Geophysical investigation of Al Jaww Plain, eastern Abu Dhabi: Implications for structure and evolution of the frontal fold belts of the Oman Mountains

Mohammed Y. Ali, Manhal Sirat and James Small

ABSTRACT

The area to the southeast of the city of Al Ain, Abu Dhabi, United Arab Emirates, is part of an arcuate sedimentary basin whose trend gradually changes from NNW near Al Ain to NNE at Ras Al Khaimah. The basin is bounded to the east by the generally N-trending Oman Mountains and on the west by an arcuate, overall west-verging fold-thrust front that involves Mesozoic carbonates. The fold-thrust front is part of the overall compressional system of Late Cretaceous age (with Late Tertiary reactivation) associated with obduction and emplacement of the Semail Ophiolite, Haybi, Hawasina and Sumeini sheets onto the continental margin of the Arabian Plate. Near Al Ain, the fold-thrust front is expressed as the remarkable, NNW-trending Jabal Hafit that rises one kilometer above the gravel-filled Al Jaww Plain. Gravity and magnetic investigations were carried-out in the Al Jaww Plain, an area of approximately 550 square km. The interpretation of these new data, including measurements of physical properties of rock samples from the area, were integrated with a new interpretation of an industry seismic reflection profile to provide constraints on the modelling of the subsurface structure and evolution of the sedimentary basin beneath Al Jaww Plain.

We recognised four major tectono-stratigraphic units in the seismic profiles: autochthonous shelf carbonates, the Hawasina allochthon, Upper Cretaceous foreland basin sediments (primarily Fiqa Formation), and Tertiary neo-autochthonous units. Along-strike variations in the residual Bouguer gravity field were interpreted as being due to either variations in the thickness, or even total absence, of the Hawasina sheet. Comparison of two E-W gravity profiles, one in the southern part of our study area and the other to the north, suggest that the Hawasina sheet underlies little of the southern area but almost all of the northern area. Magnetic anomalies are weak (< 50 nT) over most of the area but peak (> 300 nT) in the easternmost part of the southern profile, where the high-susceptibility rocks of the Semail Ophiolite are exposed. Thus, we interpret that no continuation of the ophiolite extends westward from this outcrop into the subsurface of the study area.

The structural geometries described here have resulted from two major tectonic events. The first, a Late Cretaceous phase, emplaced the obduction-related allochthonous thrust sheets of the Oman Mountains westward onto the Mesozoic carbonate platform. This phase primarily affected the eastern part of the study area and contributed to both the high magnetic (> 300 nT) and residual Bouguer gravity (> 14.0 mGal) anomalies. The second event, a Tertiary deformation phase, affected most parts of the area and produced a series of asymmetrical anticlines and synclines trending in a NNW-SSE direction. This phase contributed to the low residual gravity anomaly (< -9.0 mGal) in the center of the study area. We modelled that area as containing a sequence of post-Eocene carbonate sediments with a minimum thickness of 2.0 km.

The Tertiary folding and thrusting formed as a result of a regional compressive deformation, whose principal compressive stress axes were sub-parallel to those of the Late Cretaceous compressional stress regime. The younger event reactivated high-angle reverse faults within the Mesozoic platform succession. Precise timing of the Tertiary deformation is debatable; it is most likely that the rejuvenation of the E-W to ENE-WSW Cretaceous stress regime took place in the Late Eocene-Miocene but gradually shifted to become N-S to NE-SW. This shift could be due to the collision of the Arabian and Eurasian plates and the opening of the Red Sea which started during Late Eocene and continues until the present-day.
INTRODUCTION

Geophysical techniques have long been employed for the investigation of subsurface geological features including crustal and mantle structures. In particular, gravity and magnetic techniques have been used, for example, to delineate and interpret tectonic boundaries (Manghnani and Coleman, 1981; Shelton, 1990; Jallouli et al., 2002; King and Barr, 2004; White et. al., 2005), basement and sedimentary structures (Waris, 1990; Khattab, 1995; Benson and Floyd, 2000; Hope and Eaton, 2002), crustal structures and flexural rigidity (Karner and Watts, 1983; Stewart and Watts, 1997; Ravaut et al., 1997) and shallow faulting (O’Donnell et al., 2001; Ursin et al., 2003).

The subsurface structural configuration along the unexposed western leading edge of the deformed thrust front belt that flanks the Oman Mountains in the United Arab Emirates (UAE) is less well understood compared with the knowledge at the surface of the Oman Mountains. However, determining the subsurface structures of this area is of great interest for hydrocarbon exploration as several gas condensate fields, such as Khusub, Margham, Sajaa and Hamidiyah, occur along this trend (Figure 1).

In this paper we present the findings of geophysical investigations carried-out in the Al Jaww Plain (Figure 1) using gravity and magnetic techniques, together with an interpretation of a seismic reflection profile. In addition, rock samples were collected and analysed to obtain densities for gravity modelling. The results of the survey indicated that the geophysical methods employed are valuable tools in documenting the deformation style and stratigraphy of the Upper Cretaceous section and its relationship to the Tertiary sequences, as well as identifying the factors that may have influenced this deformation. The gravity and magnetic methods detected several major subsurface structures and indicated that the Semail Ophiolite occurs only in the eastern part of the study area, whereas the Hawasina Complex extends further to the northwest of Al Jaww Plain towards Al-Ain city.

GEOLOGICAL SETTING

Two major compressional events formed the Oman Mountains. The first of these occurred from the Late Cenomanian to the end of the Early Maastrichtian (Searle and Cox, 1999; Searle, 2007). This tectonic event involved the emplacement of a number of thrust sheets, each of which has been emplaced from NE to SW onto the Tethyan rifted continental margin of the Arabian Plate. The margin formed during the Permian-Early Cretaceous following the breakaway of the Cimmerian Superterrane from the Arabian Plate and the formation of Tethyan oceanic crust (Glennie et al., 1974; Lippard et al., 1986; Searle, 1988, 2007; see review in Ruban et al., 2007).

