Characterization of Karst and Fault-Fracture Networks and their Impact on Thermal EOR in a Tight Carbonate Reservoir, Awali Field, Bahrain*

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Abstract

Extreme ranges in reservoir properties challenge the effectiveness of thermal enhanced oil recovery projects, but understanding these extremes unlocks development opportunities. For example, the Cretaceous Mishrif Limestone in Bahrain was subject to faulting, fracturing, erosion and karsting. Locally named the “Rubble Formation”, dissolution-enhanced tectonic fractures and well-connected karst vugs and channels have permeabilities tens to hundreds of times that of the tight matrix. Core and well logs capture episodes of matrix dissolution, brecciation, soil infiltration, and compaction associated with karst cavity formation and collapse. Crevasses extend down more than ten feet and cavity collapse is observed deeper. Often the karst fabric exhibits elevated permeabilities, as demonstrated by distributed temperature surveys (DTS) in horizontal wells where injected steam enters the karst intervals while bypassing unaltered formation.

Two fault systems slice through the Awali Anticline. One set are NW-SE wrench faults with narrow damage zones. The second set are NNE-SSW conjugate normal faults that form a graben complex with abundant NE-SW fractures. Wellbore image logs and core show tectonic fractures with solution-enhanced apertures, indicating their presence during subaerial exposure and the likelihood they facilitated the deep vertical infiltration of leaching meteoric fluids. Intersecting karst, faults, and fractures dictate fluid flow. Primary wells with 10-20% matrix water saturation produce with 70-100% water cut. Production logging tools, DTS, and temperature logs run on horizontal wells show produced fluids and injected steam enter and exit the wellbores through these features. Formation brine and condensed steam support fluid contacts within the well-connected secondary porosity such that contacts rise during steam injection and fall during fluid production. The higher conductivity improves steam injectivity, however these features are not confined to the Rubble, so significant steam is lost out of zone instead of heating near-wellbore matrix oil. Wells producing from the underlying reservoir experience large increases in water production soon after Rubble steam injection commences. An integrated study was undertaken to delineate Rubble karst and fracture networks for guiding more effective steam placement and containment so to maximize heat transfer to the matrix oil. Methods, results, and recommendations will be shared in this article.

Selected Reference

Wennberg, O.P., G. Casini, S. Jonoud, and D. Peacock, 2016, The characteristics of open fractures in carbonate reservoirs and their impact on fluid flow: A discussion: Petroleum Geoscience, v. 22/1, p. 91-104.

