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Groundwater exploration and evaluation by using geophysical interpretation (case study: Al Qantara East, North Western Sinai, Egypt)

Sultan Awad Sultan · Hatem M. Mekhemer · Fernando M. Santos

Abstract Different geophysical tools such as geoelectric, gravity, and magnetic have been applied to detect groundwater potentiality and structural elements, which controlled a geometry of the groundwater aquifers in the study area. Nineteen vertical electrical soundings measured using ABEM SAS 4000 equipment through Schlumberger configuration of AB/2 ranged from 1.5 to 1,000 m; the quantitative interpretation was carried out using manual and analytical techniques. The results of quantitative interpretation used to construct six geoelectrical cross-sections indicate that the subsurface sequence of the study area consists of seven geoelectrical units. These units are Quaternary sand sheet and sand dunes, Quaternary aquifer, marly limestone, clay, sandy clay, clay with sandstone intercalation, and deep Nubian sandstone aquifer. The isopach map of the Quaternary aquifer exhibits thickness of the Quaternary aquifer that increased at the northern and southern part (50 m) and decreased at the eastern and western part (5 m), and the depth of the aquifer increased at the northern part (40 m) and decreased at the central part to 6 m. The isoresistivity map of the aquifer shows a high resistivity at the northern part but the southern part reveals low resistivity according to the lithology. The water salinity increases in the direction of groundwater flow from 500 to 10,500 mg/l. The low water salinity is due to direct recharge from El-Sheikh Zayed Canal, which supplied fresh water to this area. Sixty-five gravity stations were measured using Auto-Grav gravity meter; different gravity corrections were applied on raw data. The corrected gravity values were plotted to represent a Bouguer anomaly map; the residual gravity anomaly map was used for delineation of the fault elements. The area was dissected by different fault elements of trends NW–SE, NE–SW, and E–W. In addition, 65 ground magnetic stations were measured at the same sites of gravity stations. The results of magnetic interpretation indicate that the depth of the basement is shallow at the western and southern parts of the area (4,500 m), but the central part exhibits greater depth of 7,900 m.

Keywords Groundwater aquifers · Geophysical tools · Schlumberger configuration

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Introduction

Some groundwater aquifers in Sinai are still ambiguous. More efforts carried are out to investigate these ambiguous aquifers. In this study, the integrated geoelectric, gravity, and magnetic interpretation can give reasonable results and clear picture about the subsurface formations. This study is complementary for Bedouin settlement project. Integrated geophysical tools, especially resistivity, electromagnetic, and, more recently, the nuclear magnetic resonance methods, are commonly used in groundwater exploration mainly due to the close relationship between electrical conductivity

and some hydrological parameters (Goldman and Neubauer 1994). Gravity method is used in groundwater exploration and in the detection of structural trends controlling the regional geometry of the groundwater aquifers (Murty and Raghavan 2002). Magnetic method is an important tool to detect the upper surface of the basement and, indirectly, the thickness of the sedimentary cover. Many geophysical investigations have been carried out around the study area. Sultan and El Sorady (2001), Ibrahim et al. (2004), and Monteiro Santos et al. (2006) studied groundwater potentiality at the northern and eastern parts of the study area. The aim of the present study is essentially for groundwater exploration of Quaternary and Nubian sandstone aquifer, evaluating structural elements which are dissecting study area and are controlled on the geometry of the aquifers, determining depth of the basement and defining sedimentary basins, which may contain oil accumulations. Two main surface canals intersect the study area. El-Salam Canal is located at the northern part of the study area. El-Sheikh
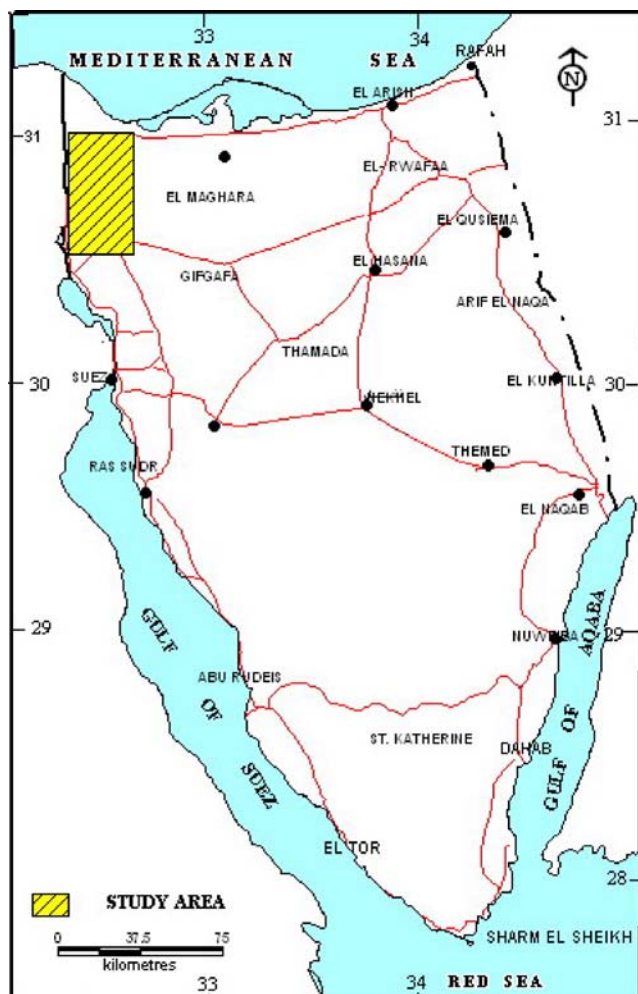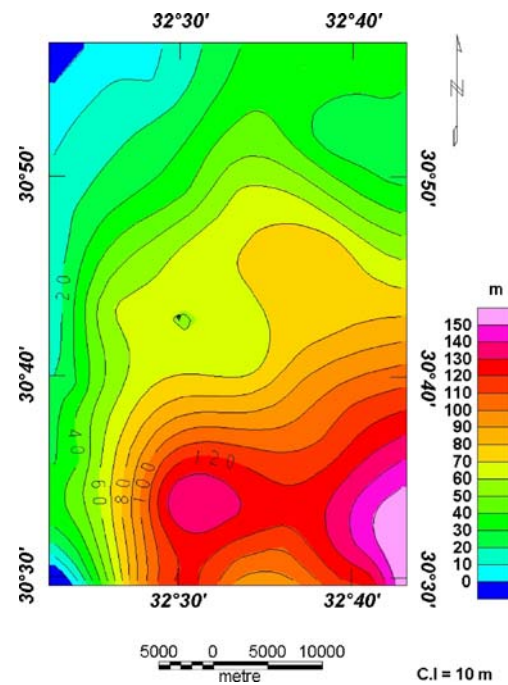