From structurally lowest to highest position, these allochthonous sheets (illustrated in Figures 1 and 2) include the Sumeini Group, comprising shelf-edge and slope-carbonate sediments; the Hawasina Complex, comprising distal-slope and deep-sea Tethyan sediments; the Haybi Complex, comprising Mesozoic exotic limestones (Oman Exotics), volcanics (Haybi volcanics), mélanges, sub-ophiolitic metamorphic rocks, and the Semail Ophiolite complex, a massive slab of oceanic crust and mantle of Cenomanian-Turonian (c. 95–98 Ma) age, which formed above a NE-dipping intra-oceanic subduction zone. Regionally in the northern Oman Mountains the Semail Ophiolite and subjacent allochthons dip eastwards (Searle, 1988, 2007).

Westward obduction of the Semail Ophiolite and genetically related westward telescoping of the eastern Oman continental margin caused loading and down-flexing of the underlying autochthonous passive margin shelf carbonates. The flexing resulted in the development of the foreland basin and flexural bulge to the west of the obducted allochthons. The obducted allochthons were intensely deformed, whereas the underlying Mesozoic shelf carbonates remained undeformed except for minor extensional faulting associated with the flexural bulge (Warburton et al., 1990; Boote et al., 1990). However, the regional uplift due to a westward-migrating flexural bulge in the front of advancing thrust sheets caused removal by erosion of thick shelf carbonates and contributed to the formation of the break between the Wasia and Aruma groups, which separates passive margin deposits from foreland deposits (Patton and O’Connor, 1988; Robertson, 1987a,b). In the Sharjah area (UAE)
Geophysical investigation of Al Jaww Plain, eastern Abu Dhabi

Figure 1: (a) Topography of the Arabian Peninsula and surrounding region showing plate boundaries which are often delineated by earthquakes (red dots). The data are based on a 1 x 1 minute GEBCO grid (British Oceanographic Data Centre, 2003). (b) Simplified regional geological map of the UAE and Northern Oman Mountains. Modified from Searle (2007).
a significant amount of the Wasia Group was removed, down-to and including part of the Nahr Umr Formation (Patton and O’Connor, 1988). In central Oman, up to 600 m of uplift and erosion of the Natih Formation has been caused by flexural bending due to the emplacement of thrust sheets (Robertson, 1987a).

The foreland basin was filled with Upper Coniacian to Campanian deep-marine mudstones of the Fīqa and Juwaiza formations. The sequence thickens to the northeast reaching up to 4,300 m in the area west of the central Oman Mountains (Glennie et al., 1974). The foreland sequence is, in turn, overlain by Upper Maastrichtian to Palaeogene conglomerates and shallow-marine limestone of the Qahlah and Simsima formations (Glennie et al., 1974; Lippard et al., 1986). The stratigraphy along the western side of the northern Oman Mountains is shown in Figure 2.

<table>
<thead>
<tr>
<th>Period</th>
<th>Epoch</th>
<th>Group</th>
<th>Age (Ma)</th>
<th>Comments</th>
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<td>Fars</td>
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<td></td>
<td>Oligocene</td>
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<td>Eocene</td>
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<td>Paleocene</td>
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<tr>
<td>CRETAUCEOUS</td>
<td>Maastrichtian</td>
<td>Campanian</td>
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<td>Santonian</td>
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<td>Coniacian</td>
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Figure 2: Generalized tectono-stratigraphy of the Northern Oman Mountains showing the stratigraphic relationship of the Tertiary and Upper Mesozoic groups.
A second compressional post-obduction event occurred in the Late Eocene-Miocene during which the Arabian Plate moved north-eastwards and collided with the Eurasian Plate (Searle et al., 1983; 1988). This event produced large-scale folding and the reactivation of deep-seated faults in the frontal fold and thrust belt and adjacent foreland basin (Boote et al., 1990; Dunne et al., 1990; Searle et al., 1990). In addition, an uplift of at least 3,000 m has occurred along the western flank of the northern Oman Mountains near the Al-Ain area (Boote et al., 1990). As a result of this uplift the sedimentary succession was deeply eroded and the stratigraphic record of its evolution was partially removed. However, the history of the emplacement of the allochthons and of the Late Tertiary deformation is recorded in the thick Upper Cretaceous and Tertiary sections, which are still preserved beneath Al Jaww Plain. Therefore, the use of gravity, magnetic and seismic reflection profile data can be used to reconstruct the structural and stratigraphic evolution of the area.

DATA ACQUISITION

Survey Location

The geophysical survey was conducted at Al Jaww Plain, which is located in the area east of a N-S line that passes through the city of Al Ain, east of Abu Dhabi Emirate, and to the Jabal Hafit, and west of the northern Oman Mountains (Figure 3). The plain is a westward sloping, low-relief alluvial piedmont that occupies an area of approximately 550 square km. Surface sediments consist mainly of gravels and other coarse clastics derived from the nearby mountains.

Rocks exposed in the area have undergone complex, compressional deformation (Figure 4). The eastern side of Al Jaww Plain is characterised by NNW-trending exposures of allochthonous Semail Ophiolite and Hawasina Complex (Figure 5). These units are unconformably overlain by the neo-autochthonous Qahlah and Simsima formations, which are in turn unconformably overlain by Tertiary units. On the western side of the plain the topographically prominent Jabal Hafit anticline (Figure 6) exposes shallow-marine carbonates of Eocene to Miocene age in outcrop belts that trend parallel to the mountain range.