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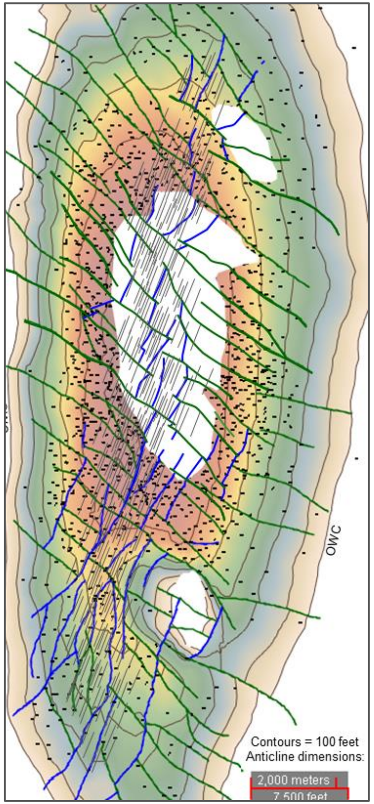
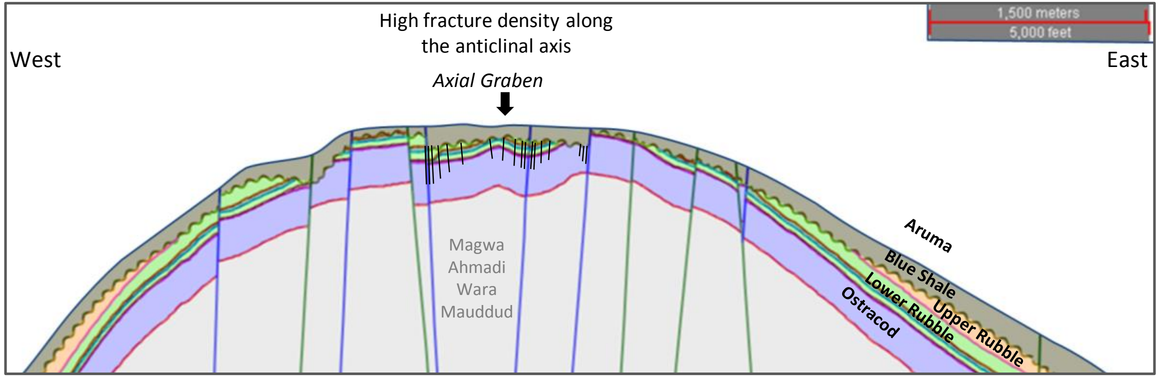
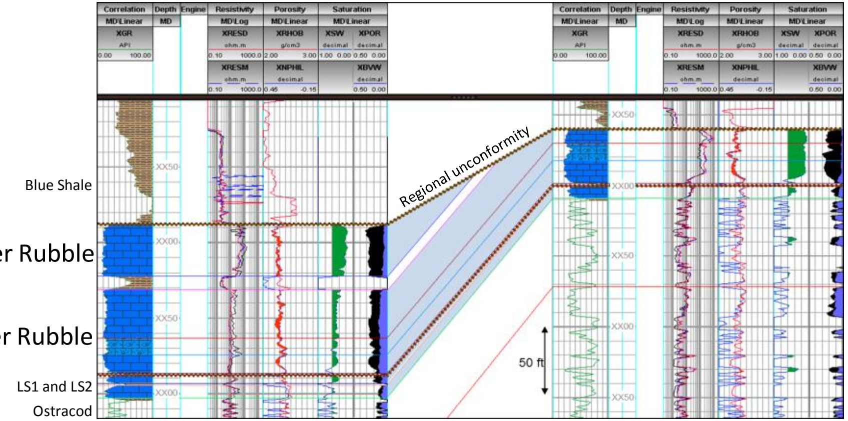
TATWEER PETROLEUM