Fig. 2 Topographic map of the study area

Zayeid Canal is located at the eastern part of the study area. Those two canals can contribute appreciable amounts of fresh water to the groundwater aquifers especially the Quaternary aquifer. Study area is located at the eastern bank of the Suez canal of northwestern part of Sinai around Al
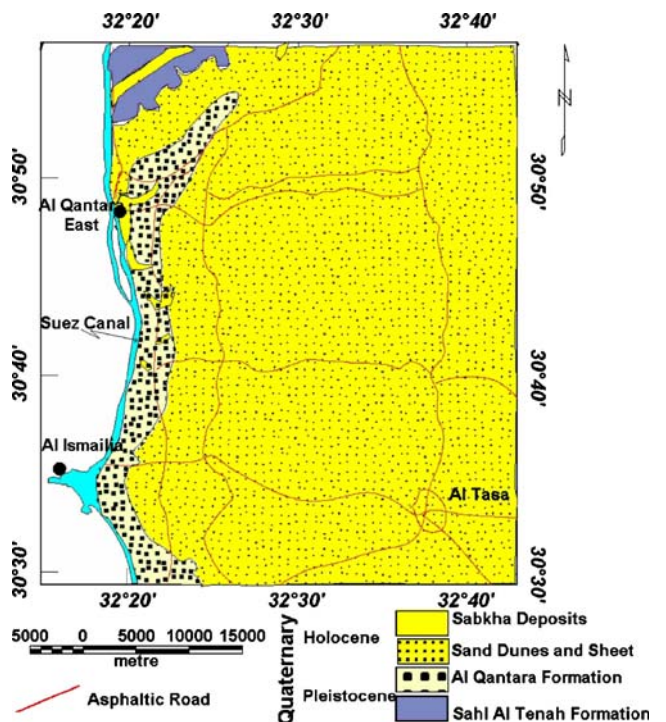

Fig. 1 Location map of the study area

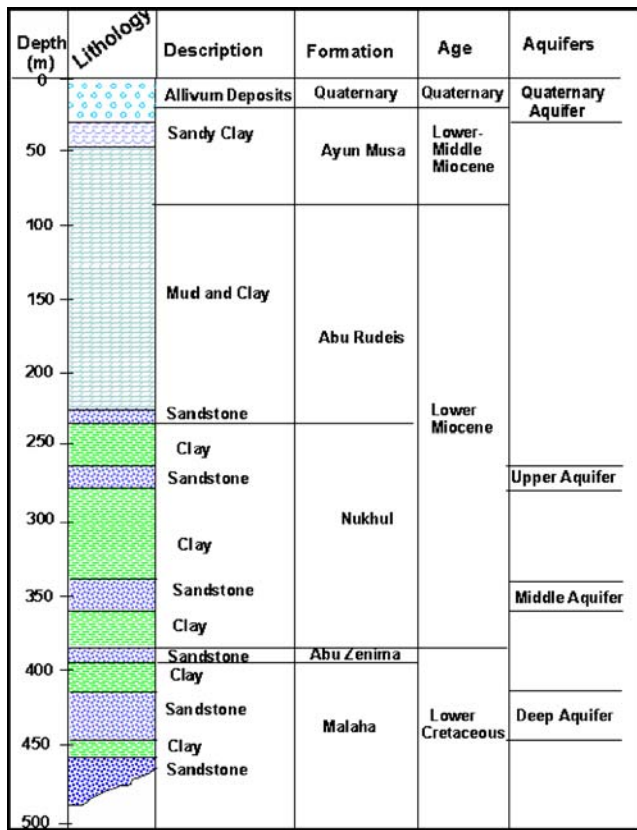Fig. 3 Geologic map (modified after UNSECO Cairo Office 2005)

Fig. 4 Al Qantara borehole

Qantara East and lies at latitudes 30° 29′ 35″ and 30° 56′ 43″ N and longitudes 32° 22′ 34″ and 32° 43′ 06″ E and represents an area of 1,648 km² as shown in Fig. 1.

Geomorphology

Generally, the study area exhibits low land topography and covered by sand sheets and sand dunes. The topographic map of the study area, as shown in Fig. 2, reveals a gentle slope in northwestward direction. The elevation changes from 150 to 10 m asl.

Geology of the study area

The surface geology has been described through a geological map of Sinai, which was constructed by the UNSECO Cairo Office (2005). The geologic units belonging to the Quaternary deposits were divided into Holocene and Pleistocene. Pleistocene includes two formations: The first is Sabakha located at western part of the area beside the eastern bank of Suez Canal and at the northwestern part of the area. The second formation is represented by sand sheet and sand dunes, where it covers most of the study area. The Pleistocene deposits are represented by two

formations: The first is the Al Qantara Formation, which consists of sand and grill with minor clay inter-beds, and the second Formation is Sehl Al Tinah Formation, which consists of a mixture of black and white sand and silt as shown in Fig. 3. The subsurface stratigraphy sequences were described from borehole at distance of 60 km south the study area at Ayun Musa Coast Village at latitude of 29° 50′ 31″ and longitude 32° 39′ 36″ of depth 500 m. The stratigraphy of this borehole is composed of alluvium deposits up to 30 m depth, Middle Miocene of depth from 30 to 80 m, and represented by Ayun Musa Formation, which consists of sandy clay. Lower–Middle Miocene is represented by two formations: first one is Abu Rudeis Formation, a depth from 80 to 230 m and consists of mud and clay; second formation is Nukhul Formation, which is composed of clay and sandstone. The Miocene deposits overlay Lower Cretaceous, which is represented by Malah Formation and consists of sandstone intercalated with clay and represented the deep Nubian sandstone aquifer in the area as shown in Fig. 4.
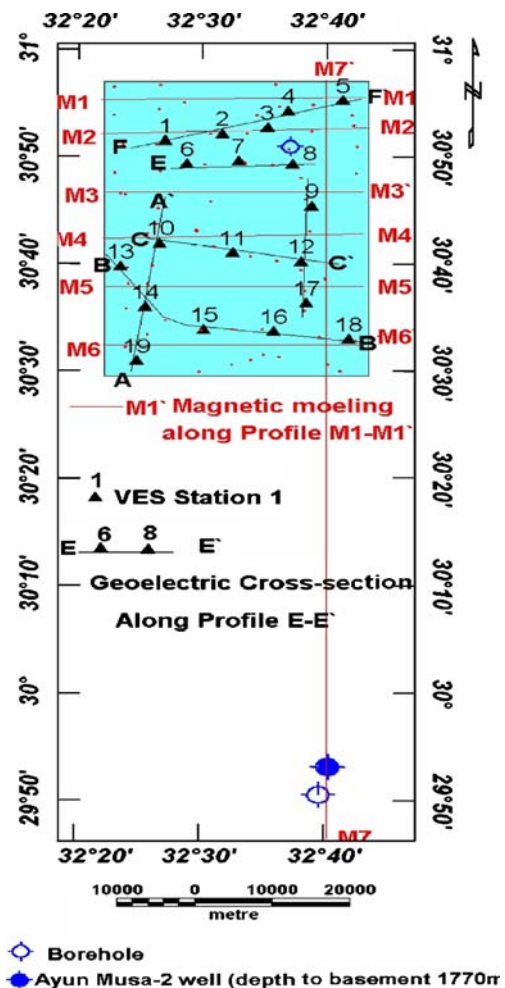