Previous Geological and Geophysical Studies

Detailed geophysical investigations have not been previously carried-out in the study area. However, several studies have documented a series of folds and thrust faults in Al Jaww Plain and surrounding areas. Woodward (1994) used seismic reflection data to identify a series of NNW-trending folds and faults in the eastern Abu Dhabi region, including Al Jaww Plain. The seismic profiles were shallow (1.5 sec two-way-time, TWT), owing to the focus of the study on shallow aquifers, and so do not show the Lower Tertiary and Mesozoic sections. Ravaut and Warsi (1997) composed a Bouguer gravity map over the northern Oman margin, which was based on a compilation of regional gravity datasets sourced from both industry and academia. The map was used to assess the crustal structures and flexural rigidity of the region. However, while the dataset is largely restricted to Oman, the Bouguer gravity map also covers the eastern part of Al Jaww Plain where a distinct negative anomaly was observed.

Other geological and structural studies that have been carried-out in the surrounding areas include Jabal Hafit (Warrak, 1996; Nowier, 2000; Sirat et al., 2007), Jabal Malaqet-Jabal Mundassa (Noweir and Eloutefi, 1997; Osman et al., 2003), Jabal Rawdah (Noweir and Abdeen, 2000), and Jabal Autha-Jabal Huwayyah (Noweir and Alsharhan, 2000), Jabal Sumeini (Searle et al., 1990), Faiyah range (Noweir et al., 1999) and Suneinah foreland (Boote et al., 1990). These studies were based on structural interpretations of outcrops and seismic reflection profiles.

Data Acquisition Procedures

The seismic profile was part of a large seismic survey collected in 1982 for hydrocarbon exploration in the area. The acquisition and processing parameters were designed primarily to image the Lower Cretaceous shelf carbonates of the Wasia Group. The total length of the profile is approximately 12 km.
and it runs across Al Jaww Plain with an orientation of ENE-WSW. The shot-detector configuration used was 96 channels split-spread, with shots located midway between geophone groups 48 and 49. The shot interval was 90 m with a 10-station shotpoint gap resulting in a near-trace offset of 495 m. The vibroseis source consisted of an array of four vibrators to generate the sweep signal. In addition, uphole surveys were acquired at 2 km intervals along the seismic line.

Gravity measurements were acquired using a Scintrex CG5 gravimeter (with a cited instrument precision of 0.01 mGal) in April 2006 at 416 stations over an area of approximately 500 square km (Figure 3). The gravity stations were spaced approximately 1.0 km apart, except in areas where logistical difficulties limited physical access. A base station was established at the centre of the survey area to monitor the drift of the gravimeter and was visited every 3–5 hours. Care was taken to minimise measurement errors, and any ambiguous measurements were double-checked. Latitude, longitude,
and elevation were taken at each station using a handheld Garmin GPS receiver. These readings were corroborated with SRTM (Shuttle Radar Topography Mission) data. Additionally, two E-W gravity profiles of 15 km and 22 km lengths with 1.0 km station spacing were acquired for detailed modelling of the subsurface structure.

Twenty rock samples were collected representing each of the main rock types at various locations throughout the Al Jaww Plain (Table 1). Although the number of samples available for measurement was limited, some clear trends emerged. The Semail Ophiolite and Hawasina rocks were generally found to have higher densities than the Tertiary sediments.

Magnetic field data (total field anomaly) were acquired using a Geometrics G-858 magnetometer (with a cited instrument precision of 0.05 nT) along the same two E-W survey profiles as the gravity, but with 500 m spacing between stations. At least two magnetic readings were taken at each station and averaged. Typically, the largest variation in the readings at any station was in the range of only 8–10 nT. Thus the effects of cultural and other forms of magnetic noise were minimal in this study.
Table 1
Grain densities of rock samples from Al Jaww Plain and surrounding areas.

(A) FORMATIONS, ROCK TYPES AND GRAIN DENSITIES

<table>
<thead>
<tr>
<th>Formation</th>
<th>Rock Type</th>
<th>Sample Number</th>
<th>Density (g/cm³)</th>
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</thead>
<tbody>
<tr>
<td>Asmari</td>
<td>Bioclastic nodular limestone</td>
<td>AS1</td>
<td>2.588</td>
</tr>
<tr>
<td>Dammam</td>
<td>Nummulitic limestone</td>
<td>DM1</td>
<td>2.667</td>
</tr>
<tr>
<td>Dammam</td>
<td>Nummulitic limestone</td>
<td>DM2</td>
<td>2.667</td>
</tr>
<tr>
<td>Dammam</td>
<td>Marly limestone</td>
<td>DM3</td>
<td>2.678</td>
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<tr>
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<td>Nodular limestone</td>
<td>RS1</td>
<td>2.704</td>
</tr>
<tr>
<td>Rus</td>
<td>Dolomitised limestone</td>
<td>RS2</td>
<td>2.712</td>
</tr>
<tr>
<td>Rus</td>
<td>Nodular limestone</td>
<td>RS3</td>
<td>2.694</td>
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<tr>
<td>Rus</td>
<td>Massive limestone</td>
<td>RS4</td>
<td>2.688</td>
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<tr>
<td>Simsima</td>
<td>Fine-grained packstone</td>
<td>SM1</td>
<td>2.687</td>
</tr>
<tr>
<td>Simsima</td>
<td>Fine-grained packstone</td>
<td>SM2</td>
<td>2.705</td>
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<tr>
<td>Semail Ophiolite</td>
<td>Serpentnised peridotite</td>
<td>SO1</td>
<td>2.98</td>
</tr>
<tr>
<td>Semail Ophiolite</td>
<td>Peridotite</td>
<td>SO2</td>
<td>2.79</td>
</tr>
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<td>Semail Ophiolite</td>
<td>Serpentnised peridotite</td>
<td>SO3</td>
<td>2.82</td>
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<tr>
<td>Hawasina</td>
<td>Red chert</td>
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<td>2.77</td>
</tr>
<tr>
<td>Hawasina</td>
<td>Red chert</td>
<td>HW2</td>
<td>2.60</td>
</tr>
<tr>
<td>Hawasina</td>
<td>Green chert</td>
<td>HW3</td>
<td>2.59</td>
</tr>
<tr>
<td>Hawasina</td>
<td>Red chert</td>
<td>HW4</td>
<td>2.73</td>
</tr>
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(B) RANGE OF GRAIN DENSITIES FOR SEQUENCES