Upper Cretaceous Rubble (Mishrif) Limestone Reservoir in Bahrain Field

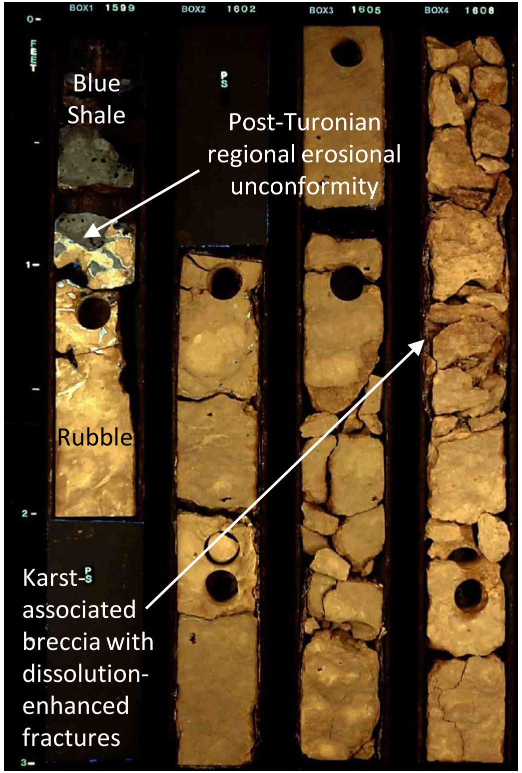




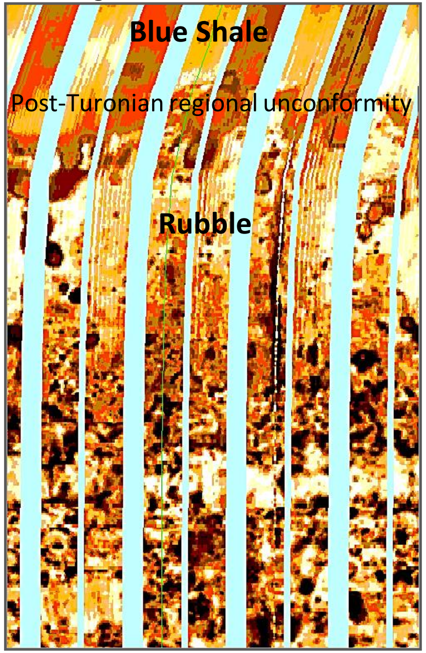


Late-Cretaceous Post-Turonian Regional Unconformity

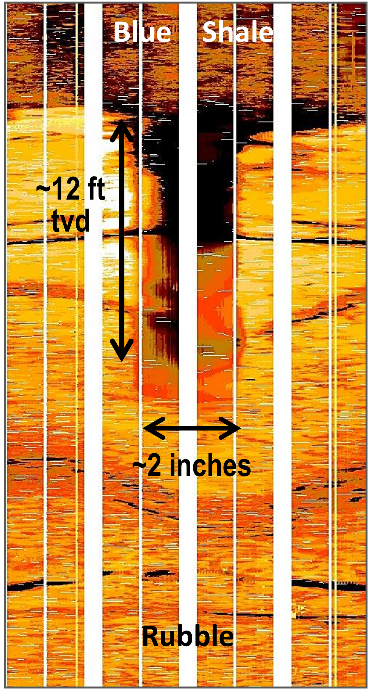
Top 12 ft of Rubble (Mishrif) core under UV light



FMI image at Blue Shale-Rubble contact



FMI image with 12 ft deep fissure



8½ inch drill bit

Awali Field outcrop, Bahrain

Jabel Hafit area, UAE (Dr. Sirat)