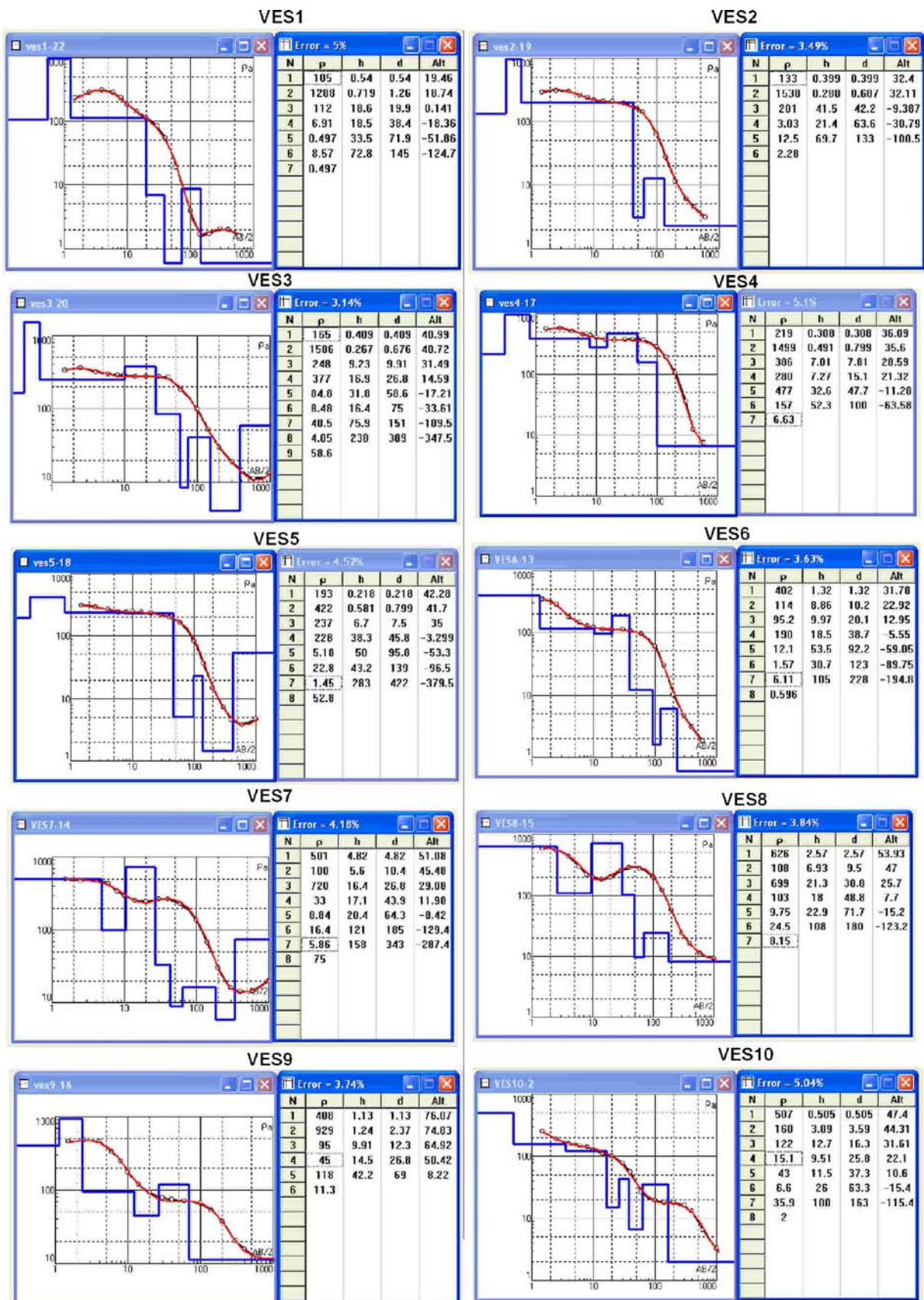Fig. 5 Location of VES, gravity, and magnetic measurements profiles

