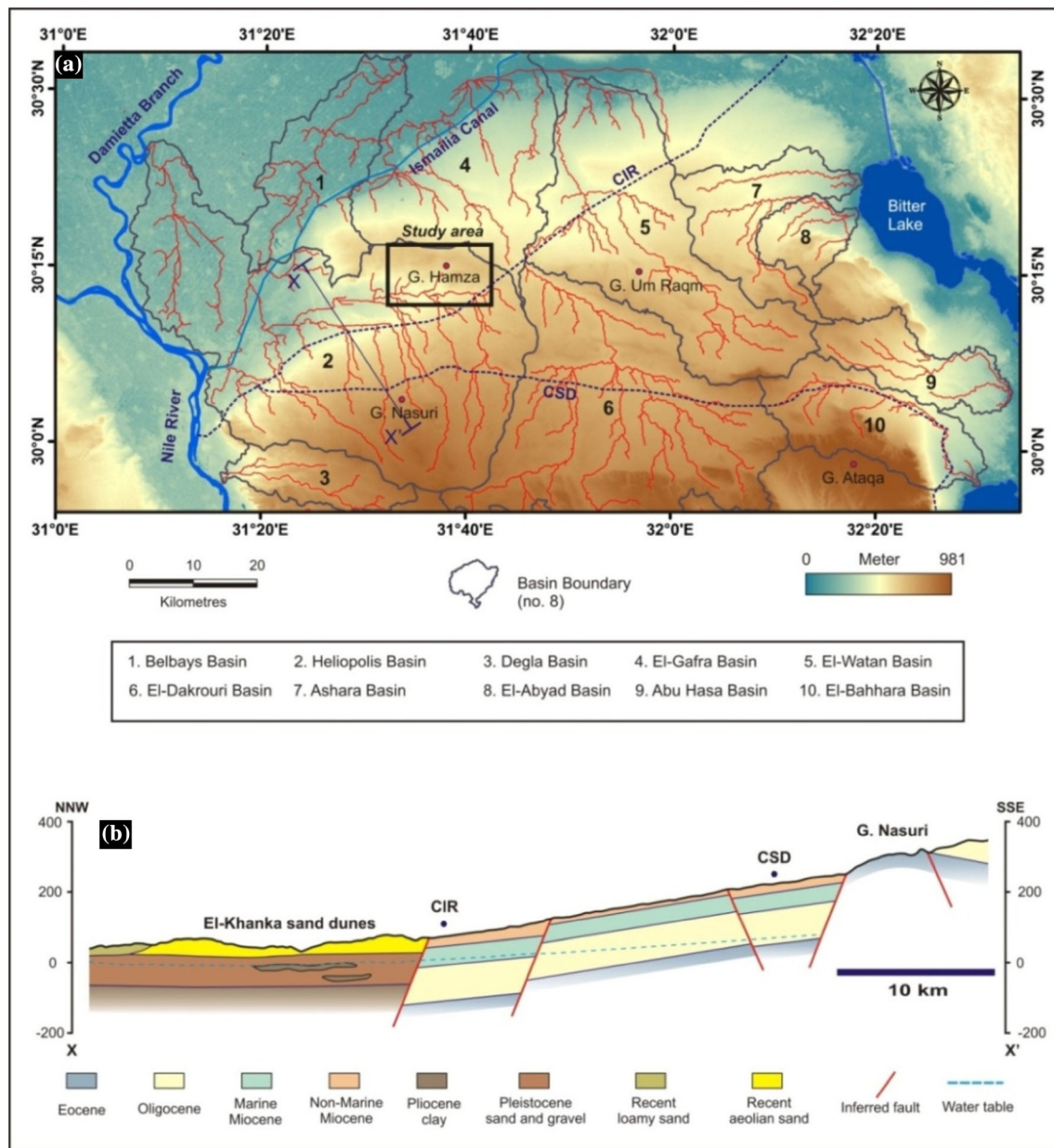


Figure 3. (a) Hydrographic basins of Cairo-Suez District overlaid on SRTM DEM. (b) Hydrogeological cross section through Heliopolis basin (Compiled from El-Fayoumy 1968; El Haddad 2002; Ismael 2007; Attwa and Henaish 2018; present study). CSD Cairo-Suez District and CIR Cairo-Ismaelia road.

morpho-tectonic basins such as Heliopolis and El-Dakruri basins. The study area (G. Hamza area) is located at Heliopolis basin (the main watershed at east of Cairo), which discharges water to the Damietta branch (Fig. 3a), East Nile Delta.

From hydrogeological point of view, Oligocene, Miocene and Pleistocene aquifers were detected at the western parts of CSD (e.g., RIGW/IWACO

1991), Figure 3b. In general, the Pleistocene aquifer was mainly recorded close to Ismailia Canal and its surroundings (i.e., northeastern parts of CSD). On the other hand, the Miocene and Oligocene aquifers were delineated at the central and western parts of CSD (e.g., G. Hamza). Abou Heleika and Atwia (2015) stated that the aquifers distribution is structurally controlled by faults. Along the fault planes

and accompanied fractures, basaltic flows intruded to overlie Oligocene deposits (sands and gravels) and underlie the marine Miocene rocks (El Haddad 2002). Accordingly, the faults and basaltic intrusions play a vital role in discriminating the aquifers (i.e., Oligocene, Miocene and Pleistocene) boundaries. Moreover, hydrochemical analyses indicated that the collected Miocene and Oligocene groundwater samples are suitable for industrial purposes only (e.g., Abou Heleika and Atwia 2015).

RESEARCH APPROACH, DATA AND METHODS

Workflow of the Present Study

Domal structures enclose an internal deformation of associated complex pattern of faults and fractures. Such deformation complexity should be mapped and traced with awareness and integrated methodologies for reducing the uncertainty of structural modeling. As far as the authors are aware, no published works exist on detailed mapping of internal architecture of domes using detailed surface structural and shallow geophysical techniques of the area under investigation. In this research, an integrative approach was used to characterize a fault-related dome at a highly deformed area, which could be applied elsewhere particularly in arid to semiarid

areas (Fig. 4). The approach includes integration of field investigations, outcrop structure analyses, boreholes and geophysical data (DCR soundings and ERT data), Figure 4. Based on the integration of detailed surface and subsurface data, (1) the overall structural model of the fault-related dome is produced and (2) the aquifers distribution can be well delineated.

Given that the groundwater flow is expected to be controlled by geological structures in such highly deformed area, fault damage zones should be well characterized to understand better the water flow behavior. In general, the integration of several types of data is widely used to assess the groundwater resources and water flow (e.g., Magaia et al. 2018). The present workflow (Fig. 4) addresses that using outcrop data with near-surface investigation (e.g., 2D-ERT data) is vital for fault zones characterization. Moreover, the fault core properties are assessed using the shale gouge ratio (SGR) method, which is commonly used for hydrocarbon studies, for fault seal prediction. The SGR is based on the estimation of the fraction of shale that has slipped past a certain point along a fault using the following equation (Yielding et al. 1997):

$$\text{SGR} = \frac{\sum[(\text{Zone thickness}) * (\text{Zone shale fraction})]}{\text{Fault throw}} \times 100\%$$