Karst Associated Dissolution and Breccia

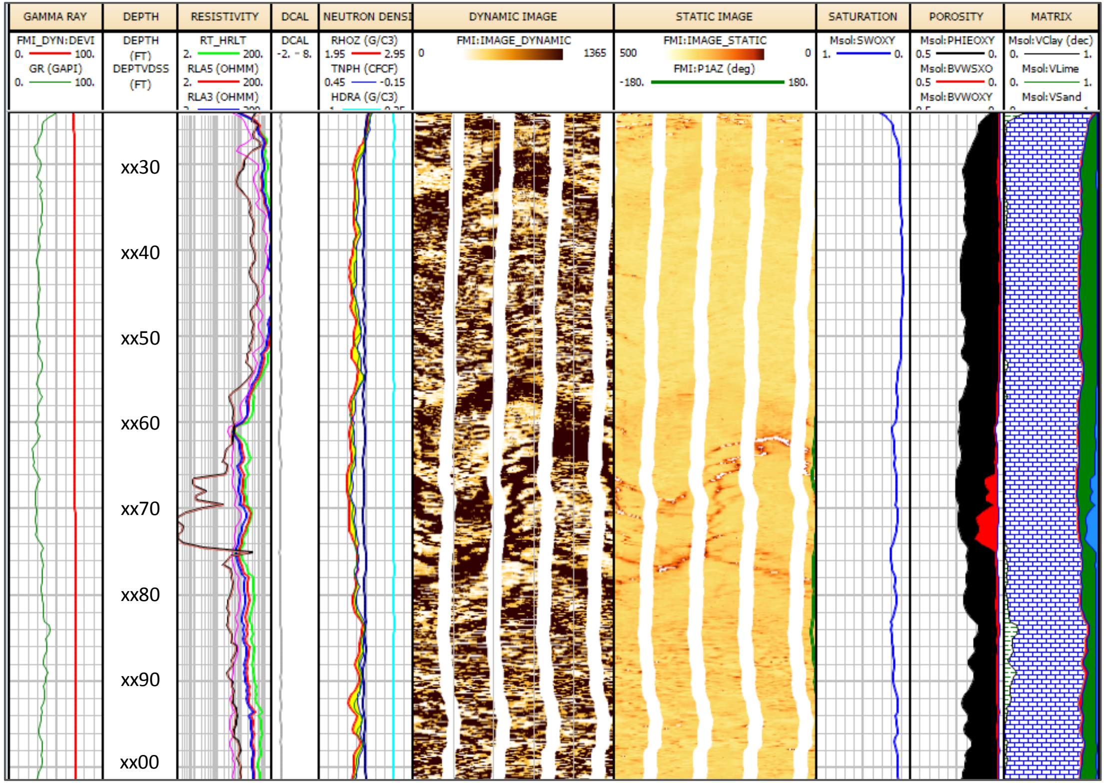
Large dissolution features

Floating clasts in karst sediment fill

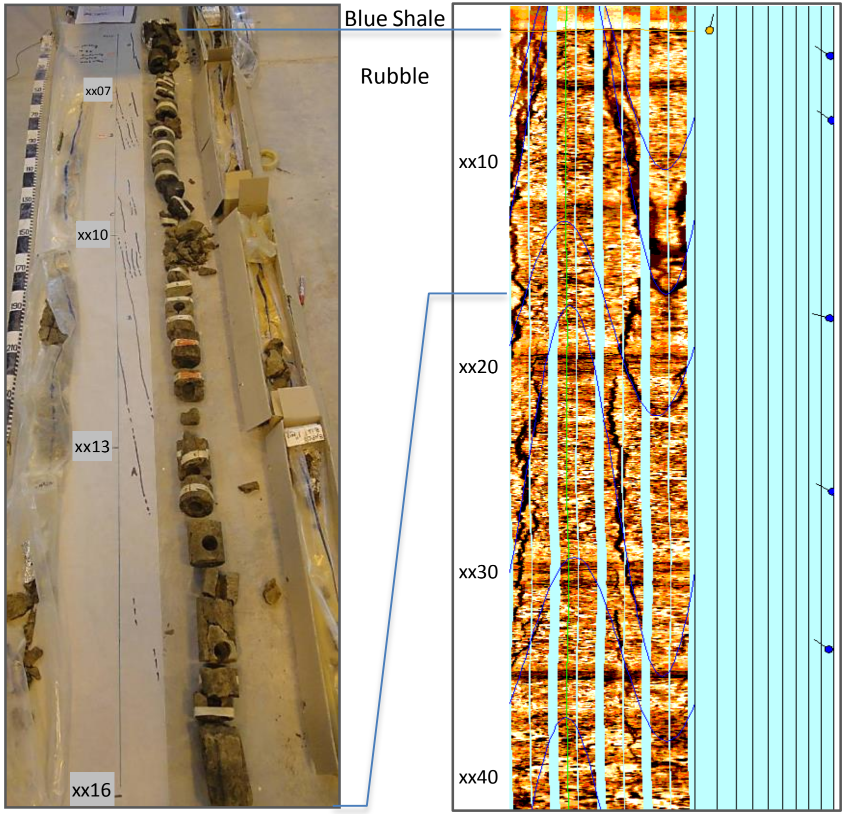
Partially cemented breccia fractures

Leached matrix breccia rims

Composite wireline log showing porous and permeable breccia fractures

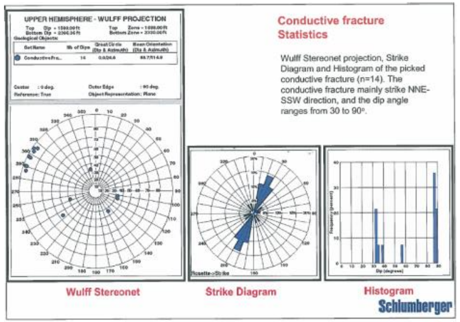


Faults and Associated Fractures



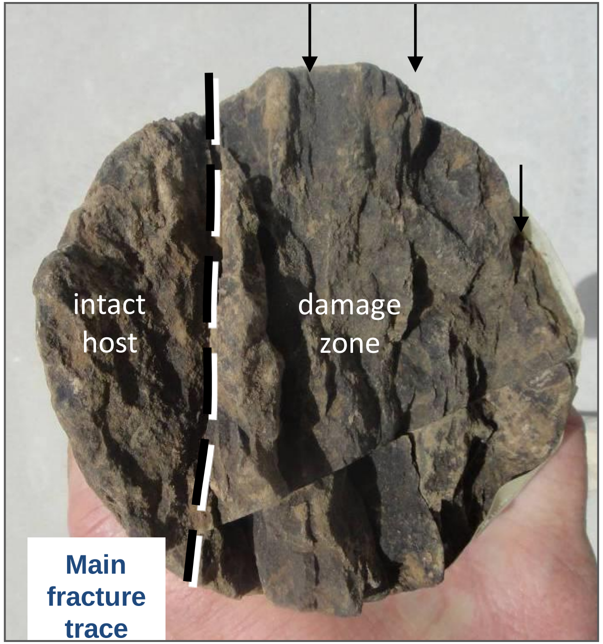
Opening-mode tensile fracture