Fig. 6 **a** Interpretation of VES stations from 1 to 10 using IPI2win software. **b** Interpretation of VES stations from 11 to 19 using IPI2win software
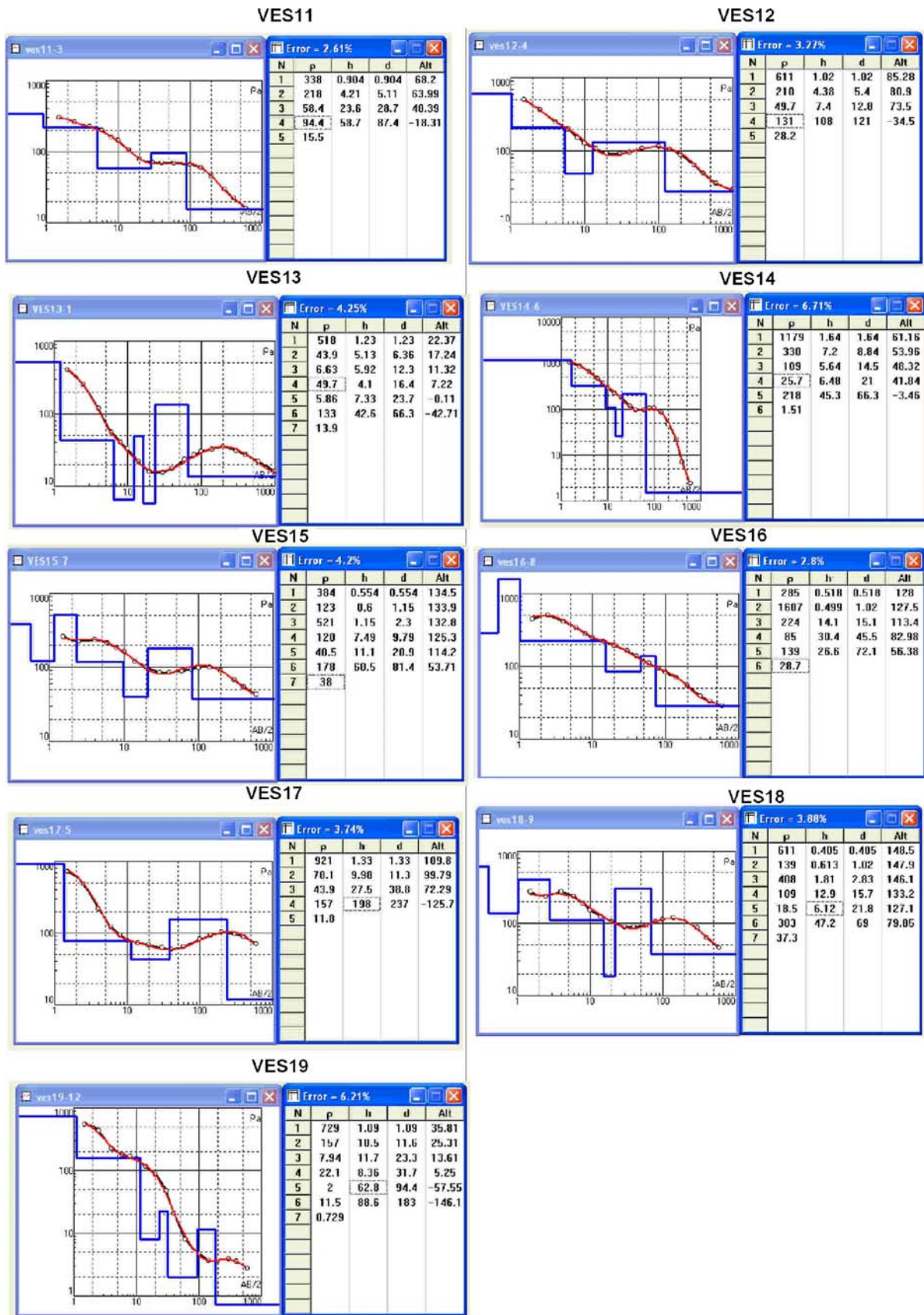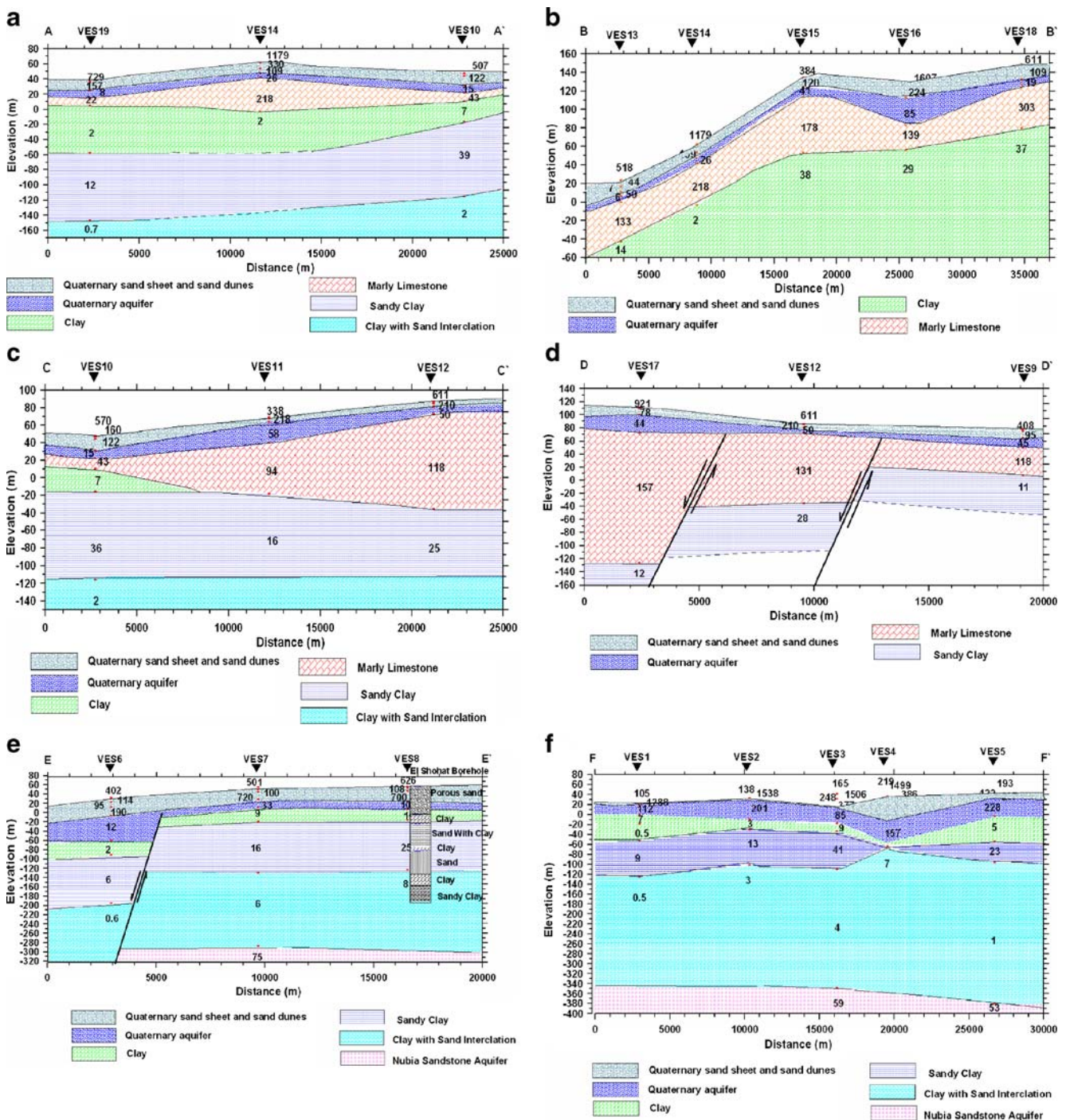
Fig. 6 (continued)

Fig. 7 Geoelectric cross-section along profiles A, B, C, D, E, and F

Hydrogeology

In the area of study, two potential aquifers were nominated. The first aquifer is represented by the Quaternary deposits and occupied the area to the north of Suez Canal—El-Tasha road. It is composed of sand intercalated with silt and clay. Generally, the groundwater is flowing toward the north-

west. The water salinity increases in the direction of groundwater flow from 500 to 10,500 mg/l. The low water salinity is due to direct recharge from El-Sheikh Zayed Canal, which supplies fresh water to this area. The depth to water table changes from 2 to 28.2 m. Referring to hydraulic parameters of the aquifer, the calculated transmissivity is about 300 m²/day. The measured total