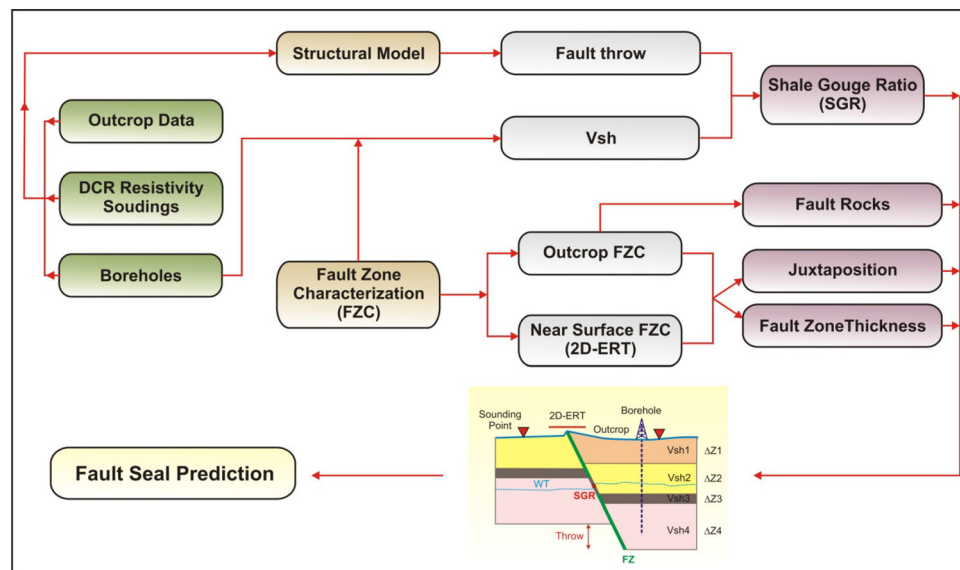


Figure 4. Workflow of detailed structural mapping and preliminary fault seal prediction at highly deformed areas. Note Vsh refers to volume of shale.

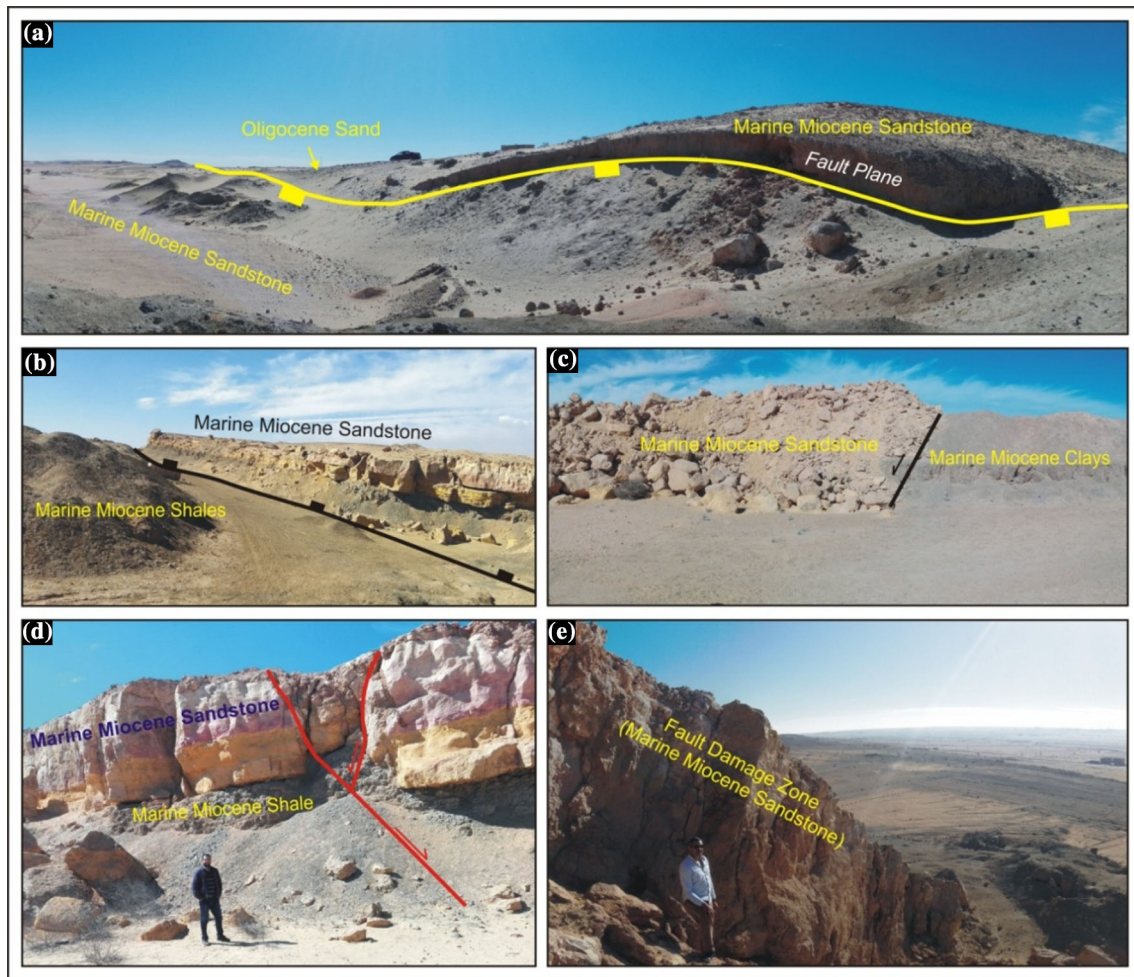


Figure 5. Examples of measured structural field data including faults as well as fault damage zones.

Outcrop Structural Data

In the present study, the G. Hamza area (Fig. 2) was investigated with satellite images (Landsat ETM + and Google Earth images) and field investigations. Based on the above-mentioned workflow (Fig. 4), stratigraphic sections were defined and measured. Additionally, geometry of bedding planes (i.e., strike and dip) was recorded in order to map out the change in attitudes of the strata. Moreover, the geological structures that form the overall architecture of the area have been studied in detail (Fig. 5). Faults as well as fault zones were measured in the field and recorded in the light of their types and attitudes (i.e., strike, dip value and dip direction). Furthermore, faults were located in their accurate location on the map.

Structural data of G. Hamza domal structure were analyzed by stereographic analysis. The geometric characters of such dome were determined throughout analysis of pairs of neighboring structural domains. The domains were defined by the attitudes of the bedding planes and the location of fold axes in such a way that the strike and dip data of each domain are reliable. Beta diagrams were constructed by plotting the poles to planes of adjacent domains using Stereonet 9 (Allmendinger et al. 2012). Strike and dip of the axial planes were determined using best fits. Furthermore, the strikes of the axial plane as well as attitudes of bedding planes have been correlated to boundary faults in order to categorize the type of such dome.

As a requirement for determining fault zones characteristics and its impact on groundwater flow, an outcrop focused study has been achieved on three

selective fault zones concerning stratigraphic juxtaposition. The examined fault zones attributes include: length, orientation and aperture of fractures within fault zones, and in addition, the displacement along faults was measured.

Subsurface Field Data Acquisition, Processing and Inversion

Considering approaches followed by Attwa and Henaish (2018) and Henaish and Attwa (2018), the geophysical results were validated using the available borehole data, regional geological and hydrogeological information and the above-mentioned detailed surface structural mapping. The available boreholes with hydrogeological database were accumulated from Arab Drilling Company, RIGW/IWACO (1990), Hussein (2001), Ismael (2007), Attwa et al. (2014) and Abou Heleika and Attwa (2015). Figure 2b shows the location of DCR measurements using a SYSCAL R2 device (IRIS instrument). In view of the ground surface and aridity conditions, stainless-steel electrodes were used. In addition, saltwater and bentonite were added around electrodes to improve the electrical contact of electrode with ground. Accordingly, the ground contact resistance was less than 15 k Ω . Considering the noise level, the measured DCR data were stacked ten times and final data were recorded when the data quality factor value was minimized (i.e., stacked error $\sim < 4\%$). Further, the measurements of standard deviation below 5% were used for inversion process. Three field surveys were carried to conduct the geo-electrical data in October and December 2017 and January 2018. The electrode coordinates (i.e., precise locations and elevations of the DCR measurements) were obtained using a GPS unit with 2 m accuracy.