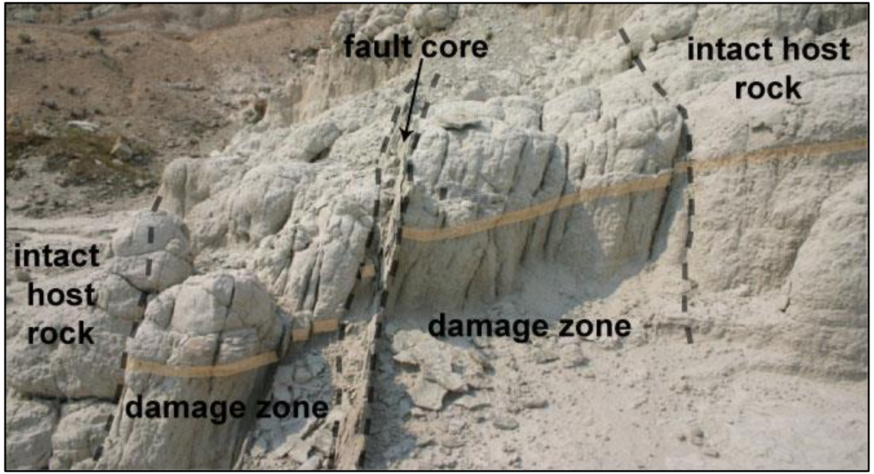
Oil stained fracture face



Conjugate fracture sets

Fault Damage Zones and Associated Fractures, Fabric



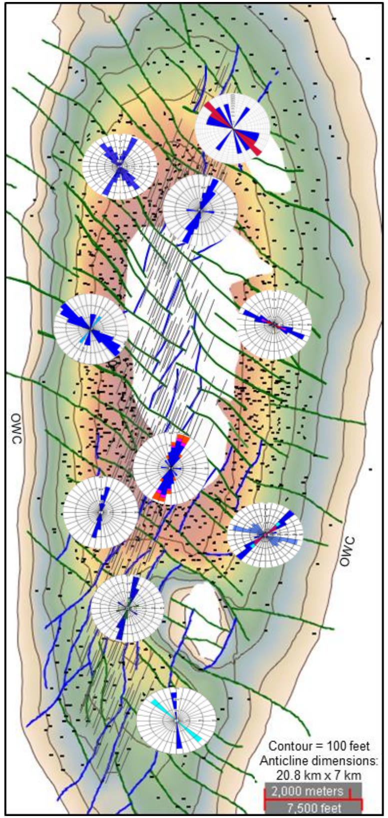


Owais Khattak @ Learning Geology

Faults & Associated Fractures – Subsurface FMI vs Surface Outcrops

3D Seismic and FMI

- Anticlinal axis comprised of NE-trending graben normal faults and abundant associated fractures.
- East and west flanks dominated by NW-trending strike-slip faults with damage zones.