<table>
<thead>
<tr>
<th>Sequence</th>
<th>No. of Samples</th>
<th>Density (g/cm³)</th>
<th>Standard deviation (g/cm³)</th>
</tr>
</thead>
<tbody>
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<td>Upper Tertiary (Asmari)</td>
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<td>-</td>
</tr>
<tr>
<td>Lower Tertiary (Dammam – Simsima)</td>
<td>9</td>
<td>2.667 – 2.712</td>
<td>0.016</td>
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<td>Semail Ophiolite</td>
<td>6</td>
<td>2.75 – 2.98</td>
<td>0.082</td>
</tr>
<tr>
<td>Hawasina</td>
<td>4</td>
<td>2.59 – 2.77</td>
<td>0.091</td>
</tr>
</tbody>
</table>

DATA PROCESSING AND MODELLING

Seismic
A standard processing sequence was applied to the seismic data by a data processing service company. The noise content and clarity of the data was primarily reduced by the application of three fundamental processes: deconvolution, CMP (Common Mid-Point) stacking, and migration. In addition, secondary processes were applied, which included corrections for weathering-related statics derived from uphole surveys and a bandpass filter of 6–40 Hz.

Gravity
The gravity data were corrected for instrumental drift, Earth tides, elevation, latitude and terrain. The drift was assumed to be linear between consecutive base station readings and was subtracted from the observed value. The effect of latitude was corrected using the 1967 International Gravity Formula (Mittermayer, 1969):

\[
g = 978031.846(1+0.005278895 \sin^2 \phi) + (0.000023462 \sin^4 \phi)
\]

where \( g \) is the predicted value of gravity in mGal and \( \phi \) is the latitude. The data were reduced to Bouguer anomaly using an average density of 2,600 kg/m³ rather than the more commonly used...
Figure 5: Field photograph of the Jabal Mundassa (east of Al Jaww Plain), showing serpentinised ultramafic rocks of the Semail Ophiolite unconformably overlain by the neo-autochthonous carbonates of Eocene in age. View towards northeast.

Figure 6: Panoramic view of the eastern limb of Jabal Hafit structure showing overturned limb, and box fold affecting Eocene and Oligocene shallow water sediments.
value of 2,670 kg/m$^3$ in surveys in other parts of the world, because 2,600 kg/m$^3$ reflects the average value for the different kinds of rocks outcropping in the study area. The survey was tied to the Sharjah base station (25°21.1’N 55°24.2’E; $g^\prime =$ 978887.900 mGal).

Terrain corrections were applied to obtain the Complete Bouguer anomaly which corrects for irregularities due to variations in terrain in the vicinity of the gravity stations. Geosoft Montage software was used to calculate the terrain corrections. The software utilises a combination of the methods described by Nagy (1966) and Kane (1962). Finally, the regional gradient was removed from the data by applying a high-pass filter with cut-off wavelength of 40 km. By filtering out the regional trend (long wavelength, generally deep sources) from the Bouguer data, a residual gravity data set (shorter-wavelength, near surface source) was obtained.

The two E-W gravity profiles were modelled using the 2.5-D GM-SYS program in order to determine the subsurface structure of the area. The models are based on the main lithologies that crop out in the surrounding areas. The models were constrained by the existing seismic reflection data, and additional constraints for the gravity modelling were provided by bedrock density measurements.

**Grain Density**

Density measurements were conducted on bedrock samples collected in the field. The grain volume of rock samples were obtained at ambient lab conditions using a conventional Boyle’s law helium expansion digital porosimeter. Measurements were made by compressing a known volume of helium gas at a known pressure into a core plug that was originally at atmospheric pressure. The grain density ($\rho_g$ in grams per cubic centimetre) was determined using the equation:

$$\rho_g = \frac{W_{\text{dry}}}{V_g}$$

where $W_{\text{dry}}$ is the dry weight in grams and $V_g$ is the grain volume in cubic centimeters. The obtained results are summarised in Table 1.

Measured densities of the ultramafic rocks of Semail Ophiolite are slightly lower than the values cited by Telford et al. (1990). Densities of originally olivine-rich ultramafic rocks decrease greatly, with increasing serpentinisation, from values of about 3,300 kg/m$^3$ for fresh dunites and harzburgites to less than 2,400 kg/m$^3$ for highly serpentinised ultramafics. Thus, we suspect that our samples are, on average, more serpentinised than those of Telford et al. (1990).

**Magnetic**

The main magnetic field of the Earth, as defined by the International Geomagnetic Reference Field (IGRF 1990), was removed from all observed readings to yield field residual values. In addition, diurnal variations were corrected using repeated readings at a base station. Magnetic modelling was not attempted because magnetic susceptibility measurements were not conducted in the field and there were no measurements of remnant magnetization available for the rocks in the study area.