Thirty-seven DCR soundings were conducted in 2017 to (1) gain a general overview about the regional geological and structural settings of the investigated domal structure and (2) identify the groundwater occurrences in such highly deformed area. Because the area has many mountains, hills and quarries, the DCR soundings distribution was not in a grid-like form. However, the DCR soundings were distributed to cover the investigated domal structure at G. Hamza (i.e., fold core and limbs, Fig. 2b). The DCR soundings were acquired using Schlumberger array with 1500 m maximum half electrode spacing (AB/2). DCR sounding data from

nearby boreholes were utilized for calibration purpose.

In general, the DCR sounding interpretation results can only be applied to the immediate of the sounding point surroundings (i.e., for 1D structural mapping). Accordingly, the 2D-ERT surveys were conducted in 2018 for selective faults to characterize fault damage zones based on stratigraphic juxtaposition (i.e., for 2D structural mapping). Consequently, relationship between water flow and structural complexity can be understood in the area under investigation. Figure 2b shows the location of ERT profiles (i.e., P1–P5) crossing the main fault zones based on our field observations. Here, the inversion results of ERT data were validated with surface geological/structural mapping and subsurface information considering borehole data and 1D-DCR inversion results. The 2D-surveys were performed using the Wenner beta electrode array, which can be considered as a combination between Wenner alpha and dipole–dipole arrays. Further, Wenner beta array has good signal-to-noise ratio (e.g., Henaish and Attwa 2018). Accordingly, Wenner beta electrode configuration has better sensitivity to horizontal structures mapping than conventional individual Wenner alpha and dipole–dipole arrays (e.g., Usman et al. 2019). Electrode spacing for all 2D-ERT profiles was 15 m using 30 electrodes. The 2D-ERT profiles P1 + P2 and P3 + P4 were overlapped; each profile was 435 m long with an overlap of 120 m and 75 m, respectively.

Depending on four neighboring data filtering, the DCR sounding data were preprocessed using a MATLAB in-house code (Raji and Adeoye 2017) to remove the noise data representing spurious values. In an attempt to reduce the uncertainty of 1D interpretation, the apparent resistivity data of DCR soundings were inverted applying a sequential use of conventional and non-conventional inversion schemes (genetic algorithm, GA). The 1D forward modeling of the conventional inversion scheme is carried out using a linear filter with a single starting model. On the other hand, the GA is based on Darwin's evolution theory (Basokur et al. 2007) and, accordingly, a large number of starting models must be used for inverting the DCR data which, in turn, increases the chance to obtain the best model (e.g., Akça and Basokur 2010).

Considering the 1D linear filter inversion results (i.e., conventional scheme), Figure 6 portrays an example of inversion process using GA of DCR sounding No. 9 (for location, cf. Fig. 2b). Here, the

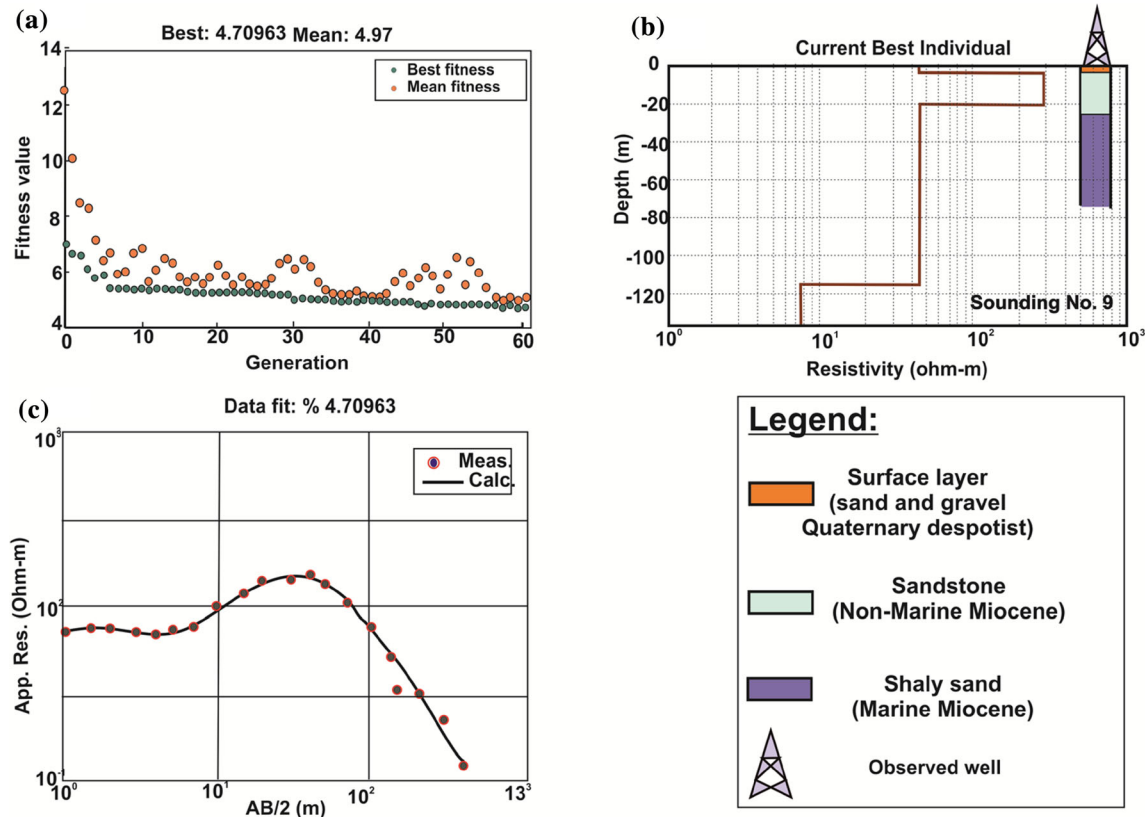


Figure 6. Inversion results applying GA of DCR sounding point No. 9 (for location, cf. Fig. 2a) using GA with borehole data calibration; the population size and generation number were 60.

population size and generation number were 60 (Fig. 6a), where the best fit between measured and calculated data can be gained (Fig. 6b). Figure 6c shows a good correlation between the borehole data and DCR inversion results. Finally, the 1D inversion results were used to construct the stitched resistivity sections.

The 2D-ERT data were processed by DC2DInvRes resistivity inversion program (Günther 2004), including bad DCR data point rejections (i.e., stacking error was more than 4%) from the field resistivity data. In reciprocal data lake, the uncertainty of the apparent resistivity data was assessed using error model of 3% plus $10 \mu\Omega$ as suggested by Udphuay et al. (2011). The forward problem of 2D-ERT data was solved with 2D finite-difference (FD) modeling using the classical standard smoothness constrained least-squares inversion. Then, the 2D inversion process was carried out using DC2Dpro software developed at the Korean Institute of Geosciences and Mineral Resources.

