Carbonates in a foreland basin petroleum province: the Zagros margin of the Arabian Plate

By Andrew Horbury, 20/10/15
Context

• Statement of the obvious: there is a lot of petroleum in the Middle East
• However.... much of this is reservoired in carbonates that formed during plate compression, which is unusual for a foreland basin
• Why did this happen?
• Why is this important?
Introduction

• Basin Evolution
• Pre-Foreland Geology
• Foreland Geology
• Discussion
• Conclusions
### Introduction: Palaeogeog Map Legend

#### Subsurface Facies

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Basin Evolution
Basin Evolution

- Thick Cenozoic sediment wedge

From Goff et al., 1995
Basin Evolution

- Palaeocene-Eocene

Sediment wedge up to 2000m thick on NE margin of basin

From Goff et al., 1995
Basin Evolution

- Palaeocene-Eocene

Sediment wedge up to 2000m thick on NE margin of basin
Sediment starved basin centre

From Goff et al., 1995
Basin Evolution

- **Palaeocene–Eocene**

  Sediment wedge up to 2000m thick on NE margin of basin
  Sediment starved basin centre
  Broad platform <1000m thick on SW side

  From Goff et al., 1995
Basin Evolution

- Oligocene-Lower Miocene

Sediments >600m thick in basin centre, plug unfilled end-Eocene accommodation space

From Goff et al., 1995
Basin Evolution

- Mid Miocene - Recent

Loading of second basin formed due to strong final compression; very thick (>4000m) fill in centre

From Goff et al., 1995
Pre-Foreland
Pre-Foreland

- Pre-Turonian, only exposed in High Zagros

Surdash area, Kurdistan
Pre-Foreland

- Source rocks largely sit in pre-foreland

Sargelu Formation, Bajocian-Bathonian, Sargelu, Iraqi Kurdistan
Pre-Foreland

- In intrashelf basins, e.g. Kazhdumi (Albian)
Pre-Foreland

- Clastics enter from SW, e.g. Burgan (Albian)
Pre-Foreland

- Carbonate platforms on Tethyan side (Albian)

Kazhdumi intashelf basin
Burgan Fm.
Sarvak Fm.
Pre-Foreland

- Carbonate reservoirs of Sarvak and Qamchuqa
Pre-Foreland

- Carbonate reservoirs of Qamchuqa in Iraq

Qamchuqa platform above Sarmord slope facies, Qamchuqa Gorge, Iraqi Kurdistan
Pre-Foreland

• And Sarvak in Iran
Pre-Foreland

- And Sarvak in Iran

Courtesy B. Vincent
Pre-Foreland

- High temperature dolomite reservoir

Zebra dolomite fabrics, Qamchuqa platform, Qamchuqa Gorge, Iraqi Kurdistan
Pre-Foreland

- Top-Mishrif/Sarvak (end of pre-foreland)
Pre-Foreland: Summary

- Commonly developed intrashelf basins that may have highly restricted (=source rock) and often evaporitic infills
- Pre-foreland basin geometries largely independent of present-day plate margin palaeogeographic context
- Thick (1-1.5km) and often aggrading carbonate platforms around basin margins
- Most clastics enter from SW side of plate
Pre-Foreland: Petroleum Geology

- High-temperature dolomite reservoirs common
- Fracture-enhanced; dual porosity systems
- Problems: limestones generally very low porosity (in f.t.b.)
- Problems: typically poor quality intra-Pre Foreland sealing facies which usually fracture/fail within high-amplitude anticlines
Foreland

• Four phases of development:
  – Upper Cretaceous to Eocene
  – Oligocene to Aquitanian
  – Burdigalian
  – Middle Miocene to Recent
Foreland: Upper Cretaceous

From Saura et al., 2011
Foreland: Upper Cretaceous

- Upper Cretaceous and Palaeogene continuum:

From Saura et al., 2011
Foreland: Upper Cretaceous

- Massive SW-prograding sediment wedge

From Saura et al., 2011
Foreland: Upper Cretaceous

- Initial drowning of Albian-Cenomanian platforms during Turonian (Kometan, Ilam)
Foreland: Upper Cretaceous

- Initial drowning of Albian-Cenomanian platforms during Turonian (Kometan, Ilam)

Qamchuqa platform, Kometan basinal limestones, Qamchuqa Gorge, Iraqi Kurdistan
Foreland: Upper Cretaceous

- Initially generally deeper-water (e.g. Ilam)

Ilam basinal carbonates above older Sarvak platform, Lurestan
Foreland: Upper Cretaceous

- Later development of platforms and flysch

Isolated platforms in SE Turkey and N. Iraq
Foreland: Upper Cretaceous

- Later development of platforms and flysch

Isolated platforms in SE Turkey and N. Iraq
Flysch input off obducted ophiolites
Foreland: Upper Cretaceous

- Later development of platforms and flysch

- Isolated platforms in SE Turkey and N. Iraq
- Flysch input off obducted ophiolites
- Deepwater marls
Foreland: Upper Cretaceous

- ‘flyschoid’ coarse clastics to marls
Foreland: Upper Cretaceous

- Tanjero, Shiranish (here) in Iraq,
Foreland: Upper Cretaceous

- Gurpi (here), Amiran in Iran

Courtesy B. Vincent

Kabir Kuh, Lurestan
Foreland: Late K Petroleum Geology

- Isolated carbonate platforms (stratigraphic traps):
- Productive in SE Turkey and NW Iraq (Tawke)
- Fractured basinal carbonate reservoirs, e.g. Ain Zalah, produce best where fractures tap pre-Foreland ‘sump’ reservoir
- Sealed by flyschoid clastics
- Risk of poor topseal and thief sands is high
Foreland: Late K Petroleum Geology

- Also acts as moderate quality marly seal (sometimes!) to pre-foreland reservoirs

Shiranish over Qamchuqa, Dokan, Iraqi Kurdistan
Foreland: Palaeocene-Eocene
Foreland: Palaeocene-Eocene

- 2 sequences:
  - Palaeocene to Early Eocene
  - Middle-Late Eocene
Foreland: Palaeocene-Eocene

- Palaeocene to Early Eocene isopach

Map showing:
- Flyschoid wedge
- Sediment starved basin centre
- SW carbonate shelf
Foreland: Palaeocene-Eocene

- Middle-Late Eocene isopach (similar elements)

Flyschoid wedge

Sediment starved basin centre

SW carbonate shelf
Foreland: Palaeocene-Eocene

- **Example: Late Eocene (Bartonian)**

![Map 13a](image)

- **Basin continuous from Med to Hormuz**
Foreland: Palaeocene-Eocene

- Example: Late Eocene (Bartonian)

- ‘narrow’ carbonate shelf on NE side
- Basin continuous from Med to Hormuz
Foreland: Palaeocene-Eocene

• Example: Late Eocene (Bartonian)
Foreland: Palaeocene-Eocene

- Eocene carbonate reservoir rocks

Jebel Bamu, Iraqi Kurdistan
Foreland: Palaeocene-Eocene

- Eocene carbonate reservoir rocks (Avanah)

Jebel Bamu, Iraqi Kurdistan
Foreland: Palaeocene-Eocene

- Ophiolite derived clastics (from the NE)

Jebel Aj Dagh, Iraqi Kurdistan
Foreland: Pal.-Eocene Summary

- Development of continuous rimmed shelf margins in Pal-Eocene
- Some isolated carbonate platforms on inversion anticlines over K basins (J. Sinjar)
- Produce as deep pay within big anticlines (Avanah and Khurmala of Kirkuk)
- Always sealed directly by Miocene evaporites
- Possible secondary reservoirs in flysch clastics but these may be very immature
• Produce as deep pay within big anticlines (Avanah and Khurmala domes of Kirkuk) and may be karstified beneath big sequence boundaries (Taq Taq)
• Generally poor/less predictable quality reservoir compared to Oligo-Miocene
• Almost always sealed directly beneath Miocene evaporites so only work in areas of Miocene foreland bulge
Foreland: Oligocene – Ey. Aquitanian
Foreland: Oligocene – Ey. Aquitanian

