

## Microgravity investigation of an aquifer storage and recovery site in Abu Dhabi

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In this case study paper microgravimetry is used to investigate the geological structure of an area proposed for an aquifer storage and recovery (ASR) project in northeastern Abu Dhabi Emirate in the UAE. This study is a joint collaboration between the Environmental Agency - Abu Dhabi (EAD), Schlumberger Water Services, and the Petroleum Institute. The goal of the project is to explore the geological structure underlying the aquifer and to see if gravity can be used to help further delineate the lower aquifer boundary. The test site, approximately 4 km<sup>2</sup> in area, contains an aquifer 50 m below the surface which is bisected by a thrust fault running approximately north to south.

The pilot study sponsored by the Environmental Agency - Abu Dhabi (EAD) aims to test the potential for an aquifer storage and recovery (ASR) system in the Shuwaib area of Abu Dhabi Emirate. Schlumberger Water Services has been contracted by EAD to support the development of the test site by drilling and logging a set of site wells and by performing aquifer tests. The pilot study involves injection of desalinated water into the site's shallow aquifer, determination of water flow and mixing in the aquifer, and subsequent recovery and testing of water pumped from the site. Microgravity measurements have been conducted to investigate the underlying geological structure of the site and to explore the possibility of using gravity for further delineating the boundaries of the shallow aquifer. This work will help to support aquifer model development and to refine future planning of ASR tests and predictions for ASR system performance in this region. Current water demand and the planned near-term growth of Abu Dhabi and the rest of the UAE will require dramatically increased desalinated water production, fresh water storage capacity, and ground-water replacement. Consequently, it is expected that ASR will play a critical role in the future.

### Aquifer storage and recovery in Abu Dhabi

As of 2003, over 96% of the fresh water supplied for domestic and other uses in Abu Dhabi Emirate is produced

by desalination of brackish groundwater or imported desalinated seawater. This is due to recent massive increases in agricultural, forestry, domestic and industrial demand, with declining water table levels and increasing groundwater salinity. Despite increasing production costs and poor water quality, the remaining groundwater still remains an important resource for water management, particularly for emergency back up of desalinated water sources and for water supplies in remote locations.

A solution may be the use of excess production capacity of desalinated water to recharge existing shallow aquifers, through application of aquifer storage and recovery techniques demonstrated elsewhere (Brook, 2006). A key factor will be that modern desalination technology is considered a strategic option for satisfying current and future domestic water supply requirements in GCC (Gulf Cooperation Council) countries (Dawoud, 2005). Furthermore, use of ASR will allow long-term storage of at least one year of fresh water demand, a reasonable target given the similar lead time for constructing new desalination plants (Al Katheeri, 2007). As a consequence, in the last few years several ASR demonstration projects, such as the one in this study, have been initiated.

### Geological setting

The ASR test site of this study is located 10 km southwest of Shuwaib, east of Abu Dhabi on the western edge of the northern Oman Mountains (Figure 1). The test site is covered by low-relief sand dunes (~ 30 m high) and occupies an area of approximately 4 km<sup>2</sup>. The majority of the groundwater in the location's surficial aquifer is draining from the Oman Mountains toward the Arabian Gulf coast, about 125 km to the West.

Two major compressional tectonic events created the Oman Mountains and shaped the subsurface structures of surrounding region, including the study area. The first of these occurred during Late Cretaceous times. This event involved the emplacement of a number of thrust sheets, each of which has been emplaced from NE to SW onto the