The DC2Dpro program is based on active constraint balancing (ACB) approach (Yi et al. 2003 and Kim et al. 2009) using Lagrangian multiplier (λ) (i.e., a spatial variable) to reconstruct high-resolution and accurate tomograms. For each iteration, the λ was calculated and optimized automatically. Here, the λ was assessed between 0.05 and 0.2. Further, additional constraints using prior data (e.g., borehole information) have to be implemented to constrain the subsurface structure.

RESULTS AND DISCUSSION

Structural Mapping/1D-DCR Inversion Results

Structurally, the overall architecture of the area has been outlined through field investigation, which is signified by a fault-related domal structure. The fold limbs are clearly exposed with gentle dip values that range from 6° to 15° toward the SE or SSE for

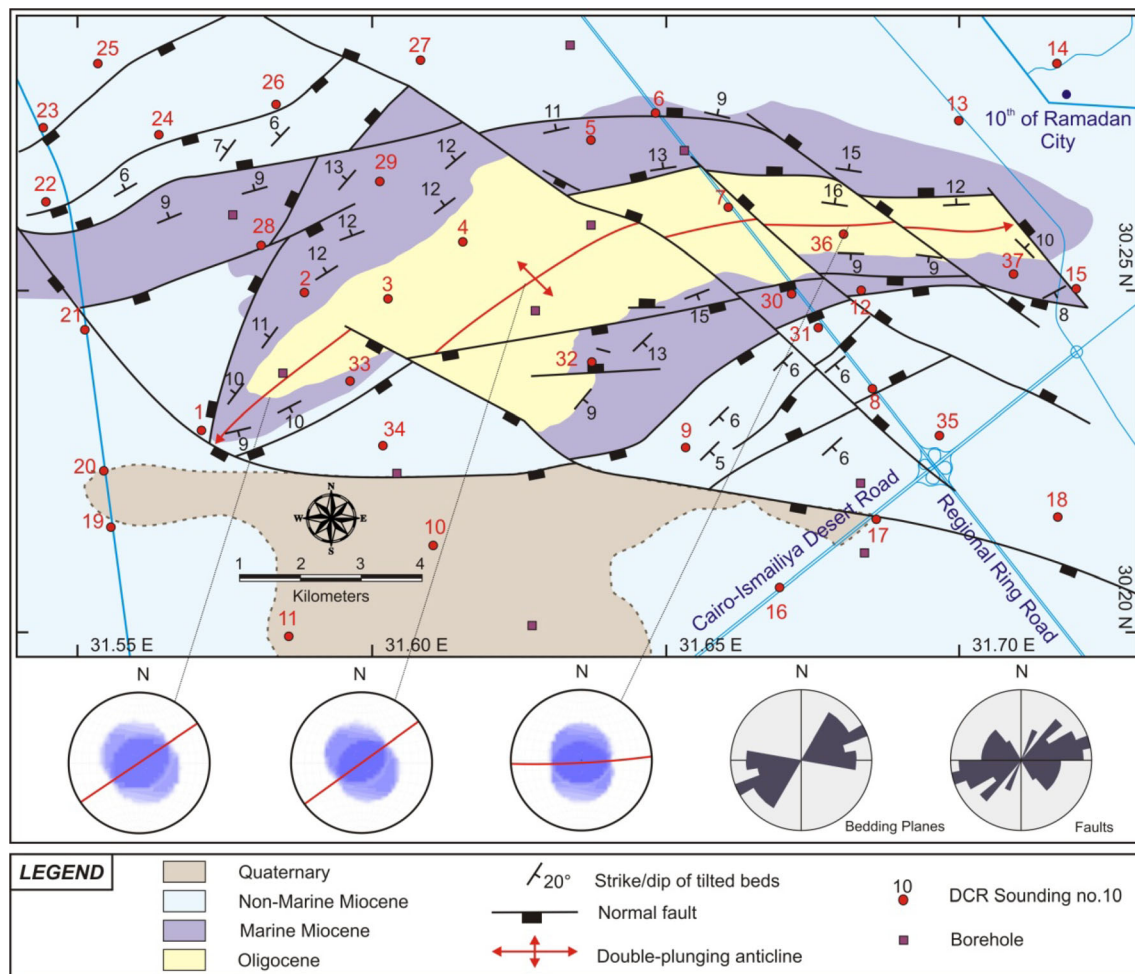


Figure 7. Geological map of the study area derived by integration of outcrop and DCR data. Note beta diagrams are displayed at the locations, which they represent. The solid red line in each diagram represents the fold axial surface. Rose diagrams are displayed for strike of bedding planes and faults of G. Hamza dome.

the southern limb and NE or NNE for the northern limb (Fig. 7). Locally, dip values of bedding planes reach 32° mainly near fault planes. Numerous faults are clearly exposed through the entire area. All the investigated faults are normal faults (Fig. 7); in addition, the measured dip data from several fault surfaces indicated moderate-to-steep angles, which generally range from 50° to 75°.

Based on the inversion results of DCR soundings, four stitched resistivity sections (Fig. 8) were constructed to delineate the regional geological, structural and hydrogeological settings considering the fault-related domal structure at G. Hamza. Abundant borehole information helped to overcome the DCR soundings ambiguities and to construct a connection among the geological information and interpreted resistivity data. Here, in our case, the

stitched resistivity sections A–A', B–B' and C–C' were constructed nearly perpendicular to the fold axis (for location, cf. Fig. 2b), i.e., NW–SE direction. On the other hand, the geo-electrical cross-section D–D' was constructed nearly parallel to the fold axis (for location, cf. Fig. 2b), i.e., ENE–WSW direction. Moreover, the measured geological and structural geometrical parameters and available hydrogeological data were recalled to be considered in the construction of the stitched resistivity sections.

Special awareness should be given to the geo-electrical layers lithology, thickness and depth due to their special role in detailed subsurface geological and structural mapping. From structural point of view, the abrupt change in resistivity values and thickness of the deduced geo-electrical layers (Fig. 8) can be attributed to the deformation of