- Four sequences but all very similar
- Located almost exclusively within axis of former Eocene basin
- ‘downdip’ of Eocene margin
Foreland: Oligocene – Ey. Aquitanian

- Oligocene isopach

Narrow attached rimmed shelf in north
Foreland: Oligocene – Ey. Aquitanian

- Oligocene isopach

Narrow attached rimmed shelf in north
Uplifted area of exposed Eocene
Foreland: Oligocene – Ey. Aquitanian

- Oligocene isopach

Narrow attached rimmed shelf in north
Uplifted area of exposed Eocene
Starved basin centre
Foreland: Oligocene – Ey. Aquitanian

- Oligocene isopach

- Narrow attached rimmed shelf in north
- Uplifted area of exposed Eocene
- Starved basin centre
- Wide attached rimmed shelf in south
Foreland: Oligocene – Ey. Aquitanian

- Oligocene (latest Chattian)
Foreland: Oligocene – Ey. Aquitanian

- Oligocene (latest Chattian)

Map 10a
late Late Chattian
HST to Pg50 MFS
(24.1 Ma)
Map dated at 23.3 Ma

Mini-basins

‘Necks’
Foreland: Oligocene – Ey. Aquitanian

- Oligocene (latest Chattian)

Map 10a
late Late Chattian
HST to Pg50 MFS
(24.1 Ma)
Map dated at 23.3 Ma

- Mini-basins
- 'Necks'
- Clastics derived from uplift in Red Sea area
Foreland: Oligocene – Ey. Aquitanian

- Progradational and offlapping carbonates

Courtesy N. Pickard
Foreland: Oligocene – Ey. Aquitanian

- Progradational and offlapping carbonates

Tang-e Gurguda, Iran

Courtesy N. Pickard
Foreland: Oligocene – Ey. Aquitanian

- Shingled/offlapping reservoir, e.g. Kirkuk

Due to local uplift in NW of structure (?inversion of underlying Cretaceous basin?)

After Daniel, 1954
Foreland: Oligocene – Ey. Aquitanian

- Ghar, Ahwaz clastics enter from SW

Lowstand bypass of exposed shelf, sediment source area in vicinity of Red Sea, bank up in front of shelf margins
Foreland: Oligocene – Ey. Aquitanian

• BUT stacked stratigraphy = even subsidence

L. Fars
Jeribe Fm.
Bajawan Fm.
Base-Bajawan congloms
Sheik Alas Fm.
Avanah Fm.

Jebel Aj Dagh, Iraqi Kurdistan (some 50km SE of Kirkuk)
Foreland: Oligocene – Ey. Aquitanian

- Ey Miocene: Ey Aquitanian
Foreland: Oligocene – Ey. Aquitanian

- Ey Miocene: (Euphrates, Middle Asmari)
Foreland: Oligocene – Ey. Aquitanian

- Aquitanian reservoir rocks
Foreland: Olig. – Ey. Aquit., Summary

- Offlapping, narrow, land-attached carbonate shelves on NE side of basin, whose rimmed margins are continuous
- Affected by local tectonics (foreland uplift) and karstification e.g. Kirkuk
- Lowstand-dominated clastics on SW margins (Ghar, Ahwaz SST)
- Progradation ‘necked off’ basins progressively, increasing restriction
• Some organic rich rocks with very high TOC’s develop in deeper-water Serikagni (Iraq) and upper Pabdeh (Iran) fms.
• Leads to development of first lowstand drawdown anhydrites (basal anhydrite) that appear in very latest Oligocene