**DATA INTERPRETATION**

**Seismic Reflection Profile (Figure 7)**

Although there was no well data available in the study, the lateral continuity of seismic horizons allowed interpretation of the geometric features on the seismic profile. As a result, the seismic stratigraphy of the area has been subdivided into four main sequences: (1) Mesozoic shelf carbonates, (2) allochthons, (3) foreland basin sequence, and (4) a Tertiary sequence (Figure 7). The foreland and Tertiary sequences are then subdivided into Lower and Upper sub-sequences. These sequences were delineated on the basis of their seismic character, reflector terminations (onlap and toplap) and reflection style including prominent reflectors, continuity and amplitude (e.g. Mitchum et al., 1977; Sheriff and Geldart, 1995).
Mesozoic Shelf Carbonates Sequence (Wasia Group)
The regional Upper Turonian Wasia-Aruma break is recognised as a local toplap with truncating terminations to Lower Fiqa reflectors. This has been interpreted as a period of plate margin uplift and erosional stripping caused by the development of a flexural bulge during the initial phases of emplacement of the allochthons. Internally the Mesozoic shelf-carbonate sequence exhibits high amplitude with continuous to discontinuous reflectors. In addition, the seismic section suggests the presence of low-displacement normal faults that offset the top of the sequence but do not continue upward into the overlying Lower Fiqa (Figure 7).

Foreland Basin Sequence
The sequence is sub-divided into two units (Lower Fiqa and Upper Fiqa), which are continuous over a large area. The thickness of the sequence is more than 1.5 sec TWT. However, the maximum thickness is expected to occur in the southeast sector of the survey area where the lowest gravity anomalies are observed. The internal geometry of the sequence provides strong evidence for the tectonic and sedimentary response of the Arabian margin to emplacement of the allochthons.

Lower Fiqa
The base of this sub-sequence is marked by an unconformity expressed as toplap and truncations of the underlying shelf carbonates sequence. This is interpreted to be the contact between the Late Cretaceous foreland basin sequence and underlying Mesozoic shelf carbonates sequence (Wasia Group). Internally the unit displays low-to-medium amplitude, sub-parallel, discontinuous, low-frequency reflectors. This seismic unit has been suggested to be Late Coniacian to Early Santonian in age (Boote et al., 1990).

Upper Fiqa
Upper Fiqa sub-sequence conformably overlies the Lower Fiqa sub-sequence in the southwestern region of the profile. However, in the northeastern part the unit shows progressive onlap as it overlies the emplaced wedge of allochthonous units. The top of the unit is laterally continuous with high-to-moderate amplitude reflectors. At the southwestern end of the profile the unit displays internal seismic reflections that show variable-amplitude, discontinuous, low-frequency and chaotic patterns. Here the boundary with the underlying Lower Fiqa unit becomes indistinct and probably passes into a correlative conformity. To the northeast of the profile the Upper Fiqa sub-sequence exhibits high-to-medium amplitude, strong and continuous reflectors.

It is possible that the top section of the unit is largely composed of Upper Campanian chert-rich Juwaiza turbidites, which are composed of debris derived from the allochthonous units of Hawasina and Haybi complexes, and Semail Ophiolite. The Juwaiza unit crops out north of the study area near Shwaib. Well data from south of the study area have also encountered the unit (Boote et al., 1990). The seismic characteristics of foreland basin sequence suggest that the Lower Fiqa was deposited immediately after the development of the foreland basin as a response to loading of the allochthonous units. In contrast, the Upper Fiqa units were deposited during the final stages of the emplacement of the allochthonous units.

Allochthonous Sequence
The base of the sequence is not well-defined and consists of medium-to variable amplitude and moderately continuous reflectors. To the southwest, the top of the sequence is similarly not well defined with reflectors displaying highly variable continuity and amplitudes. To the centre of the profile, the top of the sequence is marked by moderate to high amplitude reflectors. Internally the sequence is composed of thrust-stacking of numerous duplexes with a seismic character having variable-amplitude and discontinuous reflectors. We interpret this sequence as part of the Hawasina sheet complex, as discussed below in the section on gravity modelling.

The sequence is wedge-shaped with a maximum thickness of more than 3,000 m (2.0 sec TWT) in the most northeastern portion of the profile. The sequence can be traced from outcrops of the Hawasina complex in the east (Jabal Zarub; see Figure 15) into the subsurface where it gradually pinches out at the boundary between the Upper and Lower Fiqa units. This relation suggests that the allochthon propagated from east to west.
Figure 7: (a) Uninterpreted seismic profile across Al Jaww Plain (for location see Figure 3). (b) Interpreted seismic profile showing series of folds and a high-angle thrust fault in the Tertiary section. The main fold is a syncline whose axis is about 7.0 km to the east of Jabal Hafit. The profile also illustrates the stratigraphic correlation of Tertiary, Fīqa, Allochthon and Mesozoic sequences. The allochthon sequence is characterised by extensive duplex thrusting (yellow lines). The left end of the section represents the vertical stratigraphy before the structural deformation. The numbers in red indicate the possible time sequence of the thrusts.
**Tertiary Sequence**
The Tertiary sequence is characterised by highly deformed concordant reflections over most of the length of the section. Internally the sequence displays strong amplitude and continuous, parallel reflectors that can be mapped throughout the seismic section. The bottom section of the sequence is conformable with the Upper Fiqa and is characterised by prominent high-amplitude, continuous reflectors. This is interpreted to represent shallow-marine transgressive carbonates deposited as the margin subsided and was transgressed during Maastrichtian times. These units are named the Qahlah and Simsima formations respectively, and are exposed in Jabal Auha and Jabal Huwayyah to the north of the study area (Noweir and Alsharhan, 2000). The thickness of the Lower Tertiary and Upper Cretaceous sub-sequence is consistent throughout the seismic section and reaches approximately 1,000 m (0.7 sec TWT), whereas the thickness of the Upper Tertiary sub-sequence varies due to the uplift which caused erosion of large part of the sub-sequence.