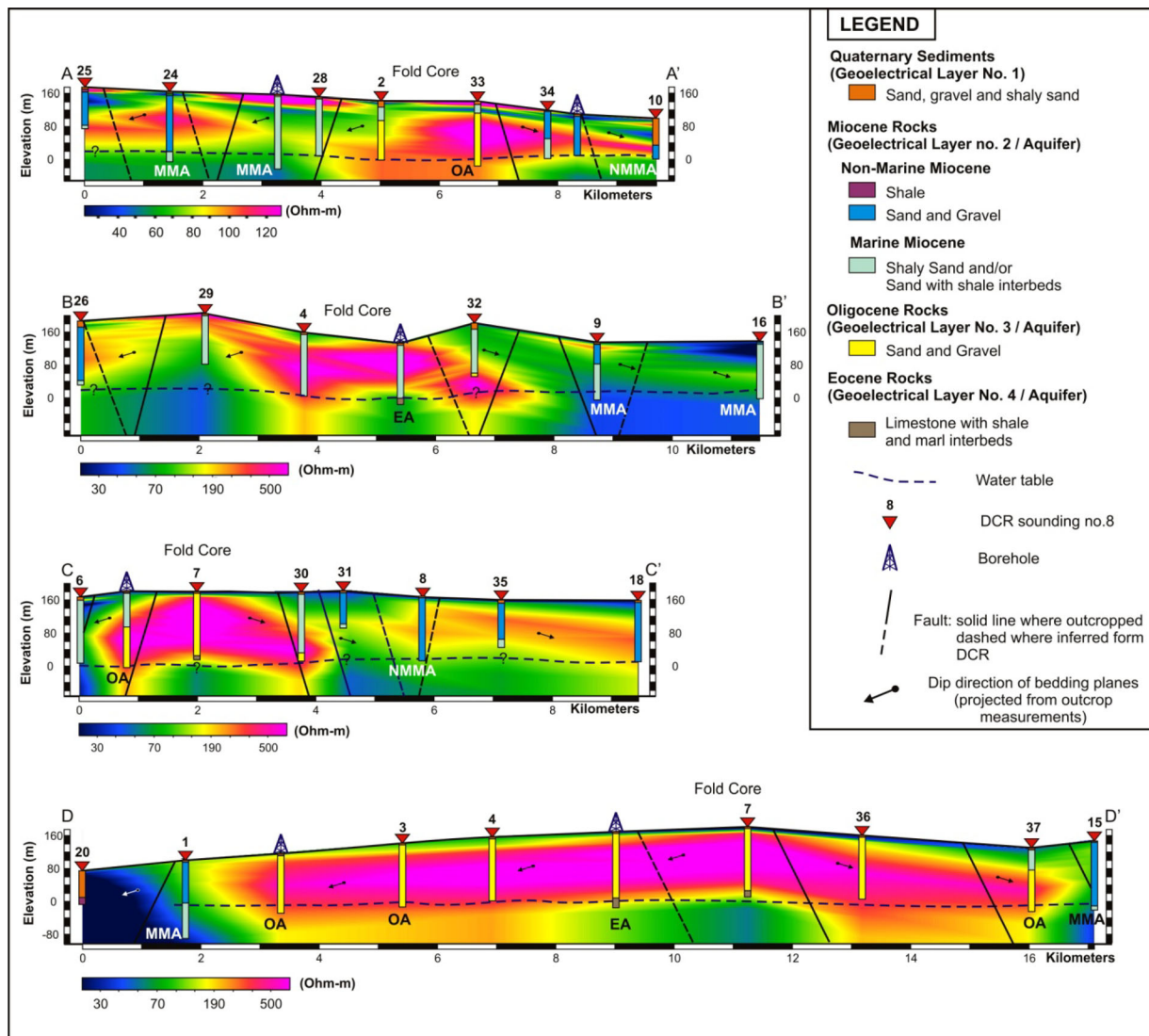


Figure 8. Constructed stitched resistivity sections resulted from DCR soundings inversion controlled by outcrop, borehole and hydrogeological database. *EA* Eocene aquifer, *OA* Oligocene aquifer, *MMA* Marine Miocene aquifer and *NMMA* non-marine Miocene aquifer.

rocks (i.e., faulting and folding). These lateral variations are also clear at the outcrops of G. Hamza (Fig. 5b and c), which control the aerial distribution of lithostratigraphic units. Four main geo-electrical layers can be recognized all over the constructed resistivity sections. The first resistivity layer is marked by highly contrasted resistivity values corresponding to Quaternary sand and gravel (> 100 O-m) and shaly sand (< 30 O-m). It can be noticed that the thickness of this layer increases toward the southwestern parts at the downthrows of the major boundary faults (~ 50 m thick, resistivity

section D–D'), i.e., away from the G. Hamza domal structure.

The second geo-electrical layer represents low-to-medium resistivity values (20–200 O-m) at the sounding points located at the fold limbs (e.g., soundings No. 8, 28 and 29, for location, cf. Fig. 2b). This layer can be interpreted as Miocene deposits, which is characterized by the significant shale enrichment especially toward the northwestern parts. In general, the upper medium resistivity values (~ 80 –200 O-m) can be interpreted as non-marine Miocene sandstone rocks. Moreover, the

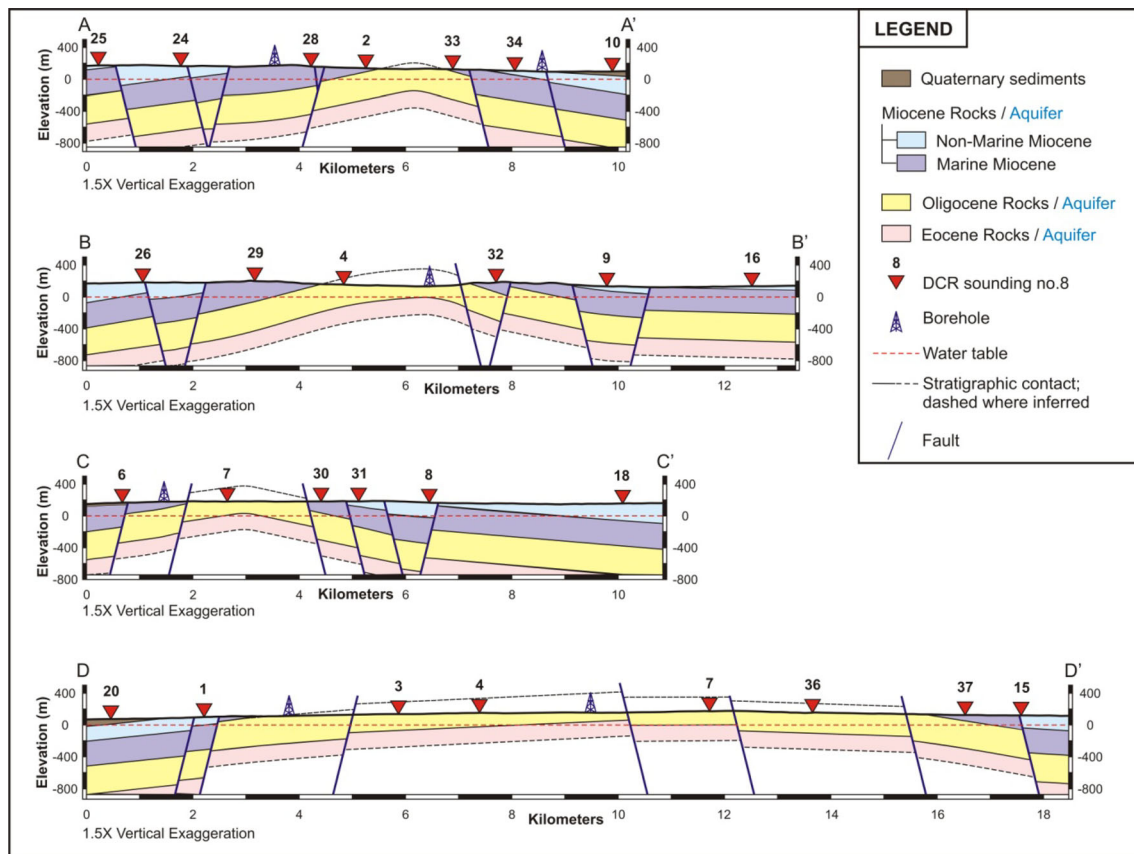


Figure 9. Constructed cross sections resulted from integration of outcrop, borehole and DCR inversion results, considering Henaish and Attwa (2018) approach.

medium resistivity values ($< 80 \text{ O-m}$) of the second geo-electrical layer can be attributed to marine Miocene reflecting shaly sand and/or sand with shale interbeds.

On the other hand, the second geo-electrical layer is followed by a very high resistivity layer ($> 300 \text{ O-m}$) at the central part of the area (i.e., at the fold core, Fig. 8). Based on borehole as well as outcrop data, this layer represents Oligocene sand and gravel with basalt fragments. Notably, the variations in the Oligocene layer depth, along and perpendicular to the fold axis, figure out the overall architecture of G. Hamza domal structure. Accordingly, the Oligocene layer is deeper at sounding points located at the northern and southern parts (e.g., soundings No. 3, 4 and 7, for location, cf. Fig. 2b) than that at the central part (i.e., fold core). In addition, the thickness reduction in the Oligocene sediments is obvious at the fold core of G. Hamza (e.g., soundings No. 3, 4 and 7, for location, cf. Fig. 2b), which is a result of crestal part erosion.