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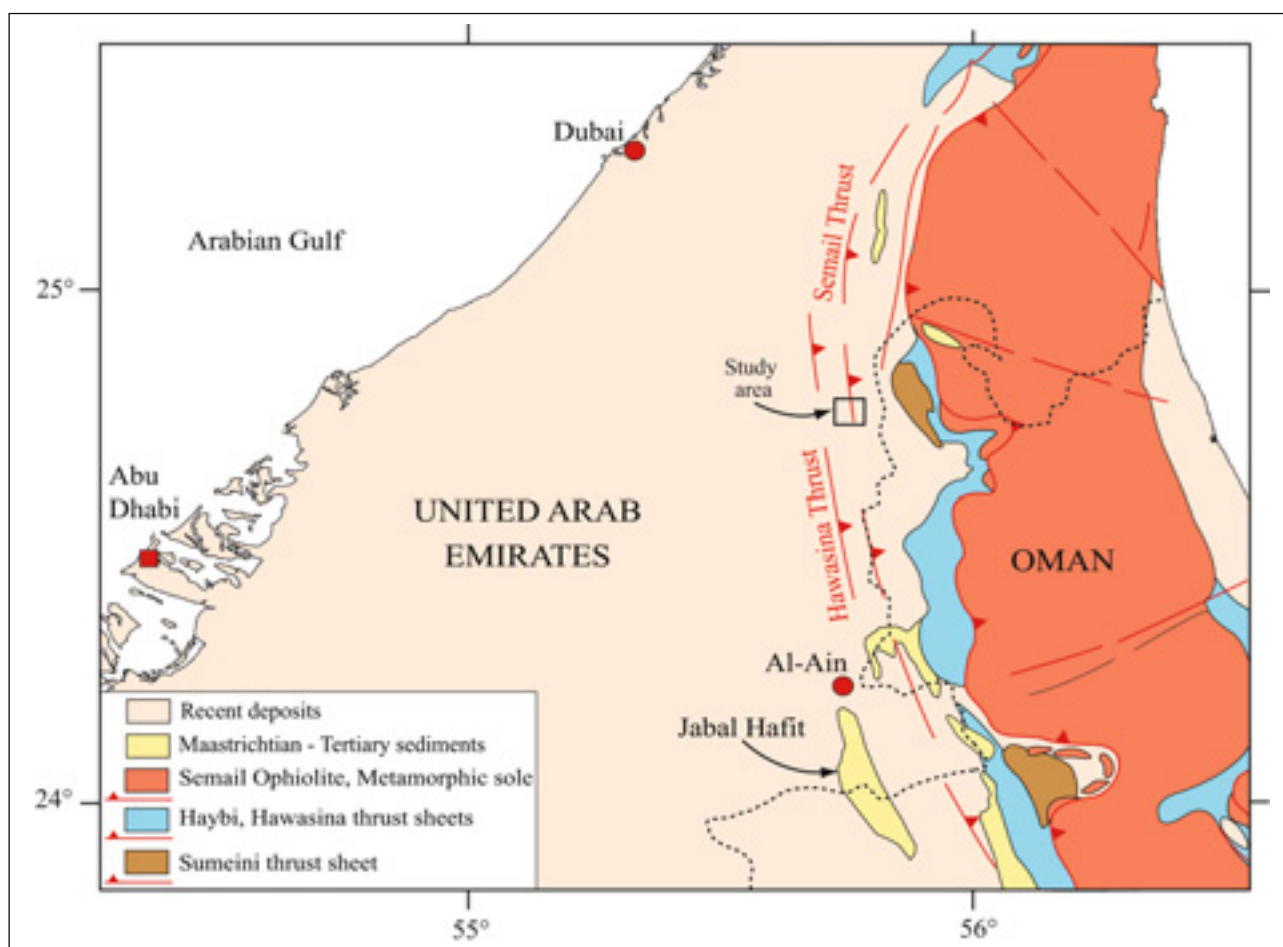


Figure 1 Location of the study area in the northeastern region of the Emirate of Abu Dhabi and on the flank of the Oman Mountains.

margin of the Arabian Plate. These thrust sheets, illustrated in Figures 1 and 2, consist of the Sumeini Group, comprised of shelf-edge and slope-carbonate sediments; the Hawasina Complex, comprising distal-slope and deep-sea sediments; the Haybi Complex, comprising Mesozoic exotic limestones, volcanics (Haybi volcanics), mélanges, and sub-ophiolitic metamorphic rocks; and the Semail Ophiolite complex, a massive slab of oceanic crust and mantle of Cenomanian-Turonian age, which formed above a NE-dipping intra-oceanic subduction zone.

A second compressional post-obduction event occurred in the Late Eocene-Miocene during which the Arabian Plate moved northeastward and collided with the Eurasian Plate (Searle et al., 1983). This event produced tight folds and thrust faults and the reactivation of deep-seated faults in the study area (Searle et al., 1990).

Woodward (1994) documented a number of tight folds and thrust faults that trend NNW-SSE in the area, based on structural interpretation of seismic reflection profiles. One of these major thrust faults that dip steeply to the east occur at

the centre of the study area (Figures 1 and 3). A goal of the microgravity measurements in the current study is to investigate the impact of this thrust fault on the ASR test site.