**Structure**
The seismic section shows a series of anticlines and synclines, which appear to have orientations similar to that of Jabal Hafit. The amplitude of the folds increases southwestwards to Jabal Hafit, which has the largest structural relief of all anticlines in the area. The seismic profile also shows that the anticline whose axis is at CMP 925 in Figure 7 is bounded on the east by a steep, west-dipping reverse fault. A similar structure has been observed in Jabal Hafit. The structure was interpreted as a detachment fold above a basal Fiqa or Lower Fiqa decollement (Warrak, 1996; Noweir, 2000), or a reactivation of pre-existing NNW-trending segments of deeper block faults possibly extending through to basement (Boote et al., 1990). However, the Mesozoic shelf carbonates exhibit little vertical displacement making it difficult to trace the reverse fault down to the Mesozoic section.

In addition, the seismic section illustrates that the leading edge of the allochthonous sequence is bounded, top and bottom, by thrust faults with an opposite sense of vergence forming a wedge-shaped triangular geometry. Similar triangular geometries have been widely recognised in many foreland thrust and fold belts (e.g. Banks and Warburton, 1986; Jones, 1996; Cooper, 1996; Medd, 1996; Xu and Zhou, 2007). The roof thrust lies at the top of the allochthonous sequence and the base of the Upper Fiqa sub-sequence where all thrusts flatten upward into it. The details of the deeper floor thrust and imbricate geometry is not well-imaged in the seismic section due to the poor-quality of the reflection profile. Nevertheless, the floor thrust is identified as a sub-horizontal to shallowly ENE-dipping discontinuous reflector at around 2.5 sec TWT that can be traced faintly across the entire section and which probably lies at the base of Upper Fiqa sub-sequence. The reflector cannot be interpreted as a multiple reflection since no overlying reflection has such a dip. Furthermore, the weak ENE-dipping fault plane reflections within the allochthon sequence provide evidence for at least four imbricate fault strands.

The tilted Upper Fiqa sub-sequence on the frontal allochthonous sequence shows thinning towards the top of the roof thrust which may indicate periodic uplift of the region caused by the duplex wedging during Late Cretaceous times. In contrast, the WSW end of the profile shows the sequences in their original stratigraphic depth before structural deformation.

**Gravity**
Contour maps of the gravity data were constructed using the Geosoft™ Montage software. The data were gridded using the minimum curvature method and a 330 m cell size. A blanking distance of 2,000 m was used to prevent extrapolation into areas without gravity stations.

**Bouguer Anomaly**
The Bouguer anomaly map of Al Jaww Plain is shown in Figure 8. The eastern area contains high-frequency gravity anomalies (> 58.0 mGal) associated with the thrusted Semail Ophiolite. The central area is associated with strong low-gravity anomalies (< 75.0 mGal), whereas the western area is associated with weak anomalies (> 70.0 mGal). This observation is consistent with the regional Bouguer gravity map of the Northern Oman Mountains compiled by Ravaut and Warsi (1997) which shows pronounced negative Bouguer gravity anomalies of around −80.0 to −60.0 mGal over Al Jaww Plain, and relatively higher Bouguer anomalies (> 50.0 mGal) towards the east.
The Bouguer anomaly map contains effects of anomalies caused by the mass of Jabal Hafit reducing the gravitational attraction by exerting an upward pull on the gravimeter. This effect is most relevant for the stations within about 3.0 km of Jabal Hafit (Figure 9c). Furthermore, the Bouguer anomaly map contains effects of anomalies caused by the lateral density changes within the crust and upper mantle; in particular a regional gradient trending NNW-SSE with values increasing towards the Oman Mountains dominates the map. Hence, the interpretation was greatly enhanced by applying terrain corrections and removing the regional field of the data.

**Complete Bouguer anomaly**
The Complete Bouguer anomaly was obtained by combining the Bouguer anomaly and the terrain corrections. SRTM data with a 90 m resolution was used for the terrain corrections as there are no local DEM data available (Figures 9a and 9b). The Complete Bouguer anomaly map (Figure 10) shows higher anomalies close to eastern limb of Jabal Hafit.

**Regional anomaly**
The regional anomaly map of Al Jaww Plain (Figure 11) indicates a gentle decrease of the regional gravity from ~64.0 mGal along the eastern edge of the survey area to ~72.0 mGal along the western edge. This gradient probably reflects westward thickening of the crust. This interpretation is consistent
with the geodynamic model of central Oman presented by Al-Lazki et al. (2002), which showed an increase of crustal thickness from 35 km in northeastern coastal plain to 40 km in the foreland basin except in Jabal Akhdar area where the crustal thickness is around 50 km.

**Residual anomaly**

By removing the regional effects from the map, the resulting residual gravity map (Figure 12) reflects the composite effects of density changes within the upper crust. Therefore, the residual gravity map defines local anomalies related to the density distribution within the sedimentary fill of the Al Jaww basin more clearly than does the simple Bouguer map (Figure 8). A spectacular negative anomaly of <- 9.0 mGal is observed in the southeastern part of the survey area. This is consistent with a model whereby the Upper Cretaceous and Tertiary sequences are thicker (> 6.0 km). The anomaly is also coincident with a syncline mapped from the seismic data.