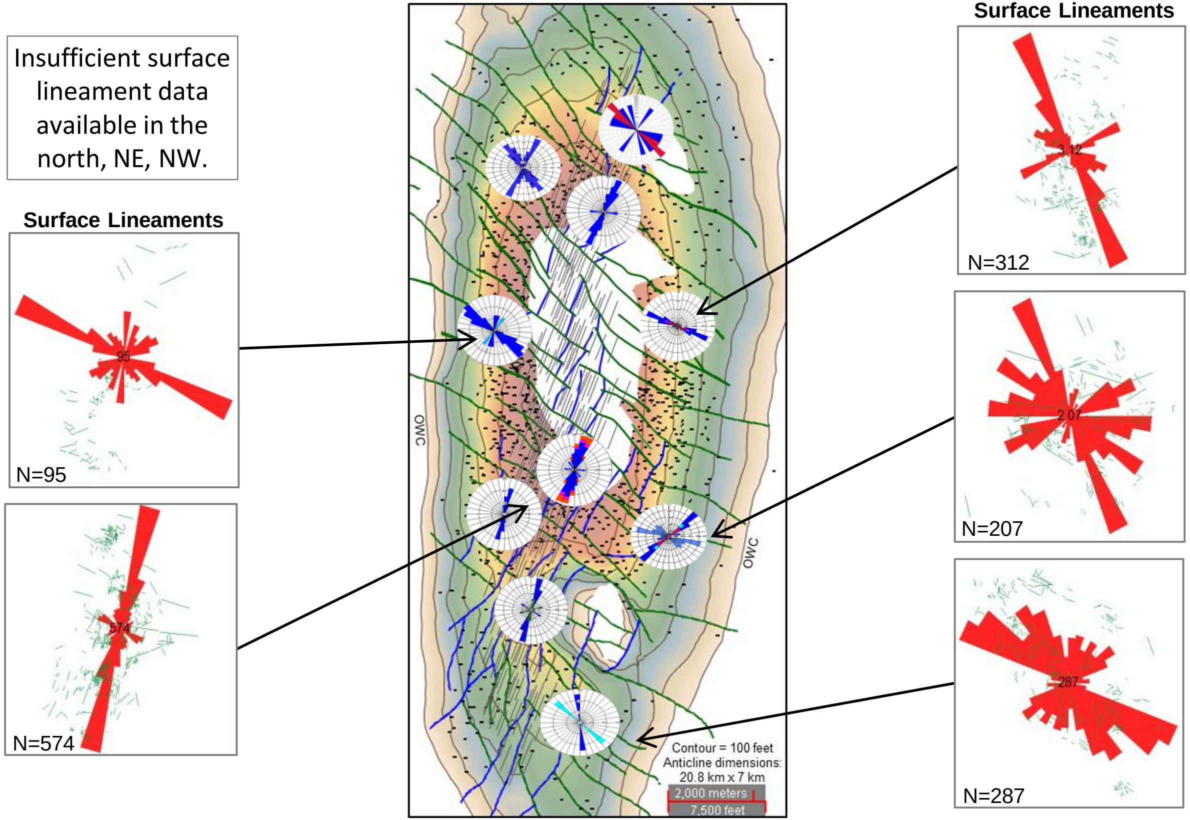
Faults & Associated Fractures – Subsurface FMI vs Surface Outcrops

3D Seismic and FMI

- Anticlinal axis comprised of NE-trending graben normal faults and abundant associated fractures.
- East and west flanks dominated by NW-trending strike-slip faults with damage zones.

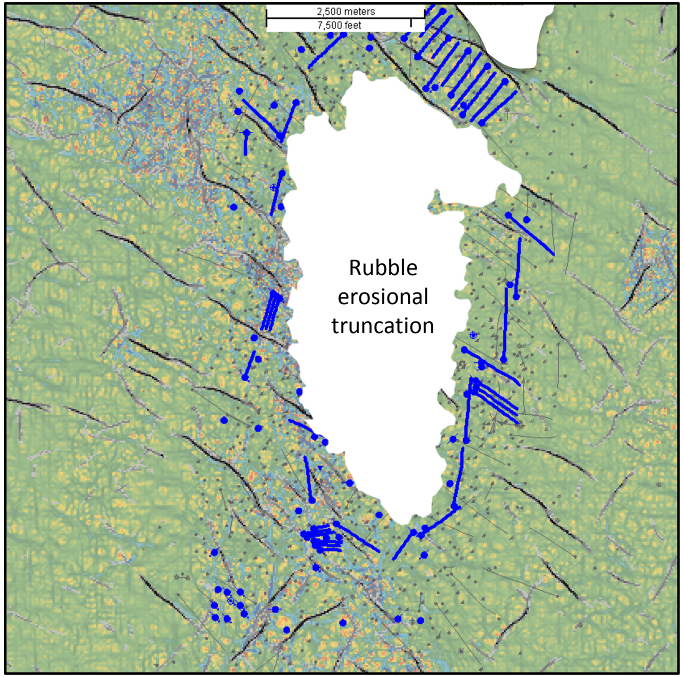
Surface Lineaments from satellite imagery and field outcrops

- Fractures present in younger rocks exposed to the surface.
- General fracture trends are similar to those in the subsurface.