It can be noticed that the Miocene deposits are thin to absent at the fold core, where the Oligocene are dominant. On the other hand, thickness of Miocene deposits increases in general, toward the fold limbs (i.e., away from fold core). Based on the folded structure and borehole data, the Oligocene deposits are followed by medium resistivity layer ($\sim 70\text{--}100 \text{ O-m}$) at the fold core corresponding to Eocene limestone with shale intercalations.

Based on the recorded rock units thicknesses from the observed boreholes, outcrop geology and the constructed stitched resistivity sections support, a series of problem-solving cross sections have been constructed to figure out the overall structural geometry of G. Hamza (Fig. 9). The constructed cross sections show that the minimum estimated fault throw is $\sim 30 \text{ m}$ at the southwestern part of the area between soundings No. 10 and 34 where the non-marine Miocene rocks are juxtaposed against the Quaternary sediments. On the contrary, the maximum estimated fault throw is $\sim 250 \text{ m}$ at the

northwestern part, where a normal fault runs through the non-marine Miocene rocks (i.e., between soundings No. 24 and 25, Fig. 9). The increase in Miocene rocks thickness at the downthrows of the normal fault indicates that these faults were active during Miocene times. Moreover, extensional structures (i.e., horst and graben structures and step faulting) are clear at all cross sections affecting the limbs and crestal part of G. Hamza domal structure. At all the constructed cross sections, folding structure is so clear about the doubly plunging nature of the mapped fold (Fig. 9).

The analysis of the derived structural data revealed a total of forty-seven normal fault segments belonging to four prominent sets oriented in descending order of frequency; ENE–WSW, WNW–ESE, NE–SW and NW–SE (Fig. 7). Data analysis showed that the strikes of the bedding planes are parallel to the orientations of the boundary faults of the domal structure of G. Hamza. In addition, the fold axis of such dome is oriented parallel to sub-parallel to the boundary faults (Fig. 7). Concerning the tectonic setting of CSD, the NW- and WNW-oriented faults resulted from the opening of the Gulf of Suez (Oligo-Miocene rifting). These faults were propagated along CSD where they acted as transfer faults that link the reactivated pre-rift ENE- and NE-oriented fault segments. This fault array pattern leads to the formation of a rhombic horst block at G. Hamza where the domal structure resulted from the drag of beds along the footwalls of the boundary conjugate faults (Fig. 1b).

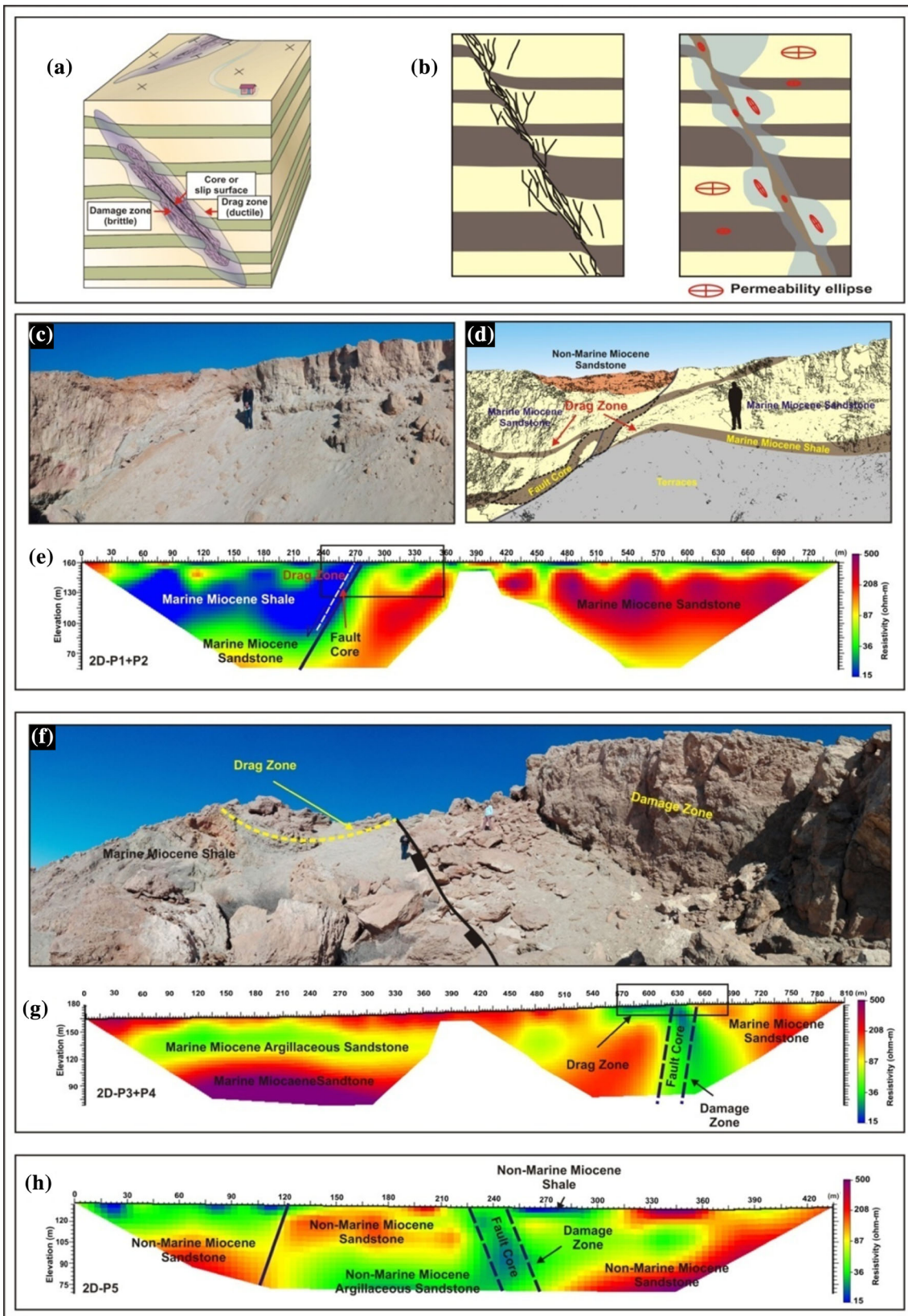
Characterization of Fault Zones

As the area under investigation is highly deformed, groundwater flow is mainly controlled by distribution of subsurface structures (faults, the overall fold structure and fractures), faults sealing potentialities and rock types. Broadly speaking, most of water flow in aquifers is horizontal in undisturbed groundwater systems. Moreover, water flows from higher pressure areas to the lower water level/pressure areas. On the other hand, the static water level and the natural water flow direction is expected to be disturbed and reversed in structurally controlled hydrogeological system such as in G. Hamza. Meanwhile, a sufficient connectivity is required between the formations/rock types for water to flow. Based on our hydrogeological field observations and the measured water table data (e.g., El

Haddad 2002; Attwa et al. 2014), it can be observed that there is a water level disturbance over the constructed geo-electrical cross section (Fig. 7). The water table is variable, and it ranges from sea level to ~ 20 m above sea level reflecting low to disconnected aquifers connectivity (e.g., Larsen et al. 2017). Obviously, the depth to the water table around the fold core (i.e., Eocene and Oligocene aquifers) is deeper (~ 0 m) than surrounding aquifers reflecting that the water flow is dominant to upward path than the horizontal direction and/or the Eocene aquifer could be recharged from other sources (e.g., Cretaceous Nubian aquifer) rather than surrounding aquifers. On the other hand, toward the fold limbs, the water table of both Oligocene and Miocene aquifers is nearly the same and the slight variation in water level of such aquifers can be attributed to the variation in discharge rate (e.g., Abou Heleika and Attwa 2015). Accordingly, understanding the aquifer connectivity and fault zone characteristics are vital for water resources management and for protecting the groundwater from degradation.