To the east, the residual Bouguer anomaly map shows a steep gradient in the gravitational field where gravity values increase by more than 10.0 mGal. This is correlated to the Semail Ophiolite that is exposed in the area. Furthermore, the residual gravity map provides strong evidence for the presence of NNW-trending anomalies. These trends coincide with the Tertiary structures mapped in the area. Generally where there is a syncline, a gravity low is observed due to thicker Upper Cretaceous and Tertiary sediments; where an anticline occurs, the gravity is high due to Tertiary uplift which caused
Figure 9 (continued):
(b) Calculated terrain corrections showing higher anomaly close to Jabal Hafit. Illumination from northeast.
(c) Comparison of the elevation and calculated terrain corrections east of Jabal Hafit (for location see Figures 9a and 9b). The effect of gravitational attraction of Jabal Hafit is important for only those stations within about 3 km of Jabal Hafit.
erosion of the sediments. To the west and close to Jabal Hafit, the residual gravity anomalies gradually increase. This has been interpreted to reflect basement uplift due to reactivation of deep faults during the Tertiary.

**Gravity Modelling with Geological and Geophysical Constraints**

The Bouguer residual anomalies were used in modelling and to assist in the interpretation of the subsurface geology. However, the modelling of the gravity anomalies can be complex due to the problem of non-uniqueness (Blakely, 1995). This can be minimised by constraining the models using other geological and geophysical data. In this study the geometry of subsurface structures of the models were constrained by outcrop data at the flanks of the plain, a seismic reflection profile, and density measurements.

The final subsurface models (Figures 13 and 14) all show a good fit between the observed and calculated anomalies. The fit was quantified by a root-mean squared (RMS) error computed by the software. The best-fit solutions of the models were determined by reducing RMS error to less than 2.0% of the total dynamic range of the gravity profile. In addition, the average depth to the base of the modelled Fiqa sequence is in reasonable agreement with that observed from the seismic data.
The models indicate that Al Jaww Plain is underlain by a series of folds that comprise a central anticline flanked by synclines, and an easterly dipping reverse fault located near the eastern boundary of the plain. The models also suggest that the Hawasina Complex extends further to the west on the northern profile (Profile 1) than it does on the southern profile (Profile 2). Finally, the models indicate that the Semail Ophiolite is not present in the subsurface of the Al Jaww Plain. These inferences are consistent with interpretations of the magnetic and seismic data (Figures 13 and 14).

**Magnetic**

Analysis of the magnetic profiles (Figures 13b and 14a) show that the observed magnetic anomaly values are weak (< 50 nT) over most of the study area. This implies that the plain is underlain by low-susceptibility rocks of the Tertiary and Hawasina groups. The increase in the magnitude of the magnetic anomalies (> 300 nT) towards the eastern corner of the survey area (Figure 14a) is attributed to the high-susceptibility rocks of Semail Ophiolite that crop out at the end of Profile 2.

Furthermore, the observed magnetic profiles suggest that the Semail Ophiolite does not extend to the northwest of the area (Figure 13b) although the method cannot discriminate between the Tertiary and Hawasina rocks since both rock types have low magnetic susceptibility. However, both seismic and gravity data indicate the presence of a thick allochthonous sheet in the plain. Therefore, it is concluded that the Hawasina Complex extends further to the northwest of the study area.
DISCUSSION

Style of Deformation

The geophysical investigations involving gravity, magnetic and seismic surveys have provided additional data of the subsurface geology and assisted in the identification of the structures within the study area. Furthermore, optimal results are achieved when a variety of techniques are undertaken and the results combined to yield an integrated subsurface model. Figure 15 shows the combined interpretation of the geophysical and geological data of Al Jaww Plain and surrounding areas.

The results reported here demonstrate the presence of a series of anticlines and synclines extending from Jabal Malaqat-Jabal Mundassa to Jabal Hafit. This series of folds comprise a central anticline flanked by synclines and steeply dipping thrust faults located near the eastern boundary of the plain. The main fold in Al Jaww Plain is a syncline whose axis is about 7.0 km to the east of Jabal Hafit. All folds and faults have axial traces that are sub parallel to Jabal Hafit, which has an axial trace striking about NNW-SSE.

Figure 12: Residual Bouguer anomaly contour map of Al Jaww area. Contour interval is 1 mGal. The E-W dark blue profiles represent the gravity and magnetic profiles, and crosses are gravity stations. The NE-SW purple line represents the seismic reflection profile. Also shown are the approximate positions of folds, thrust fault and the Hawasina and Semail Ophiolite thrust fronts.
Figure 13: (a) Interpreted seismic profile. (b) Magnetic anomaly, observed and calculated residual gravity anomaly values of Profile 1 for the model in Figure 13c. Magnetic anomaly shows low magnetic values associated with thick carbonate sediments and Hawasina Complex. (c) Gravity model for Profile 1. The model extends beyond gravity residual endpoints to avoid edge effects. For location see Figure 12.
Figure 14: (a) Magnetic anomaly, observed and calculated residual gravity anomaly values of Profile 2 for the model in Figure 13b. (b) Gravity model for Profile 2. The model extends beyond gravity residual endpoints to avoid edge effects. Magnetic anomaly shows low magnetic values associated with Semail Ophiolite. Profile 2 extends to the east of the study area closer to where the Semail Ophiolite outcrops. For location see Figure 12.

Gravity and magnetic data were useful in defining the leading edge of the Semail Ophiolite and Hawasina Complex. The Semail Ophiolite is magnetically distinct, permitting its lateral extent to be well-defined, whereas the Hawasina Complex has very low degrees of magnetisation; therefore, the interpretation has been greatly enhanced by the inclusion of the magnetic profiles. The Semail and Hawasina thrust fronts show an interesting relationship: north of Al Jaww Plain the Hawasina front occurs further west towards the foreland than the Semail thrust sheet. This is interpreted as a result of deep-seated structures which controlled the propagation of the thrust sheets. This is consistent with the observation which Dunne et al. (1990) reported in the area south of Hatta Zone (90 km north of study area) where the Hawasina front occurs more towards the foreland than the Sumeini front.