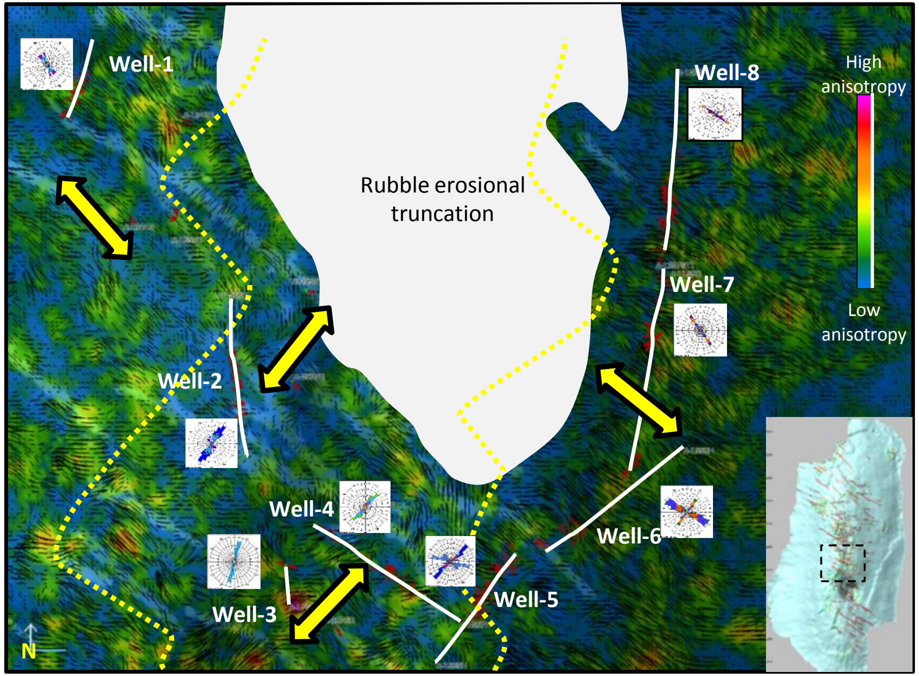
Faults and Fractures - Geophysical Fracture Modelling

Negative curvature and “ant tracks” at top of Rubble



Blue wells: Current and historic Rubble horizontal and vertical producers.
Black linear trends: Seismic discontinuity “ant tracks” extracted at top Rubble.
Blue-green-yellow: Seismic negative curvature extracted at top Rubble.

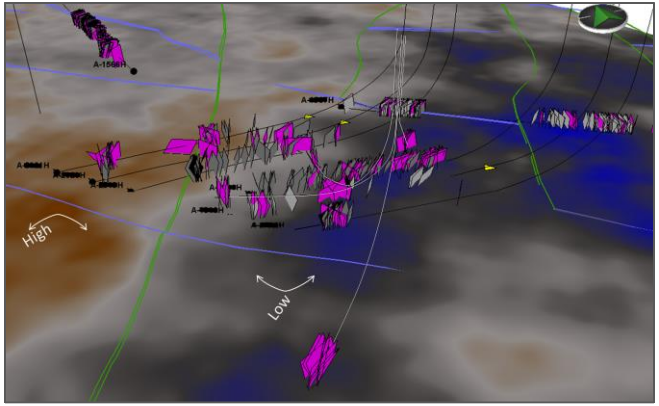
Anisotropy intensity (color) and Orientation at top of Rubble