Figure 4 shows the stratigraphy of two wells drilled in the study area. Specifically, Figure 4a corresponds to well W3 and Figure 4b to well W4, as identified in Figure 3. The shallow sedimentary formation of the area is divided into four zones: Unsaturated Aquifer, Saturated Aquifer, Upper Fars, and Lower Fars. The surface consists of unconsolidated, quartz-rich sand dunes underlain by an aquifer. The bulk of the aquifer is composed of Quaternary unconsolidated aeolian sands, silt clays, and calcareous material deposited in paleochannels incised into Miocene mudstones and claystones. This surficial aquifer divides into two units, the upper Unsaturated Aquifer and the lower Saturated Aquifer. It is underlain by fine-grained Miocene sedimentary rocks which are subdivided into Upper and Lower Fars units. The Upper Fars unit consists of primarily claystone with interbedded dolomitic marls, limestone and silstones. The Lower Fars unit is comprised mainly of mudstone and evaporites. As determined from these well logs and

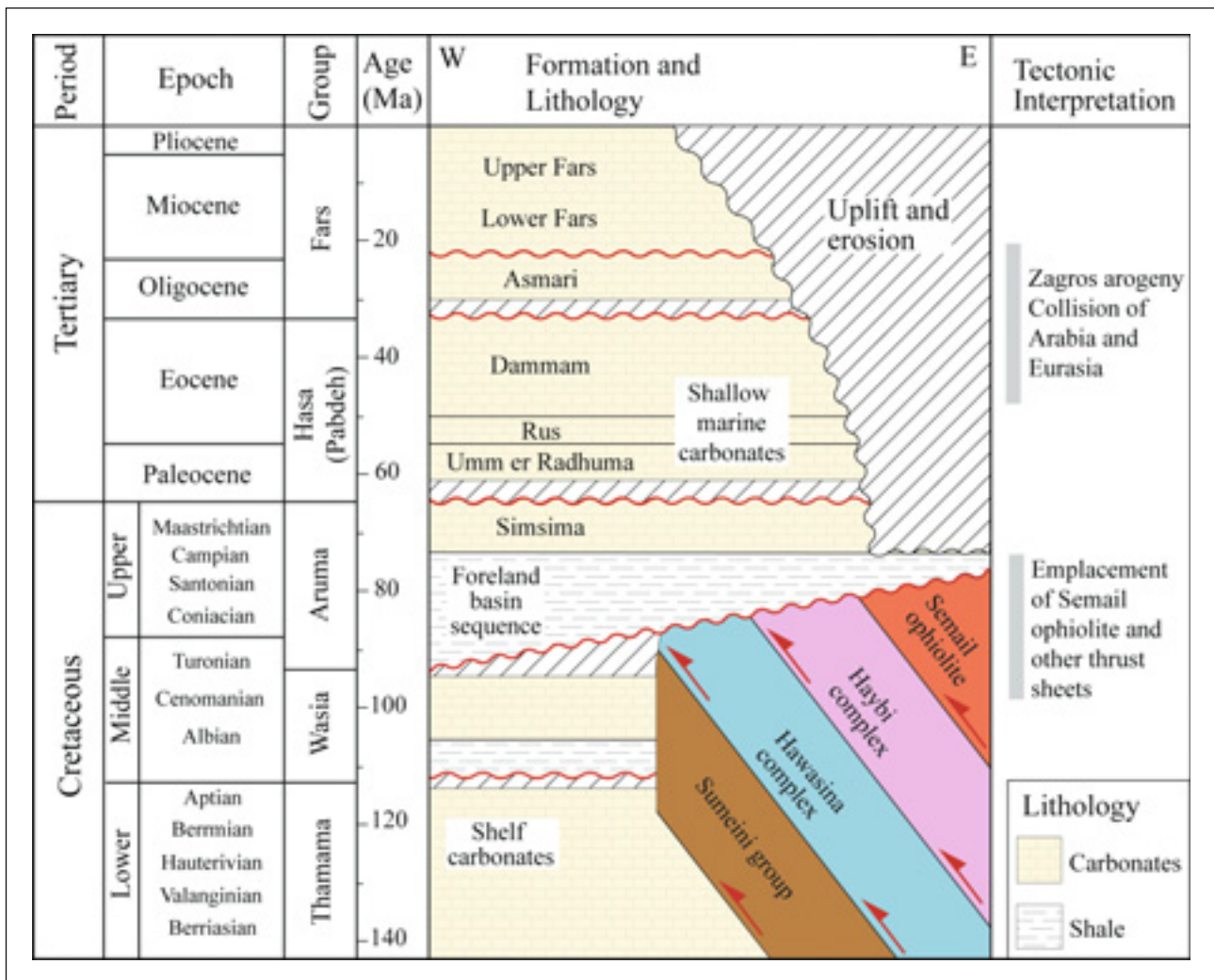


Figure 2 Stratigraphy column showing the recent Upper and Lower Fars formations and thrust sheets critical to the geology of the region.