Fig. 8 **a** Depth map of Quaternary aquifer. **b** Isopach map of Quaternary aquifer. **c** Isoresistivity map of the Quaternary aquifer
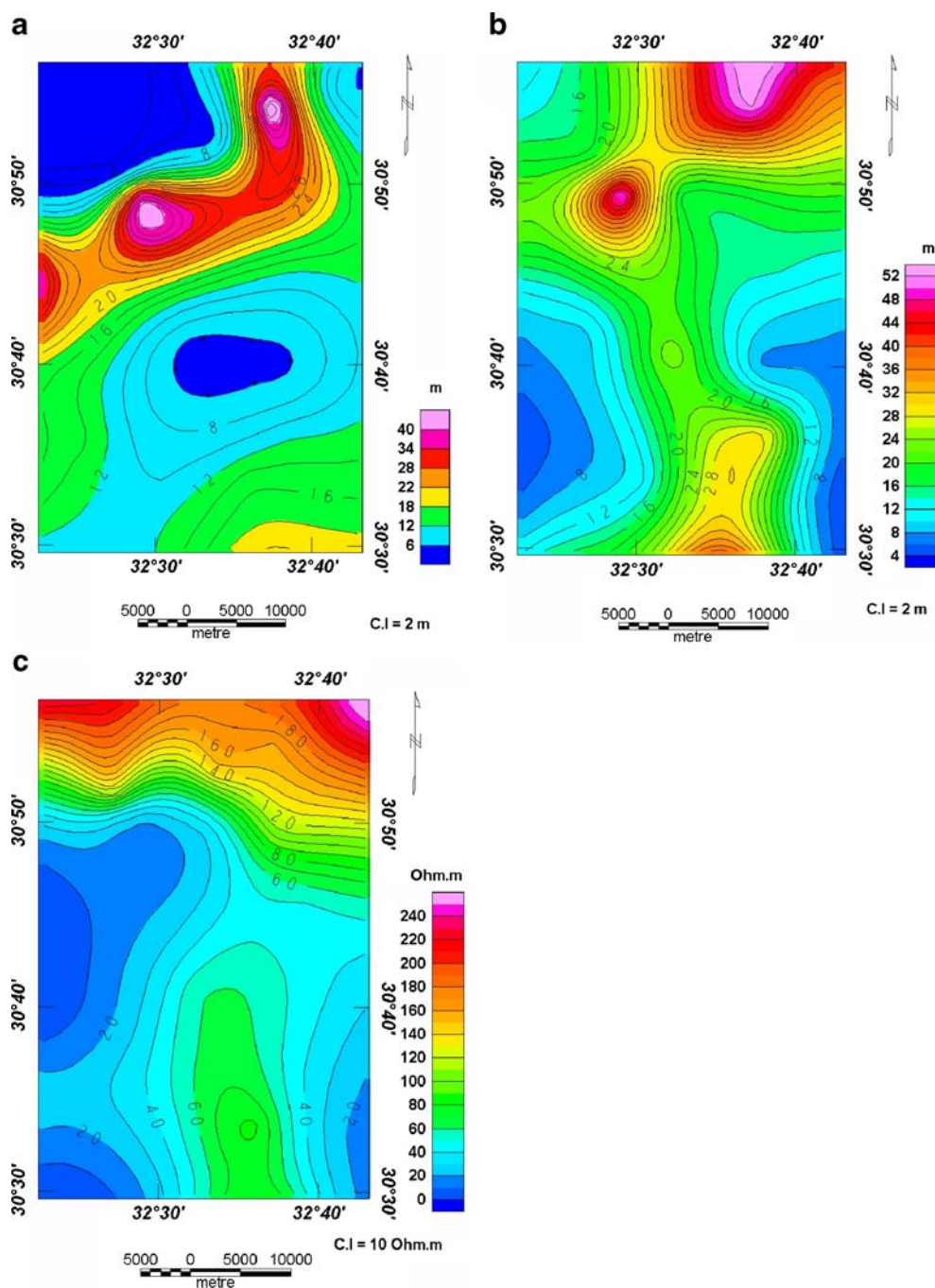
abstraction is 10,000 m^3/day, while the estimated aquifer recharge is about 40,000 m^3/day.

The second aquifer is the main aquifer in Egypt and named Nubia aquifer. It occupied the southern part of the study area, the site of Ayiun Mousa village. The Nubian sandstone aquifer is a natural discharge aquifer for the Nubia in Sinai where the water is naturally gushing from springs. In this area, the estimated transmissivity is very low where it changes from 1.9 to 3.2 m^2/day. The water salinity ranges between 2,500 and 5,000 mg/l.

Table 1 Correlation factor for different orders

Order	Value
r_{12}	0.7584
r_{23}	0.4728
r_{34}	0.25965
r_{45}	0.9999

Fig. 9 a Bouguer anomaly
map. b First-order regional
Bouguer anomaly map.
c First-order residual
Bouguer anomaly map.
d Second-order regional
Bouguer anomaly map.
e Second-order residual Bou-
guer anomaly map. f Third-
order regional Bouguer anomaly
map. g Third-order residual
Bouguer anomaly map.
h Fourth-order regional Bouguer
anomaly map. i Fourth-order
residual Bouguer anomaly map.
j Fifth-order regional Bouguer
anomaly map. k Fifth-order
residual Bouguer anomaly map