- Best reservoir in the margins rather than basin centre work best;
- Reservoirs of Lower/Middle Asmari, Kirkuk Group, Euphrates; Ahwaz SST also;
- Optimum facies are fore-reef; reef/lagoon tighter;
- Main pay within big anticlines (Lwr. Asmari and Ahwaz Sandstone in Dezful embayment; Kirkuk Gp. of Kirkuk; Euphrates in Ajeel, and Middle Asmari in Naft Khaneh)

- Reservoir varies strongly in a dip sense, but homogeneous along-strike, is vertically thick and can be massive
- Sealed directly by Miocene evaporites; locally by Aquitanian evaporites (Dhiban, Kalhur) but more commonly the younger Gachsaran/Lower Fars-Fatah of Middle Miocene age
- Potential intrabasinal source rocks but these will only work only in areas of deepest burial
Foreland: Lt Aquitanian-Ey Burdigalian
Foreland: Lt Aquitanian-Ey Burdigalian

- Significant lowstand at base of interval
- Simple couplet of drawdown evaporite plug overlain by carbonate shelf
Foreland: Lt Aquitanian-Ey Burdigalian

- Early Miocene: isopach

Absent over foreland bulge
Extensive shelf system dominates basin centre
Foreland: Lt Aquitanian-Ey Burdigalian

- Early Miocene: Mid Aquitanian lowstand
Foreland: Lt Aquitanian-Ey Burdigalian

- Early Miocene: (Dhiban, Kalhur)

Map 8d
early Middle
Aquitanian
LST to Ng15 MFS
(20.6 Ma)
Map dated 21.6 Ma

Halite basin centre plug
Local coarser clastics
Foreland: Lt Aquitanian-Ey Burdigalian

- Early Miocene: Early Burdigalian
Foreland: Lt Aquitanian-Ey Burdigalian

- Early Miocene: (Jeribe, U. Asmari)
Foreland: Lt Aquitanian-Ey Burdigalian

- Burdigalian reservoir rocks
Foreland: Lt Aquitanian-Ey Burdigalian

- Burdigalian reservoir rocks
Foreland: Lt Aq. - Ey Burd. Summary

- Major u/c and onlap above older rocks (locally Albian in Govanda area) indicates renewed foreland uplift
- Extensive sheet-like basin centre restricted shelf, no significant lateral facies changes, no obvious shelf margins or basinal facies
- Continued input of clastics from SW

- Often reservoir quality is enhanced due to dolomitization
- Produce within big basin centre anticlines (Jeribe in East Baghdad, Hamrin; Upper Asmari of Naft Khaneh)
- Sealed directly by Miocene evaporites
- Lateral continuity in dip and strike directions, but much vertical heterogeneity (cyclicity) with anhydrite interbeds leading to significant strong layering and compartmentalization
Foreland: Middle Miocene
Foreland: Middle Miocene

- Miocene: Lt. Burdigalian – Langhian isopach
Foreland: Middle Miocene

- Late Burdigalian - Langhian

Map 6a
Late Burdigalian HST to Ng30 MFS (18 Ma)
Map dated at 17.8 Ma

- Halite in basin centre
- Redbed clastics appear on basin margins
Foreland: Middle Miocene

- Fatha (Lower Fars) / Gachsaran (regional seal) Flank of Jebel Aj Dagh, Iraqi Kurdistan
Foreland: Late Miocene-Pliocene
Foreland: Late Miocene-Pliocene

- ‘Upper Fars’ fine grained continental clastics

Near Kor Mor, Iraqi Kurdistan
Foreland: Late Miocene-Pliocene

- ‘Upper Fars’ and Bakhtiar: final alluvial infill

Qara Dagh, Iraqi Kurdistan
Foreland: Late Miocene-Pliocene

- Upper Fars and Bakhtiari: burial up to 5-6km
Foreland: Late Miocene-Pliocene

- Bakhtiari unconformable over Shiranish (Lt K)
Foreland: Late Miocene-Pliocene

- Late Pliocene compression: Pleistocene onlap onto Pliocene

Near Derbendikhan, Iraqi Kurdistan
• Late Pliocene compression: development of high relief/amplitude anticlines (‘whalebacks’)
Foreland: Late Miocene-Pliocene

