Shale Diapirism and Associated Folding History in the South Caspian Basin (Offshore Azerbaijan)*

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Abstract

The Caspian Sea is a Neogene basin associated with the Alpine-Himalayan collision and has one of the major sedimentary accumulations in the world. The South Caspian Basin, in particular, comprises a thick (~10 km), fluviodeltaic sequence, the Productive Series, deposited during the late Miocene to middle Pliocene (~6-3 Ma) over a rapidly subsiding crust of probable oceanic nature. The uppermost sedimentary cover is affected by numerous detachment folds cored by overpressured, organic-rich muds derived from the marine source rock of the Maykop Series; of Oligocene to early Miocene age. The tectonic evolution of the South Caspian Basin triggered mud migration of the Maykop Series trapping oil and gas in anticlines structures. Major reservoirs are concentrated there in the Productive Series and the stratigraphic seal is a late Pliocene unconformity (~3 Ma).

Our study focused on the geometrical analysis of the folding history in offshore Azerbaijan. We use a post-stack 3D seismic cube tied with data from two exploration wells. The overall geometry of the Productive Series reflects low-dipping sequences of different delta systems propagating basinward, and sedimentary thickness is approximately constant. Fold geometries evolve along strike from symmetrical, gentle anticlines, to close, box-like folds that can host double-vergence reverse faults. Anticline culmination coincides commonly with an hourglass-like mud diapir, where mud ascent and extrusion in the upper tear created vertical welds.

Folding occurred simultaneously with mud diapir perforation and extrusion, along with tilting and differential subsidence toward basin centre, whilst shortening rates vary along fold axis. Maximum shortening estimates are inferred in regions pierced by the overpressured mud, and folding structures indicate a single, low-dipping detachment level at 9.5-11 km depth. A first major folding pulse occurred during the middle Pliocene (~3.5-3.1 Ma), toward the end of the deposition of the Upper Productive Series. Folding rates decreased afterwards during the late Pliocene, although a second, syn-growth folding episode occurred at ~1.5-1 Ma.

We also implement the algorithms to analyze in 3D this detachment folding-type that departs from the classic examples because punctuated...
deformation is accompanied by progressive tilting and differential subsidence between fold flanks.

References


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Objectives

• Characterize in 3D the fold shape
• Reconstruct the $xy-t$ evolution of the folding history (shortening magnitude and rate)
• Infer-relationships between folding and mud-diapirism
Objectives

- Structural control on subsurface fluid migration
1. Geology of the South Caspian Basin

from numerous sources
Oc. crust from Berberian (1983)
1. Geology of the South Caspian Basin

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Series / Stages</th>
<th>Formations</th>
<th>Sea Level (m)</th>
</tr>
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<tbody>
<tr>
<td>11.5</td>
<td>Pleistocene</td>
<td>Gelasian</td>
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<tr>
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<td>Apsheron</td>
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<td>2.59</td>
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<td>Akchagyl</td>
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<tr>
<td>3.60</td>
<td>Piacenzian</td>
<td>Surakhany</td>
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<td>Tortonian</td>
<td>Macotian</td>
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<td>8.00</td>
<td>Sarmatian</td>
<td>Distomaceous</td>
<td>8.2</td>
</tr>
</tbody>
</table>

- Abreu and Nummedal (2007)
- Inan et al. (1997)
- Jones and Simmons (1996)
- Krijgsman et al. (2010)
- Miller et al. (2005)
2. Structure
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2. Structure

PS-top (3.1 Ma)
2. Structure

PS-top (3.1 Ma)

3 km
2. Structure

PS-top (3.1 Ma)
Folding and Shale Diapirism in the South Caspian Basin

2. Structure

PS-top (3.1 Ma)

3 km
3. Shortening magnitude and history

\[
\bar{S}(z) = \frac{A_{sr}}{H_d}
\]

\[
S(z) = L_d - L
\]

\[
S_c = L_d - L
\]

Shortening:
- curvimetric \((S_c)\)
- \(S_a\), based \(A_{sr}/z\)

\[
S_a = \frac{dA_{sr}}{dz}
\]

González-Mieres and Suppe (2006)
Epard and Groshong (1993)
Poblet et al. (2004)
3. Shortening magnitude and history

Non-parametric Statistics is used to fit the complete fold shape
3. Shortening magnitude and history

```
Non-pierced fold
(S sect.)

sea-floor
Apsh
Akch

“incremental” $S_c =$
difference between $S_c$
at bottom and upper
surfaces per layer
```

Curvimeteric Shortening (m)

High above PS-bottom (m)
3. Shortening magnitude and history

**Non-pierced fold (S sect.)**

- **Linear fit:** $R^2 = 0.71$
- **Polynomial fit:** $R^2 = 0.95$
- **Detachment depth:** 2797 m below reference (9368 m bsl)

**Key Points:**
- **Lower PS**
- **Upper PS**
- **Akch**
- **Apsh**
- **Sea-floor**

**Graph Details:**
- Y-axis: Structural Area (x10^2 m^2)
- X-axis: High above PS-bottom (m)
- Data points and trends indicated.
3. Shortening magnitude and history

- 3 fold sections (non-pierced anticlines)
  - $S_c = 1808$ m (14%)
  - $S_c = 1230$ m (9%)
  - $S_c = 995$ m (6%)

- Curvilinear Shortening with respect to final (%)

- Sedimentation rate (mm/yr)

- Age (Ma): 0, 1, 2, 3, 4, 5, 6
3. Shortening magnitude and history

![Diagram showing 3 fold sections (non-pierced anticlines)](image)
Conclusions

- Anticline culmination shows a sigmoidal axial trace with curved and nearly-radial, crestal faults
- The apparent pre-growth sequence represented by the PS series (> 3.1 Ma) register ~55-70% of the total shortening
- An early folding event is identified at the end of the PS series, during Surakhani deposition (~3.2-3.6 Ma), which coincides with a pulse in basin tilt and high sedimentation rates (5-6 mm/y)
- The syn-growth (<3.1 Ma) fold evolution had a maximum shortening event at ~1.7 Ma (Akch), decreasing monotonically up to Present
Conclusions

- Overpressured-mud crosscuts the anticline structure in those sections with shortening >15%
- This detachment anticline has a decoupling layer/surface placed at 9.5-10 km depth.
- The studied fold has a rounded geometry that departs from the standard detachment-fold model shaped by parallel layers