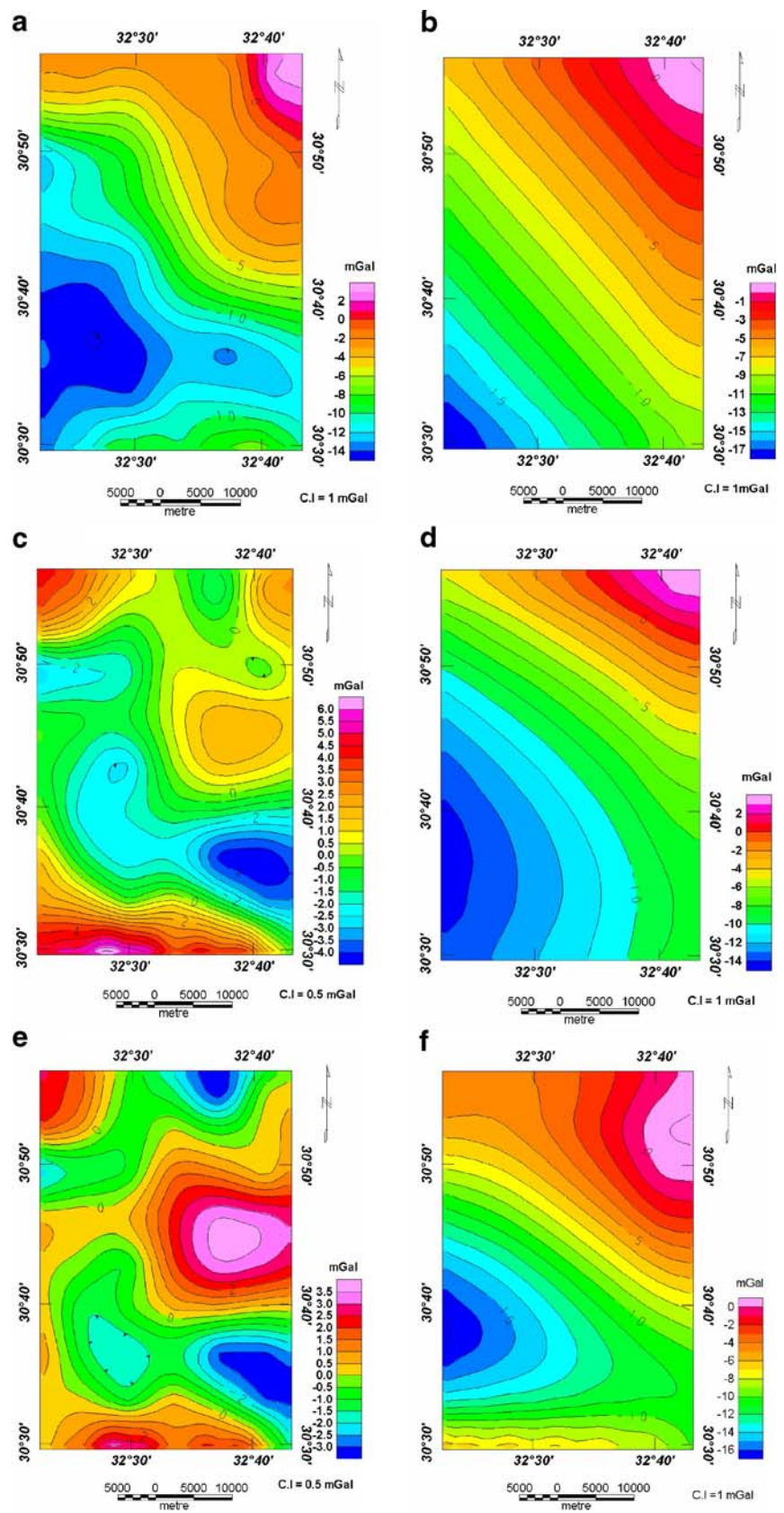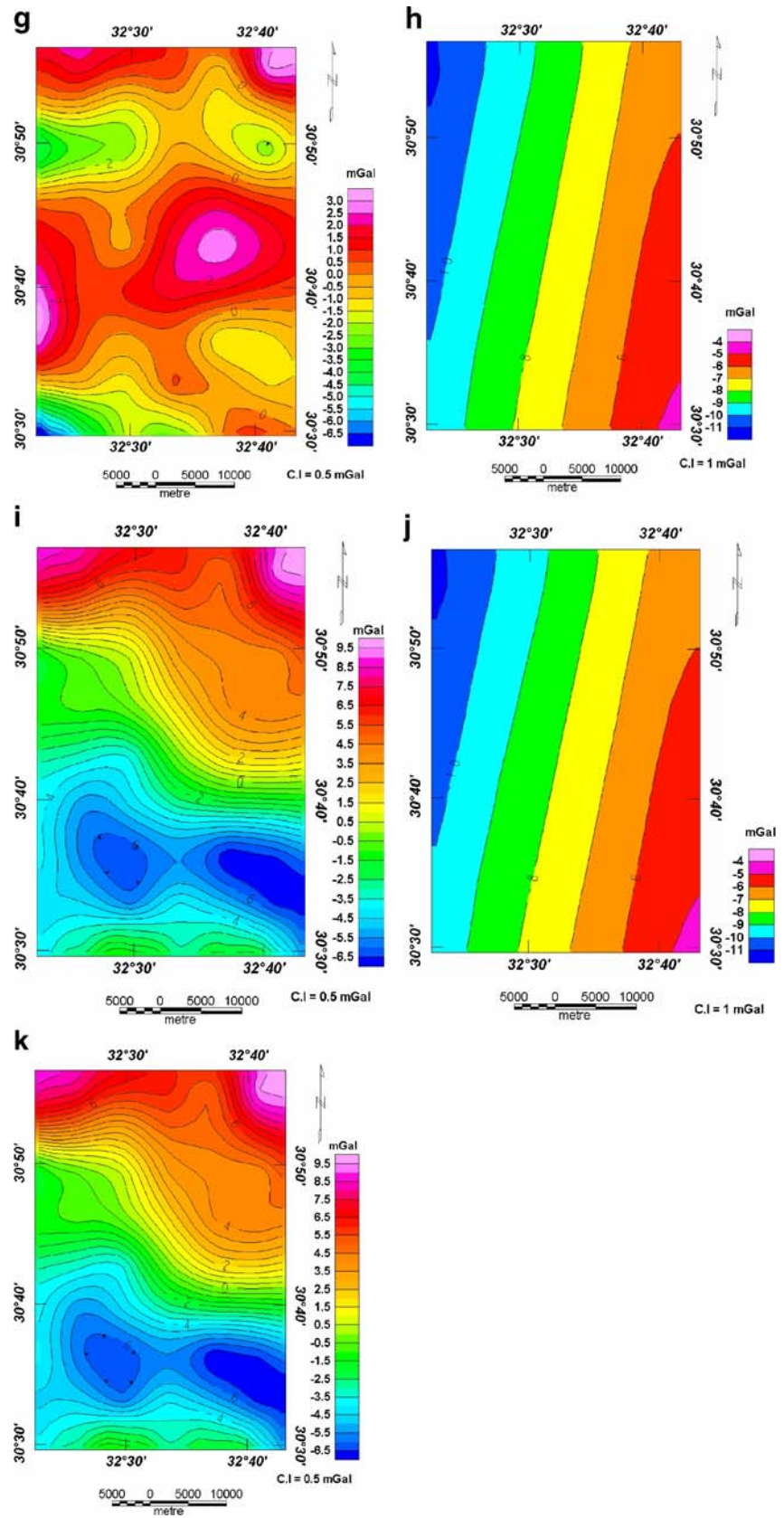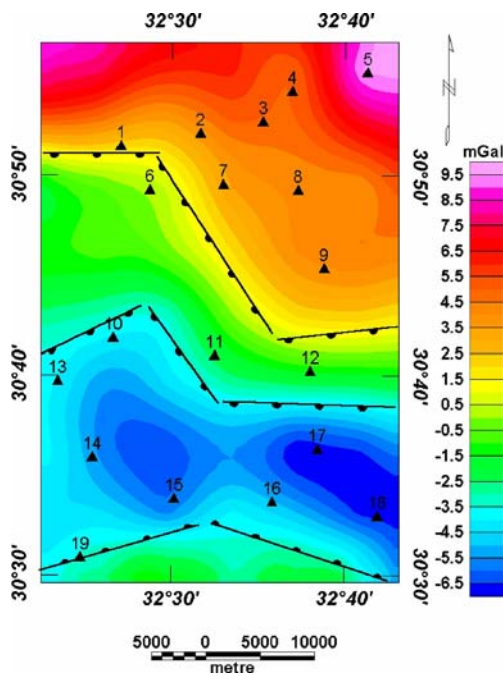**Fig. 9** (continued)

Fig. 10 Fault elements dissecting study area from gravity interpretation

## Geoelectrical measurements and interpretation

The geoelectrical data in the present study area, represented by 19 vertical electrical soundings (VES) as shown in Fig. 5, were undertaken with AB/2 spacing ranging from 1.4 to 1,000 m. The quantitative interpretation of vertical electrical soundings was carried out using a graphical method based on the two layer curves and the generalized Cagniard graphs (Koefoed 1960). The results of manual interpretation were used as the initial models for the

IPI2WIN-1D Program (2000) software in order to compute the true depths and resistivities of the one-dimensional model for each VES curve (Fig. 6a and b). This program uses a linear filtering approach for the forward calculation of a wide class of geological models, depending upon regularized fitting minimizing algorithm using Tikhonov's approach (Bobachev et al. 2001; Gian et al. 2003; Chuansheng et al. 2008). One borehole (El Shohat borehole) drilled beside VES 8 was utilized for the correlation and calibration of VES curve parameters (layer resistivity and thickness). As shown in Fig. 7, the results of VES interpretation are used to construct six geoelectric sections, A, B, C, D, E, and F, as shown in Fig. 7 a–f, respectively. The geoelectric cross-sections exhibit seven geoelectric units: The first unit is the Quaternary sand sheet and sand dunes of high resistivity values. The second unit is the Quaternary aquifer and reveals moderate to high resistivity and reflects the presence of fresh water-bearing zone. The third unit is marly limestone of high resistivity, and this unit disappears at the northern part of the study area. The fourth unit is clay of low resistivity values overlaying sandy clay of moderate resistivity, which represents the fifth unit. The sixth unit is the clay with sand intercalation and reveals very low resistivity overlaying the last unit. The last unit reflects moderate to high resistivity value, which characterizes the deep Nubian sandstone aquifer of brackish to fresh water.