- Elongated and commonly over 100km long

Sulaimaniyah area, Iraqi Kurdistan
Foreland: Late Miocene-Pliocene

- Easily visible on seismic as at surface
Foreland: Late Miocene-Pliocene

- BUT also some beneath surface synclines
Foreland: Summary

- Onset of ophiolite obduction and collision of island arcs along NE margin of plate in Turonian
- Beginning of intra-plate compression and foreland basin development along whole margin
- Evidence of local structural uplift throughout foreland phase (e.g. Kirkuk, Jebel Sinjar)
Foreland: Summary

- Basin shows geometry related to present-day compressional plate margin
- Early basin was underfilled, thick clastics pond on NE margin, bordered by carbonate shelf
- Necking to form intermediate basin(s) that have carbonate shelves on margins but remain sediment starved in their centres
- Isolated basins become evaporite plugged
- Final basins are coarse clastic dominated as compression and deformation increased
Foreland: Pet. Geology Summary

- Dual porosity reservoir systems; matrix property is commonly fracture-enhanced
- World-class caprock (Gachsaran/L. Fars)
- Problems: heavy oil (<API, >sulphur)
- Problems: if either low matrix porosity or no fractures
Discussion
Discussion

- Analogue: PNG/Coral Sea?
Discussion

- Modern carbonates in a foreland basin

From Tcherepanov et al., 2008
Discussion

- Growing in the Coral Sea to S/SW of PNG

From Tcherepanov et al., 2008

Broad carbonate province distant from source of clastic input
Discussion

- Growing in the Coral Sea to S/SW of PNG

From Tcherepanov et al., 2008

Broad carbonate province distant from source of clastic input

Narrower, more localized carbonate province close to source of clastic input
Discussion

- Similar subduction zone, arc-related setting:
Discussion

- Similar subduction zone, arc-related setting:

![Map showing subduction zones and Ophiolites](image-url)
Discussion

• Both settings (Zagros in Lt K-Palaeog., PNG) allowed carbonate platforms to grow in areas of active compression
• But deformation was never so intense as to overwhelm the basin with clastic supply
• Carbonates in both cases are associated with often exceptional reservoir quality and hydrocarbon reservoirs
• Clastics ponded updip and/or seal carbonates
Conclusions
Conclusions: General

- Foreland basin development allowed creation of significant accommodation space
- Clastic input was limited because initial collision was not continent:continent
- Underfilled space was notably encroached upon by carbonate platforms (reservoirs)
- As space restricted, basins became isolated from Tethys and significant evaporite deposits then developed during lowstands
Conclusions: General

- Progressively stronger deformation then causes input of increasingly large volumes of increasingly coarse clastics
- Loads source rocks leading to expulsion of oil, and causes fracturing of reservoirs
- Therefore we see a dominance of fractured, dual porosity carbonate reservoirs, sealed by evaporites
Conclusions: General

- Can apply lessons learnt in recent Kurdistan projects along-strike into possible new ventures in Iran; there is regional synergy
- But local complexity is always expected due to the interplay of local tectonics (e.g. basin inversion) within this compressional setting
Conclusions: Other

- Minor reservoir potential also in the very thick flyschoid Upper Cretaceous to Eocene clastics, but these are complex, poorly subdivided and with poorly understood stratigraphy, also being mineralogically immature (?diagenesis/poroperm issues),

- Some reservoir potential also in Upper Miocene and Pliocene clastics but sealing facies become a major issue at higher stratigraphic levels (caprock issue)
Many thanks for listening!

With thanks to Jo Garland, Benoit Vincent and Neil Pickard for earlier discussions on this theme, and providing graphics.