High-Resolution Electromagnetic and Gravity Imaging of Wadi Sahba in Central Saudi Arabia*

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Abstract

Wadi Sahba in central Saudi Arabia is considered to be one of the most difficult areas for seismic exploration in the whole Kingdom. The extremely low quality of the seismic data in the wadi section prevents the reliable interpretation of the boundaries of important oil and gas fields. The geologic nature of the wadi has been debated with geomorphological, dissolution collapse, and structural processes being proposed. The first model proposes the dissolution of evaporites followed by roof collapses of the formations above as the mechanism generating the wadi depression. The structural model postulates the existence of a major transcurrent fault system, possibly still active, which generated the wadi Sahba depression and other similar structures to the west. Transpressional and transtensional stress regimes along the faults would generate complex patterns of flower faults reaching the surface. The adequate imaging of the near surface with a combination of seismic and non-seismic methods enables better interpretation of the past and present geologic processes, other than providing means for improving seismic imaging by integrated velocity modeling. A high-resolution 3D multigeophysics program was acquired over the full-fold area of recent 3D seismic surveys with the scope of enhancing the near-surface velocity modeling by multi-parameter joint inversion. The program comprised helicopter-borne transient electromagnetics (TEM), audio magnetotellurics (AMT), and precision gravity. Unprecedented high resolution images of the wadi were obtained, which surpassed in quality and details any seismic data acquired to date. TEM, in particular, provided images of the wadi structures at a resolution comparable to seismic reflectivity. A first pass standalone inversion of the data illuminated sharp structural discontinuities that clarified the tectonic processes and associated deformations at the origin of the structure. Evidence from the near-surface investigation support the model of a complex pattern of faults subsiding the outcropping limestone formation of Um Er Radhuma. The extremely high resolution in the horizontal and vertical dimensions, shown in particular by TEM data, provides sharp images of the near surface that we integrate with seismic for generating enhanced velocity models for seismic imaging.

References Cited


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(Geophysics Technology, EXPEC ARC, Saudi Aramco)
Outline

• Wadi Sahba geologic setup
• Motivations and multi-geophysics acquisition
• Data analysis and inversion
• Integration with seismic (joint inversion)
• Conclusions and the way forward
Wadi Sahba - Tectonics


Central Arabian Graben System

Study Area
Wadi Sahba Geologic Challenges

- Anhydrite dissolution (Rus collapse, karsts)
- Left-lateral transcurrent faulting
- Flower faults reaching the surface
- Transpressions/transtensions
- Thick sand dunes

Complex near surface
Poor seismic imaging

Ad-Dahna sand sea

Weijermars, 1998
Wadi Sahba Geophysical Challenge

Pilot acquisition of 2D lines*:

- Precision gravity
- TDEM and AMT
- Joint inversion with seismic travel times

* Colombo, McNeice and Ley, 2012, SEG
Shallow Log Analysis: Resistivity-Velocity

Well-3: $y = 3 \times 10^{-17} x^{5.0613}$
Joint Inversion – Line A

Traveltime inversion model

Conventional processing (tomostatics) ~ 22 km
Joint Inversion – Line A

Integrated velocity model

Joint inversion and redatuming ~ 22 km
Near Surface Analysis Approach

High-resolution multi-geophysics:
- Helicopter-borne TEM
- Precision gravity
- Audio magnetotellurics

Improve velocity model for seismic imaging:
- Single-domain inversion
- Multi-domain inversion (joint)
Helicopter TEM Data Acquisition

~21 km

~18 km
Helicopter TEM Data Acquisition

100 m Xline spacing
~2.7 m Inline spacing after stacking
~1.6 Million HeliTEM points
Helicopter TEM Data Processing

Data processing:

- Automatic editing of outliers
- Masking of infrastructures
- Tilt correction for Tx and Rx
- System attitude accounted in the forward modeling
Helicopter TEM Data Processing

Data processing:

• Automatic editing of outliers
• Masking of infrastructures
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Helicopter TEM Data Processing
Helicopter TEM Data Processing
Helicopter TEM Inversion