Depth map of the Quaternary aquifer

The depth of the Quaternary aquifer varies a few meters (2–4 m) at the northwestern part and central part, but the northern and western parts exhibit deep depth of about 40 m as shown in Fig. 8a.

Fig. 11 a Total intensity magnetic map. **b** Total intensity magnetic map reduced to the pole
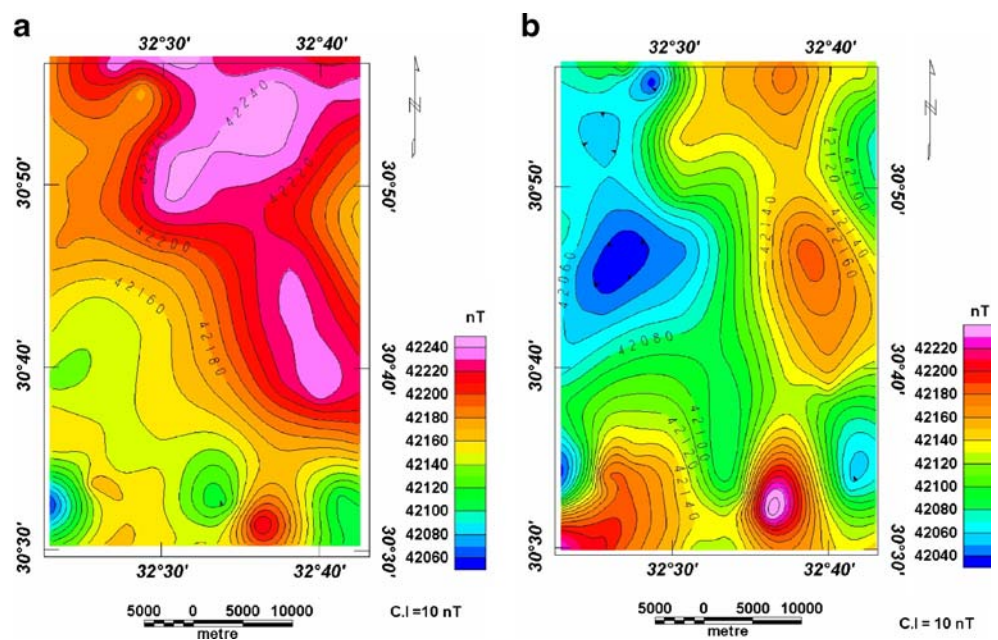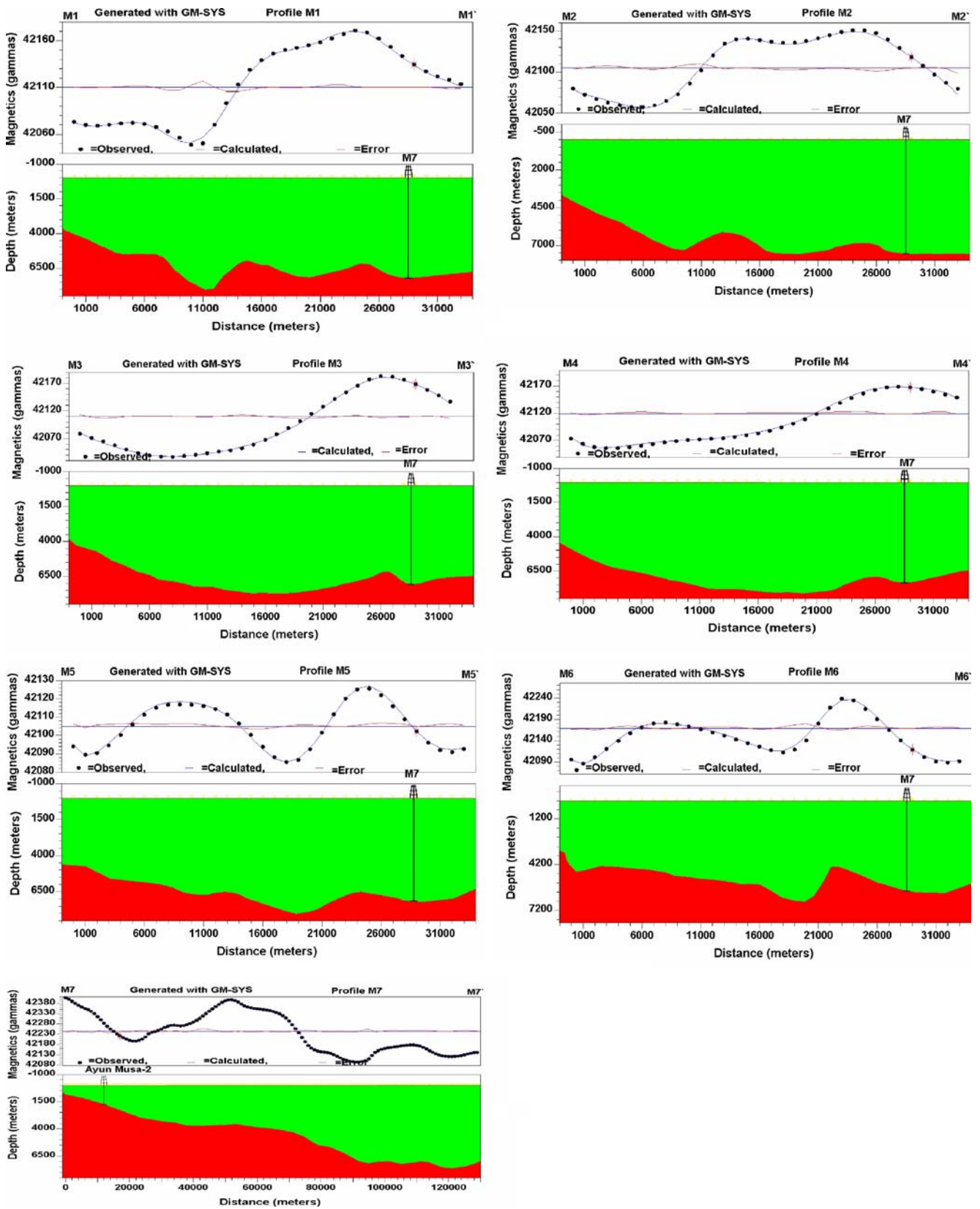
Fig. 12 2-D magnetic modeling along profiles *M1*, *M2*, *M3*, *M4*, *M5*, *M6*, and *M7*

Isopach map of Quaternary aquifer

Thickness of the Quaternary aquifer is increased at the northern and southern parts (40–52 m), but thickness is decreased at the eastern and western parts of the area (6 m) as shown in Fig. 8b.