Hydrogeologically, the disturbance of water level in the area under investigation could pinpoint the dissimilarity of fault zone characteristics, which in turn affect the permeability of faults. Figure 10a indicates the fault zone anatomy, which consists mainly of fault core and damage and drag zones (Fossen 2010). Our outcrop studies of fault zones indicate the presence of shale in combination with gouges within fault cores in the fault planes. Most of the studied fault zones dissect the Miocene marine sediments and have widths that range from 0.5 to 7 m with the presence of layered structure of shale and sand smears at the fault core with evident dragging of shale beds along fault planes. Based on conceptual geological models (Fig. 10b) of fault zone hydrogeology in siliciclastic rocks (e.g., Bense et al. 2013), sand and shale smears develop with increasing fault displacement. In addition, where observed, nearly all of the surveyed fractures within damage zones of fault planes show conjugate or orthogonal fracture sets with abundant fault-parallel fractures and lengths that reach 2 m. High proportions of open and shear fractures were recognized in the field with apertures in the 1–5 cm range.

Figure 10e, g and h represents the inversion results of the 2D-ERT profiles P1–P5 (for location, cf. Fig. 2) to characterize the fault zones within lithified siliciclastic sedimentary rock units, which constitute the aquifers in our case study. Obviously,



◀ **Figure 10.** (a) Simplified anatomy of a fault (after Fossen 2010). (b) Fault architecture and associated conceptualized permeability structures within lithified sedimentary rocks (after Bense et al. 2013). (c and d) Field photograph and measurements, respectively, showing the rock units distribution and the drag zone along the fault core. (e) 2D-ERT profiles P1 + P2 inversion results considering the observed surface structures (c and d). (f) Field photograph showing the fault damage and drag zones within Miocene rocks. (g) Inversion results of 2D-ERT profiles P3 + P4 showing the projected faults and dragged zone around fault core. (h) Inversion results of 2D-ERT profile P5 representing the projected faults and fault core between non-marine Miocene rocks. *Note* Figure 2b shows the location of the 2D-ERT profiles (i.e., P1–P5).

the correlation between the 2D inversion results and outcrop data (Fig. 10c, d and f) helped in predicting the properties of hydrogeological systems along fault zones. Figure 10c, d and e shows the inversion results of 2D-ERT profiles P1 + P2 in correlation with the near-surface fault zone between Miocene marine rocks. It can be observed that the low resistivity layer (< 15 O-m) corresponding to Miocene marine shale changes laterally to medium/high resistivity layer (> 100 O-m) attributed to Miocene marine sandstone. Such abrupt change in resistivity values along the 2D-ERT2 P1–P5 can be related to existence of a fault considering the outcrop observations (Fig. 10c and d). An increase in shale layer thickness with smearing to its lower boundary can be observed along 2D-ERT profiles P1 + P2. This can be attributed to the electrical current behavior at low resistivity layer, where the current diverges through low resistivity layers (Telford et al. 1990) causing a decrease in the potential gradient at the lower boundary that leads to smearing of its lower boundary.

Moreover, a narrow fault core can be noticed between the different lithological rock units of shale and sandstone (Fig. 10e) attributing to anisotropy along the fault damage zone. Accordingly, variations in fault zone sealing potentialities can be predicted under such geological conditions. Thus, the above-mentioned results suggest that the presence of shale smear along fault planes would favorably impede lateral flow of groundwater, while the presence of sand would not interrupt groundwater flow. Hence, the investigated fault with such anisotropy of fault core could likely to act as combined conduit–barrier systems. Moreover, the presence of open fracture network along and near fault zones will enhance the permeability along fault zones.

Figure 10f and g shows the inversion results of 2D-ERT profiles P3 + P4 in correlation with surface

outcrop data. Based on the local geological conditions, these 2D profiles were measured on Miocene marine sandstone rocks with limited shale existence along the drag zone (Fig. 10f). Two main geo-electrical layers can be observed along the 2D-ERT profiles P3 + P4 of upper medium (~ 100 O-m) to lower high resistivity layers (> 100 O-m) corresponding to argillaceous sandstone to sandstone rocks, respectively. In contrast to the 2D-ERT profiles P1 + P2 (Fig. 10e), the abrupt change between geo-electrical layers cannot be observed, which can be attributed to the absence of shale. Between 570 m and 690 m 2D profile distance (Fig. 10f), a medium resistivity zone corresponding to a fault damage zone can be well identified. Obviously, the fault core width along 2D-ERT profiles P3 + P4 is larger than 2D-ERT profiles P1 + P2. This can be attributed to the incorporation of sand and gravel along the fault core instead of shale beds, which in turn will increase the fault zone permeability (Bense and Person 2006). Accordingly, the fractures connectivity and density typically increase significantly with decreasing shale ratios within rock units.

Based on local geological and structural investigations (Fig. 7), the 2D-ERT P5 was acquired along Miocene non-marine rocks. Lateral heterogeneities can be observed along the inverted model of 2D-ERT P5 (Fig. 10h) of medium (30–100 O-m) to high (> 100 O-m) resistivity layers corresponding to non-marine argillaceous sandstone to sandstone rocks, respectively. A near-surface low resistivity layer (< 30 O-m) can be observed along the 2D-ERT P5 corresponding to Miocene non-marine shale. Around 240 m profile distance, the rock discontinuity of Miocene non-marine rocks can be attributed to the fault existence. Here, the fault core represents low-to-medium resistivity values corresponding to non-marine argillaceous sandstone and shale. The presence of clay/shale along fault planes, in combination with cataclastic deformation, suggests that these faults would slow down lateral groundwater flow (e.g., Lehner and Pilaar 1997).

The interpretation results of outcrop as well as 2D-ERT data highly coincide with the conceptual models of fault zones affecting siliciclastic sediments (e.g., Bense et al. 2013), Figure 10b. The low-to-medium resistivity within fault zones resulted from the anisotropy of wall rocks where fault zones enclose sand and shale smears. This resistivity range represents the mixed siliciclastic rocks within fault zones that give a fingerprint that is close to the resistivity values of argillaceous sandstone. On the