others at the site, average unit densities are approximately 1.9, 2.1, and 2.35 g/cm<sup>3</sup> for the Unsaturated Aquifer, the Saturated Aquifer, and the Upper Fars units, respectively. Also, a single well located 60 m southeast of W4 was logged to a maximum depth of about 300 m, showing an average density of about 2.5 g/cm<sup>3</sup> for the Lower Fars unit.

**Gravity measurements**

Two parallel tracks were selected to cross perpendicular to the fault zone and to overlap with logged wells as shown in Figure 3. Using a handheld GPS (global positioning system) for navigation, points were flagged typically 50 m apart, gravity was measured using a Scintrex CG-5 gravimeter, and then a subsequent topographical survey was conducted by differential GPS. The northern track consists of a total of 44 surveyed points. Also 12 additional gravity measurements were taken before, during, and after this set of surveyed

points for subsequent gravimeter error checking and drift correction. A southern track consisting of a total of 46 points was obtained with an additional 11 gravity measurements for error checking and drift correction. Each gravity value is a 60 s sample average from the gravimeter. As shown, the two tracks are about 0.6 km apart, approximately 2.4 km long from West to East at an approximate bearing of 080° (10° North of East).

The gravity data was processed to account for earth tides, gravimeter drift, elevation, and regional variations in gravity. The earth-tides correction was calculated with the embedded software of the Scintrex CG-5 gravimeter, its algorithm based on the Longman formula (Longman, 1959). The resolution of the gravimeter is 0.001 mGal (1 × 10<sup>-8</sup> m/s<sup>2</sup>). A drift correction of 0.503 mGal/day was determined from repeated measurements at an on-site base station. An overall elevation correction of +0.227 mGal/m is used, based on an estimated

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free-air correction of +0.307 mGal/m and a -0.0797 mGal/m Bouguer correction (using the average surficial density of  $1.9 \text{ g/cm}^3$  from well logs). Since the points were measured along tracks with an approximate bearing of  $080^\circ$ , the positions are given as projected distances from West to East, for each track. Finally, a regional gravity gradient of +0.400 mGal/km (increasing eastward) was determined from a 1981 regional gravity study from the Abu Dhabi National Oil Company - Exploration Division (pers. comm.), which was then subtracted from the data. The two profiles are offset such that the southern profile has an average gravity anomaly of zero. The data is not referenced to any absolute gravity measurements.

After drift corrections, the gravity measurement repeatability was  $\pm 0.003 \text{ mGal}$ . The expected accuracy of the topographic survey is  $\pm 7 \text{ cm}$  in each direction, corresponding in the vertical direction to an elevation correction uncertainty of approximately  $\pm 0.006 \text{ mGal}$ .

### Gravity modelling

The gravity anomaly profiles are shown by the circular data points in Figure 5a for the northern profile and in Figure 5b for the southern profile. For each, the gravity anomaly is shown versus projected West to East distance. In Figure 5a the distance origin coincides with a local Easting of 370,000 m while for Figure 5b the distance origin coincides with an Easting of 370,250 m. The figure shows a West to East gravity increase of 2.07 and 1.82 mGal, for the northern and southern profiles, respectively, for an average West to East gradient of +1.0 to +1.2 mGal/km. Also, by comparing the minima of

the two profiles, there appears to be a South to North gravity gradient of approximately +0.7 mGal/km. The average gravity anomaly for the northern profile is 0.46 mGal greater than the southern profile.

Both profiles are compared to calculated gravity anomaly values produced by two-dimensional earth models. The models are shown in Figure 5 with the depth indicated on the vertical axes. The layer densities are indicated by color and the stratigraphic units are labeled. For this figure, zero depth corresponds to a site elevation of 270 m, the lowest elevation of any of the measured points. The wells that are coincident with the gravity profiles are shown in black, with maximum logged depths as indicated. The differences between the observed gravity anomalies and the model values are indicated by the difference between the thin blue and red lines.