Isoresistivity map of Quaternary aquifer

Resistivity values of the Quaternary aquifer vary from low resistivity values (10 Ω m) at the southern, eastern, and western parts of the area to high resistivity (200 Ω m) at the northern part of the area. This is because the water is fresher at the northern part due to seepage from El-Sheikh Zayed Canal (branch of River Nile) as shown in Fig. 8c.

Gravity measurements and interpretation

Sixty-five gravity stations were carried out using Auto-Grav (CG3) gravity meter of sensitivity of 0.01 mGal. The measured gravity values were corrected to different gravity corrections such as drift, tide, free-air, Bouguer, latitude, and topographic corrections using specialized software (Geosoft 1998). The corrected gravity values were used to plot Bouguer anomaly map using Oasis Montaj 1998. Bouguer anomaly map in Fig. 8a exhibits high-gravity anomalies at the northern and northeastern parts (2 mGal), but the western part reveals low-gravity anomalies (−15 mGal). The regional–residual separation technique was carried out to filter the regional component, which was related to deep-seated sources, and residual component, which was related to local sources. In the present study, authors used least squares technique to apply the gravity separation, calculations for different order up to the fifth order to estimate the best order of separation as shown in Fig. 9b–k. The correlation factor was calculated for every two successive orders such as the correlation factor for first and second order (r_{12}). Table 1 shows that the best order for gravity separation is the fourth order. The fourth-order residual gravity map was used for gravity interpretation to detect the structural elements that dissect study area and controlled for the geometry of the groundwater aquifers. The fault map, as shown in Fig. 10, shows different fault elements of different directions such as NW–SE trend parallel to the Gulf of Suez, NE–SW trend parallel to Gulf of Aqaba, and E–W trend parallel to the Mediterranean Sea.

Magnetic measurements and interpretation

Sixty-five ground magnetic stations have been measured using Envi-mag proton magnetometer of sensitivity 1 nT;

two instruments were used one for field work measurements and the other one for base station recording to estimate diurnal variation correction; also, IGRF correction was done for magnetic data. A corrected ground magnetic data were contoured using Oasis Montaj 1998 software to represent total intensity magnetic map as shown in Fig. 11a. In order to overcome this distortion in the appearance of an anomaly, which depends on the magnetic latitude of the survey area and on the dip angle of the magnetization vector in the body, a mathematical procedure is adopted on a grid values for the contour map of the total magnetic intensity. Therefore, the interpretation of the magnetic data starts with the conversion of the total intensity map into a more interpretable map and then reduced to magnetic pole map using magnetic inclination 45.17°, magnetic declination 2.75°, and total field strength 43,469 nT. This mathematical procedure was first described by Baranov (1957), Baranov and Naudy (1964), Battacharyya (1965–1967), and Baranov (1975). The final picture is the total intensity map reduced to the pole as shown in Fig. 11b. Total intensity magnetic map was used for magnetic interpretation to estimate depth to the basement rocks through seven two-dimensional (2-D) magnetic modeling as shown in Fig. 12. 2-D magnetic modeling along profile 7 was taken to include a deep borehole that reached to
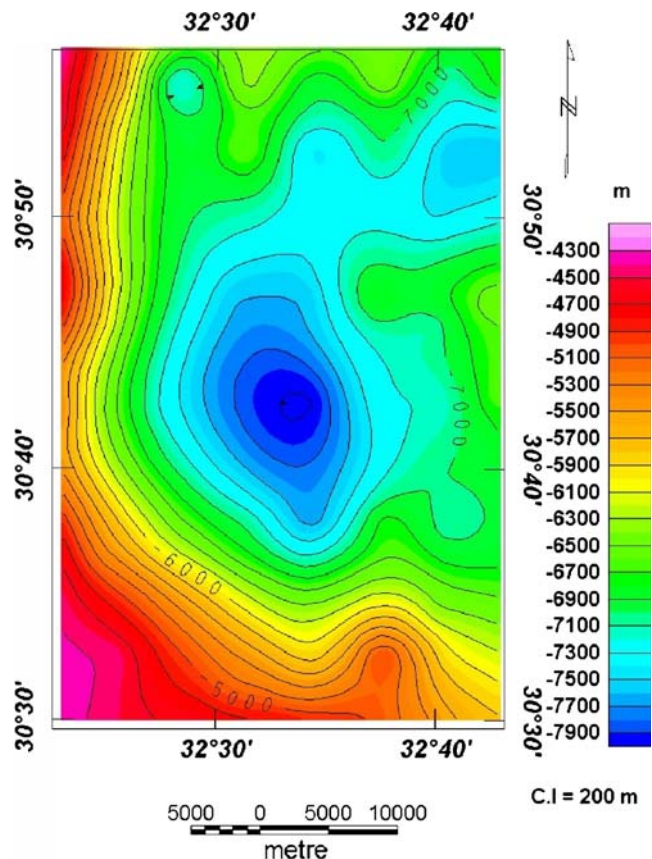

Fig. 13 Basement relief map

basement surface at depth 1,770 m (Egyptian General Petroleum Corporation (EGPC) 1986); this borehole is Ayun Musa-2 of latitude 29° 53′ 08″ and longitude 32° 40′ 20″. The borehole was used for calibration of 2-D magnetic modeling along profile M7 through GM-sys program produced by the Northwest Geophysical Associates Inc. USA (1998). The authors used average magnetic susceptibilities for the igneous rocks of 0.000750 cgs units and magnetization (m) 0.00398 emu/cm^3. The intersection points of profile M7–M7′ with other profiles, M1–M1′, M2–M2′, M3–M3′, M4–M4′, M5–M5′, and M6–M6′, were taken as indicators during the construction of magnetic modeling as shown in Fig. 12. The results of 2-D magnetic modeling were used to construct basement relief map Fig. 13, which indicates shallow basement depth at the western and southern parts (4,200 m) but the central part exhibits deep basement depth of 7,900 m. The magnetic and gravity results assist in determining the most appropriate location for drilling new wells.

Conclusion

The integrated interpretation for geoelectrical, gravity, and magnetic data indicated that the shallow section of the study area consists of seven geoelectrical units. The first unit represents Quaternary sand sheet and sand dunes of high resistivity behavior. The second unit is the Quaternary aquifer, which reveals moderate to high resistivity and reflects the presence of fresh water-bearing zone. The third unit is marly limestone of high resistivity, and the fourth unit is clay of low resistivity. The fifth unit is sandy clay of moderate resistivity. The sixth unit is clay with sand intercalations and reveals very low resistivity. The last unit reflects moderate to high resistivity value, which characterize the deep Nubian sandstone aquifer of brackish to fresh water. The study area dissected is by different fault elements of trends NE–SW, NW–SE, and E–W. In addition, the depth to the basement rocks varies from 4,200 m at the western and southern part of the area and 7900 m at the central part, which may represent a suitable location for oil accumulation. The water salinity increases in the direction of groundwater flow from 500 to 10,500 mg/l. The low water salinity is due to direct recharge from El-Sheikh Zayed Canal, which supplies fresh water to this area.

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