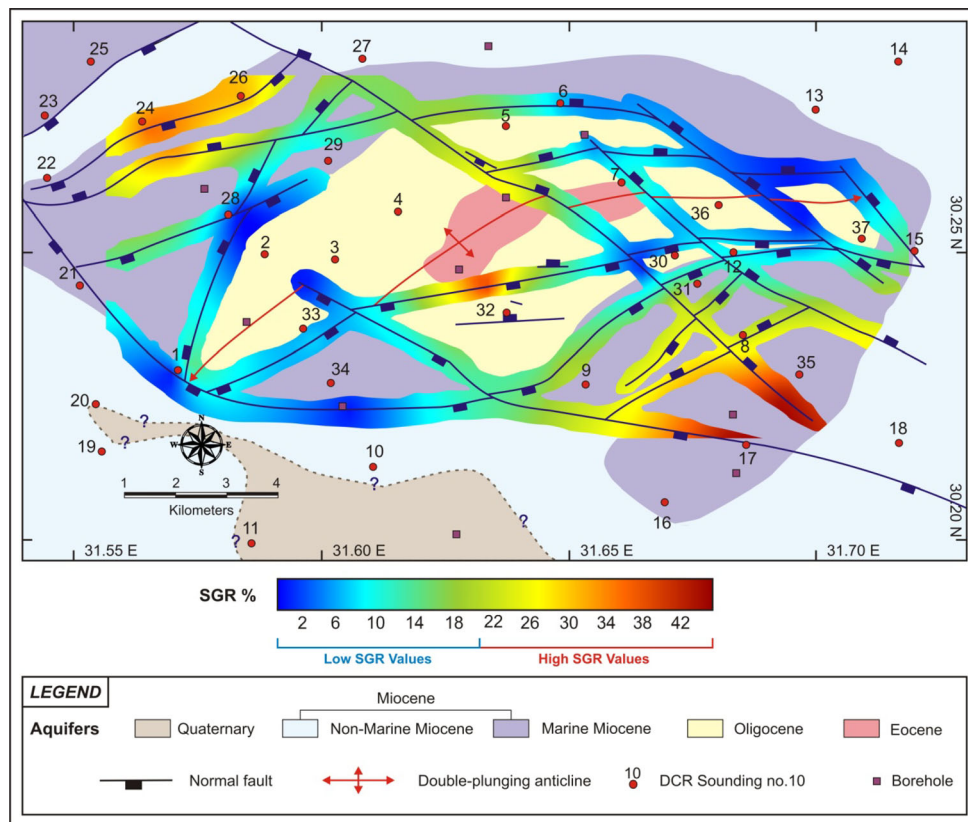


Figure 11. Subcrop map at depth = 0 m with spatial distribution of calculated shale gouge ratio (SGR) values along normal fault segments.

other hand, where the wall rocks are isotropic (e.g., sand juxtaposing sand) and where shale interbeds are lacking, high resistivities are dominant along fault planes and within faults zones. Consequently, conduit-barrier hydrogeological fault systems (e.g., Bense and Person 2006) are expected in our case study considering the strongly fault core anisotropic nature.

Hydrogeological Implication

Based on borehole data and layer resistivity distributions, inspection of the constructed geo-electrical cross sections (Figs. 8 and 9) shows three main aquifers (i.e., Miocene, Oligocene and Eocene aquifers). At the fold core (soundings No. 7 and 4, Figs. 8 and 9), a medium resistivity layer (~ 70 – 100 O-m) corresponding to Eocene limestone with shale intercalations constitutes the main aquifer attributing to the regional uplift. It can be observed

that the Eocene aquifer is of limited extension at the fold core. On the other hand, the medium-to-low resistivity layer (~ 20 – 80 O-m) corresponding to Miocene aquifers (marine and non-marine) can be well observed toward the fold limbs (i.e., NE and SE directions). Around the fold core, the Oligocene sand and gravel aquifer can be well observed. Because the Oligocene deposits are represented by sand and gravel within and basalt fragments (Abou Heleika and Atwia 2015), the Oligocene aquifer is characterized by higher resistivity values (~ 100 – 200 O-m) compared to the surrounding aquifers (i.e., Miocene aquifers). Consequently, the aquifers distribution is controlled by regional structures (i.e., faults and the overall domal structure).

For sealing assessment of fault planes, SGR was calculated for 52 points (at 0 m depth) along normal fault segments affecting the study area in the light of Vsh and fault throws (Fig. 4). Because the average water table depth is ~ 0 m, a subcrop map was constructed at depth = 0 m, where the calculated

SGR values were plotted to show the spatial distribution of sealing capacities along normal fault segments (Fig. 11). Calibration has verified that faults with SGR values $> 20\%$ have a higher chance of seal (e.g., Yielding et al. 1997; Ladevèze 2019).

The results revealed that high SGR values (i.e., $> 20\%$) are intense at both limbs of the G. Hamza domal structures where Miocene marine sediments are juxtaposed against each other along fault segments. In addition, high SGR values are found at the core of the domal structure. The above-mentioned results suggest that high SGR values are dominant where the shale smears are dominant at the Miocene shaly marine beds. Moreover, the presence of shale interbeds in Eocene rocks (i.e., fold core) plays a role in increasing the SGR values of such segments. In contrast, the low SGR (i.e., $< 20\%$) values at most the fault segments suggest the presence of less and/or lack of shale gouge along fault planes. Such low SGR values are dominant where sand-rich rock units (e.g., Oligocene and Miocene non-marine rocks) are juxtaposed against each other or against the shaly and/or sandy beds of the Miocene marine rocks. Consequently, the SGR values are greatly controlled by the structural juxtaposition of rock units, which in turn is controlled by the distribution of throws along each fault segment. Hence, at a static level, every single fault segment can partly act as a barrier or a conduit for groundwater flow across faults.

The resultant model in the light of spatial distribution of SGR values reflects that the groundwater flow could have a path that is controlled by the overall structural architecture. Therefore, the model shows that groundwater is more favorable to have a flow pathway parallel to the axial plane of the G. Hamza dome (i.e., toward the ENE direction) rather than to flow perpendicular to the axial plane of such dome (i.e., toward the WNW and NW directions). Accordingly, the groundwater flow direction can be from SW to ENE directions with expectation of mixing between Miocene and Oligocene aquifers (i.e., aquifers connectivity). On the other hand, Figure 11 reflects the disconnectivity between Eocene and surroundings aquifers (Miocene and Oligocene), where the surrounded faults are characterized as sealed especially at southeastern parts of G. Hamza. Notably, the results of our study using the suggested approach (Fig. 5) coincide with the previous hydrogeological studies of aquifers occurrence and groundwater flow directions along CSD (e.g., RIGW 1994; El Haddad 2002; Abou Heleika and Atwia 2015).

CONCLUSIONS

An integrative approach using geological, structural, borehole and geophysical data has been demonstrated for (1) delineating structural controlled aquifers and (2) understanding groundwater flow paths around and/or across fault zones. The present study is considered more accurate and faster than traditional hydrogeological studies using only drilled boreholes and hydrochemical analysis. The proposed approach was used to delineate the main structural elements in a fault-related domal structure. Additionally, sealing potentialities of fault segments have been calculated using the SGR method. Accordingly, the study has offered a model that can be taken in consideration while searching for groundwater resources in highly deformed areas.

This study has shown that a better understanding of geophysical data is essential to (1) produce a reliable subsurface structural model with low uncertainties and (2) assess a preliminary hydrogeologic setting especially when extensive conventional drillings are not available. The present study has proven that the joint use of DCR soundings and ERT data, calibrated with structural and borehole data, is valuable for optimal understating the aquifers geometry/connectivity. Moreover, fault zones characterization and seal potentialities of fault zones should always be taken in consideration where dealing with structural controlled aquifers. We conclude that it might be possible to predict the water flow direction and aquifers connectivity of given fault zones applying an integration of structural analysis, ERT and SGR data.

The present approach summarized above can be applied to improve the hydrogeological modeling studies of structural complex basins. However, fault-related dome structure needs special consideration in understating the water flow rates and/or directions in and around fault damage zones. Further studies including pumping tests and fault zone permeability measurements may offer a more robust and reliable route for predicting the subsurface fluid flow properties.

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