The well logs provide constraints on the models. First, the site wells give a consistent water table elevation of about 240 m, corresponding to a fixed 30 m deep boundary between the unsaturated and saturated aquifer units. Second, the wells coincident with the gravity profiles constrain the boundaries of the shallow units. For W1, for example, the log indicates the bottom of the aquifer near the water table elevation and an average density rising to  $2.5 \text{ g/cm}^3$  at the bottom of the well. In contrast, W2 shows saturated aquifer for most of its depth and only a modest increase in average density toward the bottom. The fault inclination used in the model is estimated from the results of Woodward (1994). The gravity models clearly show consistent thrust fault locations of about  $1000 \pm 50 \text{ m}$ , as indicated by the bold red lines. If extrapolated toward the surface, the fault location is

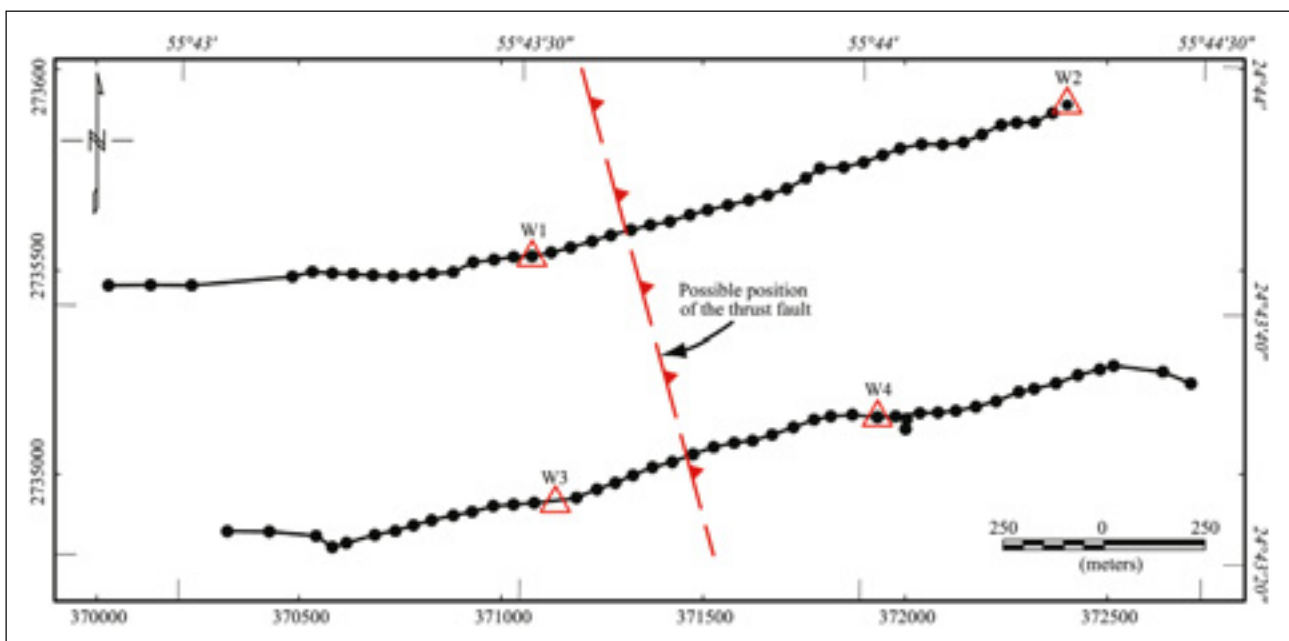


Figure 3 Site map showing a possible location of the thrust fault running through the site, the two tracks of gravity measurements, and the locations of four coincident logged wells.

at an Easting of 371,000 m along the northern profile and an Easting of 371,250 m on the southern profile. Based on the gravity data and models, the fault is consistent with the expected fault line shown in the map of Figure 3, with its surface line located only 250 m toward the West.

The models also show significant variations in the depth of the aquifer and the Upper Fars unit. In particular, in the northern profile the aquifer and Upper Fars units have areas that are notably thinner than in the southern profile.

Generally, the evaporite-rich Lower Fars unit is approximately 350-400 m below land surface, but thrusting has brought the unit to less than 100 m of the land surface. This proximity of an evaporite-rich unit to the ASR site could affect salinity of the aquifer. These results indicate that the thrust fault could be a factor in the distribution of the good quality groundwater in the area and, depending on the extent of mixing with repeated storage cycles, could play a role in the quality of water stored at this site in a future ASR scheme.