The interpretation of these results is consistent with the other published work in Al Jaww Plain and surrounding areas. For example, Woodward (1994) has documented the presence of steep easterly dipping thrust faults and tight double-plunging folds that trend NNW. Their interpretation was based on detailed mapping of the subsurface structures in Al Jaww Plain and northern Al-Ain using reprocessed seismic reflection data. Noweir and Eloutefi (1997) have mapped the Jabal Malaqat-Jabal...
Mundassa area east of Al Jaww Plain and recognised an asymmetrical anticlinal structure, the Malaqet-Mundassa anticline, which is oriented in a NNW direction with thrust faults running east and parallel to the fold axis. The structure has been interpreted as a consequence of structural ramping of the pre-existing basal thrust beneath the ultramafic rocks (Noweir and Eloutefi, 1997). In addition, studies in Jabal Hafit (Warrak, 1996; Noweir, 2000; Sirat et al., 2007), Jabal Auha-Jabal Huwayyah (Noweir and Alshahrani, 2000), Jabal Rawdah (Noweir and Abdeen, 2000), Jabal Sumeini (Searle et al., 1990), and the Suneinah foreland (Boote et al., 1990) have all suggested NNE-trending folds and thrust faults.

Timing of Deformation

Detailed geophysical investigations in Al Jaww Plain have led to the recognition of two major phases of deformation. A Late Cretaceous phase developed in the eastern part of Al Jaww Plain, which resulted from the emplacement of the Semail Ophiolite and associated sedimentary and volcanic rocks (Sumaini Group and Hawasina and Haybi complexes) onto the eastern margin of the Arabian

Figure 15: Combined interpretation of the data, which is consistent with all available geological and geophysical data. The position of folds and reverse faults are shown. The E-W dark blue lines represent the gravity and magnetic profiles and the NE-SW purple line represents the seismic reflection profile. Also shown are the approximate positions of the Hawasina and Semail Ophiolite thrust fronts.
carbonate shelf. A Tertiary deformation phase, well-developed in the central and western part of Al Jaww Plain, was responsible for the folding and thrusting of the allochthonous units and of the Upper Cretaceous and Tertiary neo-autochthonous units; it is correlated with the Zagros Orogeny in southwest Iran (Searle et al., 1983, 1985, 1990; Searle, 1988). This phase can be seen on the seismic profile (Figure 7) and is likely due to rejuvenation of E-W to ENE-WSW Cretaceous stress regime that occurred in Late Eocene Miocene.

The younger regime has gradually shifted to N-S to NE-SW with the collision of the Arabian-Eurasian Plates and with the opening of the Red Sea and Gulf of Aden which started during the Late Eocene and continues till present-day. This shift is most obvious in the Musandam Peninsula where crustal shortening by thrust stacking is transferred from the NE-trending Dibba Zone to the NS-trending Musandam Zone (Searle, 1988). Furthermore, these pre-existing thrust faults are likely to be reactivated at depth as strike-slip faults giving rise to a more complicated pattern of deformation as propagated upwards throughout the Tertiary rocks cover.

The age of the two phases of deformation cannot be proven directly from the current data set. However, the timing of the deformation can be interpreted in the context of major tectonic events that affected the Arabian Plate in the Late Cretaceous and Tertiary times.

**CONCLUSIONS**

The study demonstrates how the integration of gravity and magnetic methods with seismic reflection data can be employed to optimally map subsurface geological structures. The integrated geophysical survey provided key subsurface information needed to better understand the structure of Al Jaww Plain and surrounding areas.

In summary the study found that:

1. The study area is underlain by a series of folds with axial traces that are sub-parallel to Jabal Hafit. The axial traces of all folds generally trend NNW to SSE and appear to be fault controlled. Both the seismic reflection profile and the gravity data identified these structures.

2. Seismic stratigraphy of the area can be subdivided into four sequences on the basis of their seismic character, these are: shelf carbonates, allochthonous, foreland basin and Tertiary sequences.

3. The Semail Ophiolite is magnetically distinct thus permitting its lateral extent to be well-defined, whereas the Hawasina and Tertiary groups have very low degrees of magnetisation.

4. The measured gravity anomaly gradually decreases from a high near the outcrops of the Semail Ophiolite in the east, to a low over the synclines in the center of the study area.

5. The gradual increase in the gravity anomaly to the west can be explained by the presence of uplifted basement beneath Jabal Hafit. This is consistent with the presence of the back thrust, which has been interpreted as a result of reactivation of deep-rooted faults.

6. A major thrust fault that dips at a steep angle to the east and strikes parallel to the fold axes is modelled at the eastern edge of the plain.

7. Geophysical data suggest that the Semail Ophiolite is limited to the east of the study area. The data also suggest that the Hawasina Complex extends further to the west in the north of Al Jaww Plain close to Al-Ain city.

8. There are two major phases of tectonic events in the area. The first, a Late Cretaceous phase in the eastern part is associated with both high magnetic (> 300 nT) and bouguer gravity (>58 mGal) anomalies. These effects are a result of from the emplacement of the obduction-related allochthonous thrust sheets of the Oman Mountains. The second, a Tertiary deformation phase is developed in most parts of the plain and produces a series of plunging asymmetrical anticlines and synclines. The Tertiary folding and thrusting is formed as a result of regional compressive deformation due to the rejuvenation of the Late Cretaceous thrust faults during post-Middle Eocene times.
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