1D laterally-constrained inversion*

*Rovetta, Colombo and McNeice, 2013, SEG
AMT Data Static Correction

TEM model response

Resistivity Ohm.m

1:1
AMT Data Static Correction

TEM model response
AMT Data Static Correction

TEM model response
3D AMT Inversion

1 = TEM inversion
2 = AMT inversion
3D AMT Inversion

1 = TEM inversion
2 = AMT inversion
Gravity Data Processing

Observed (residual) reduced to TOPO

1D Model response reduced to TOPO

Seismic time slice 160ms
Gravity Data Processing

- Observed (residual) reduced to TOPO
- 1D Model response reduced to TOPO
- Observed - Model response

Images show the distribution of gravity data in mGal.
Summary of Standalone Inversion Results

<table>
<thead>
<tr>
<th>Tomography</th>
<th>TEM inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ohm.m)</td>
<td>100</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>2000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AMT inversion</th>
<th>Gravity inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ohm.m)</td>
<td>100</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>-2.28</td>
</tr>
</tbody>
</table>

3D TEM – Seismic Joint Inversion

1. Multiparameter model space

\[ m = [m_1 m_2 ...]^T \]

2. Pattern constraints (H) & empirical relations (W)

\[ \Phi = r^T V^{-1} r + \lambda_1 m^T L^T L m + \lambda_2 m^T H m \]

- Data residual term
- Regularization
- Structural Pattern

3. Least-square minimization of \( \Phi \)
Joint Inversion Results

Elevation = 340 m a.s.l.

Topographic elevation

- Elevation (m)
  - 360
  - 370
  - 380
  - 390
  - 400
  - 410
  - 420
  - 430
  - 440
  - 450
  - 460
  - 470
  - 480
  - 490
  - 500

- P-velocity (m/s)
  - 1500
  - 1750
  - 2000
  - 2250
  - 2500
  - 2750
  - 3000
  - 3250
  - 3500
  - 3750

- Resistivity (Ohm.m)
  - 10
  - 100
Joint Inversion Results

Elevation = 340 m a.s.l.

Resistivity from TEM Inversion

P-velocity (m/s)

Resistivity (Ohm.m)
Joint Inversion Results

Elevation=340 m a.s.l.

P-velocity from Joint TEM-Seismic Inversion (rms = 32.8 ms)

P-velocity (m/s)
- 3750
- 3500
- 3250
- 3000
- 2750
- 2500
- 2250
- 2000
- 1750
- 1500

Resistivity (Ohm.m)
- 100
- 10
Joint Inversion Results

Elevation=340 m a.s.l.

P-velocity (m/s)

Resistivity (Ohm.m)

Elevation (m)

P-velocity from tomographic inversion (rms = 32.8 ms)
Joint Inversion Results

Elevation=220 m a.s.l.

TEM inversion

P-velocity (m/s)

Resistivity (Ohm.m)
Joint Inversion Results

P-velocity from joint TEM-seismic inversion

Elevation=220 m a.s.l.

P-velocity (m/s)

Resistivity (Ohm.m)
Joint Inversion Results

Elevation=220 m a.s.l.

P-velocity from tomographic inversion

P-velocity (m/s)

Resistivity (Ohm.m)
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion

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Color bar for P-velocity (m/s) and Resistivity (Ohm.m):
- P-velocity:
  - 3750
  - 3500
  - 3250
  - 3000
  - 2750
  - 2500
  - 2250
  - 2000
  - 1750
  - 1500
- Resistivity:
  - 10
  - 100
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion

A-B-C

P-velocity (m/s)  Resistivity (Ohm.m)
3750  100
3500  3750
3250  3500
3000  3250
2750  3000
2500  2750
2250  2500
2000  2250
1750  2000
1500  1750
10  10
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Joint Inversion Results

1. Standalone tomographic inversion
2. Joint TEM seismic inversion
3. Standalone TEM inversion
Conclusions and Ongoing Work

- TEM provides details of the near surface at a resolution comparable to seismic reflectivity.
- TEM and precision gravity show higher resolution than velocity fields as derived from typical tomographic inversions.
- TEM and Seismic 3D joint inversion (cooperative) boost resolution of seismic velocity fields.
- Work will continue to a full (simultaneous) joint inversion.
Acknowledgments

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