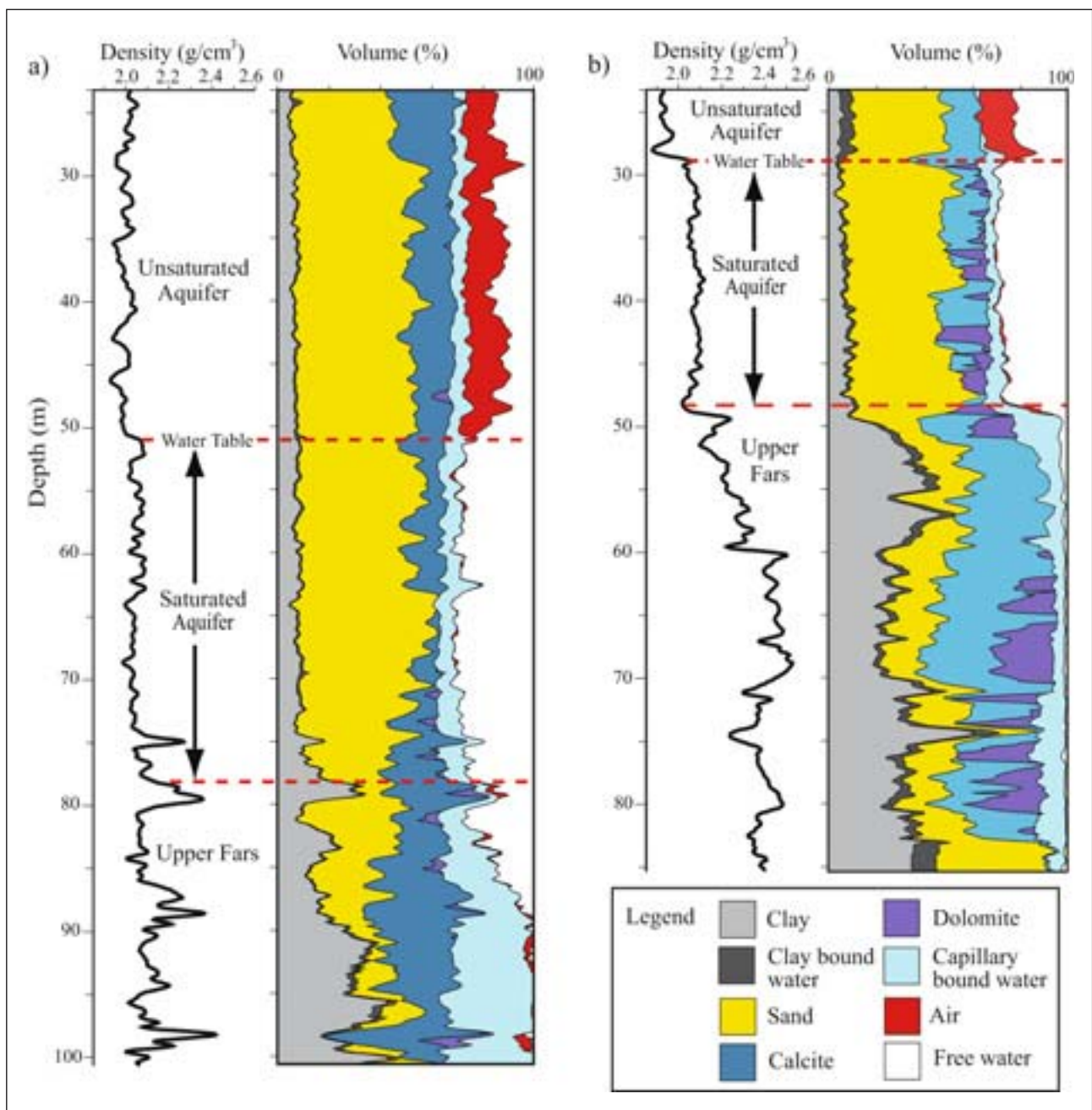


Figure 4 Well log geophysical data and interpretation, showing depth of the water table and formation boundaries, for (a) well W3 (b) well W4.

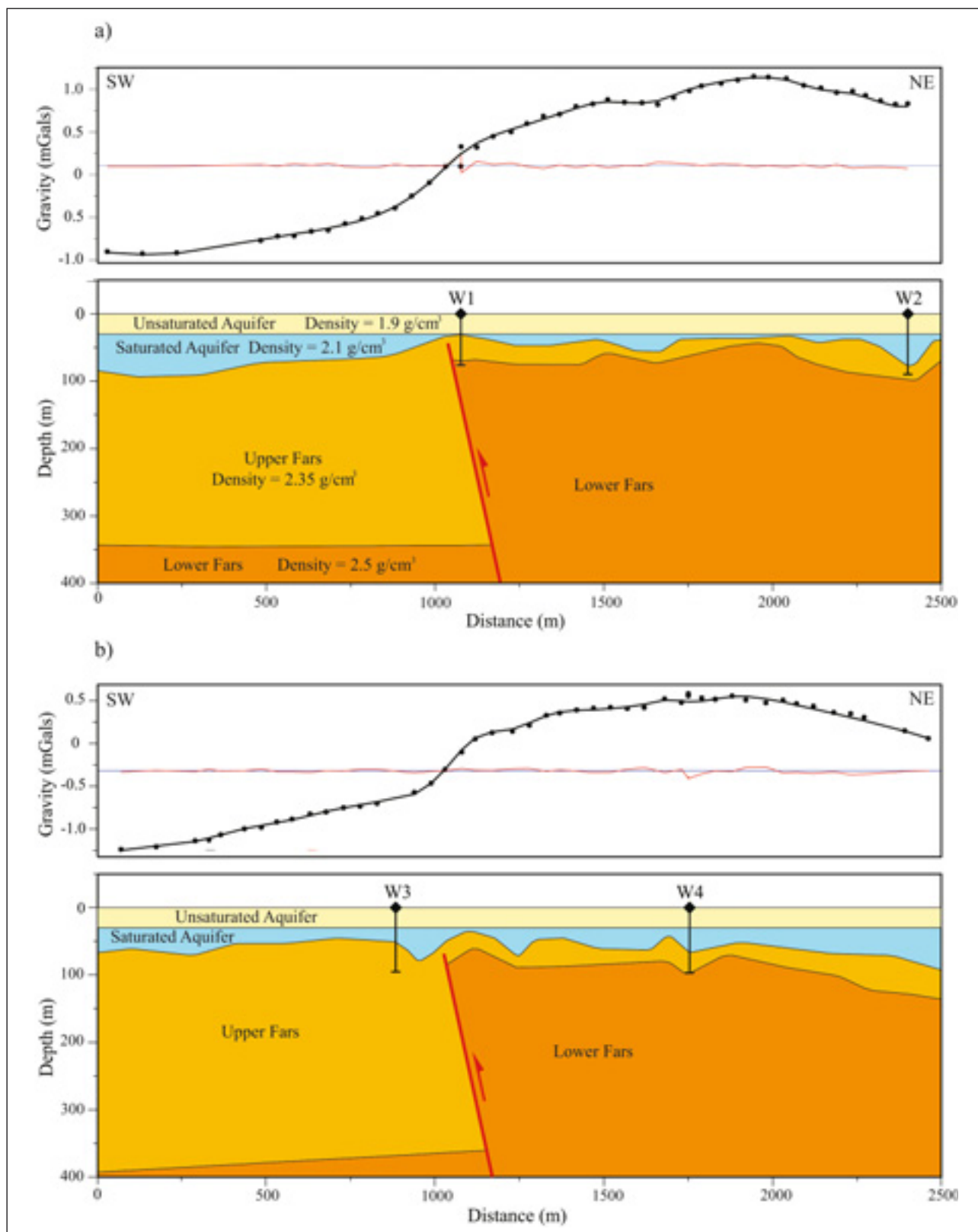


Figure 5 (a) Northern and (b) southern Bouguer gravity anomaly profiles and corresponding earth models, showing the thrust fault location and variations in the surficial aquifer thickness.

## Conclusions

This microgravity study has revealed improved detail about the geological structure underlying the ASR site and about the boundary between the saturated aquifer and the denser Fars units. Important features of relevance to future development of the field for ASR include the uplifted Lower Fars with its higher concentration of evaporites and variations in the depth of the lower aquifer boundary that are likely to influence water flow during water injection and recovery. These results motivate future gravity measurements in order to further explore the North to South density variation and to reveal other trends and structural details of the aquifer.

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