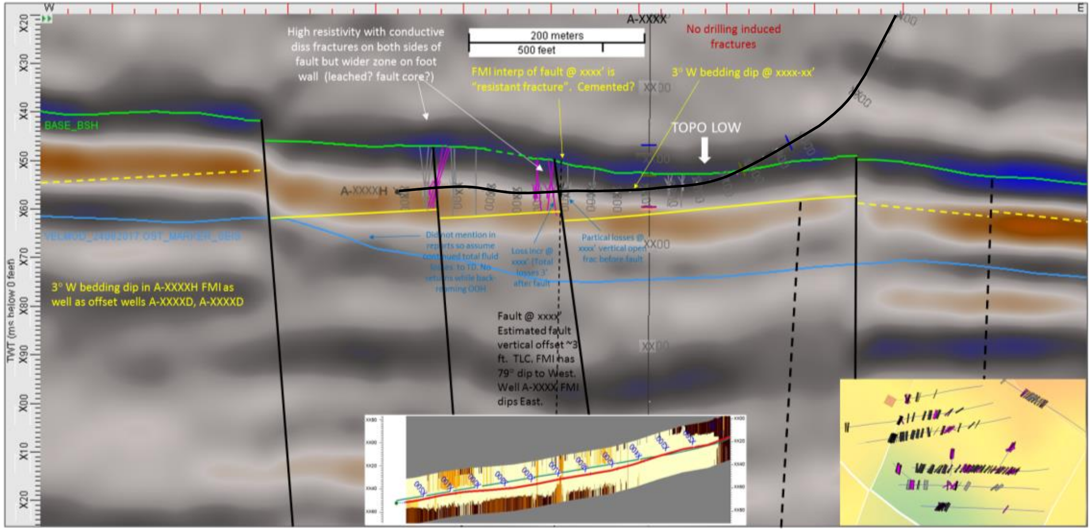
Black Glyph: Size of glyphs represent magnitude of anisotropy and glyph direction represents anisotropy orientation. Possibility of 90° ambiguity in the fracture dip orientation.
Red Glyph: Direction of glyphs represent orientation of fractures in Rubble horizontal well FMIs.

Integrated Seismic, Drilling Operations Data, Well Log and FMI Data

3D seismic time slice at top of Rubble with fault polygons, Rubble wells and FMI interpretations



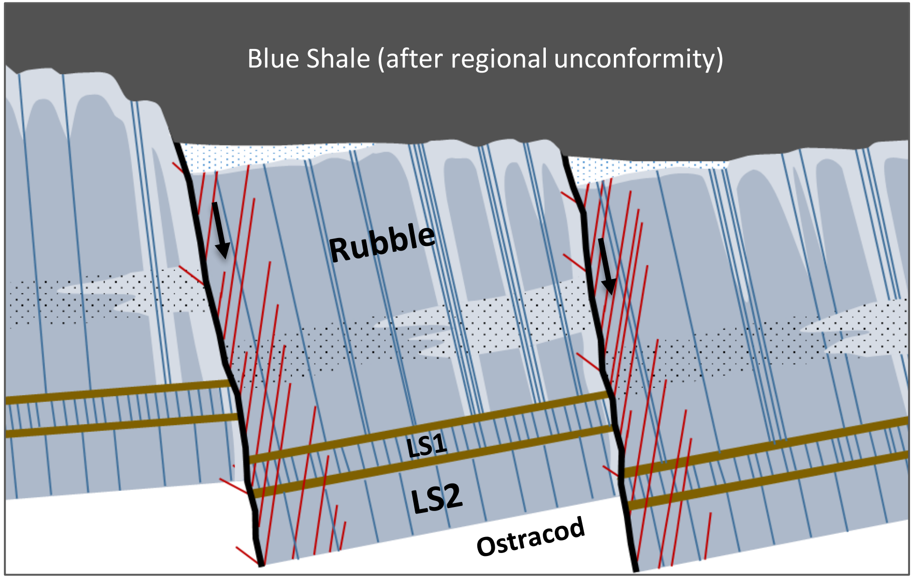
Horizontal well cross-section with geosteering interpretation, drilling fluid losses, FMI interpretation, and 3D seismic backdrop



Axial graben with well connected fractures

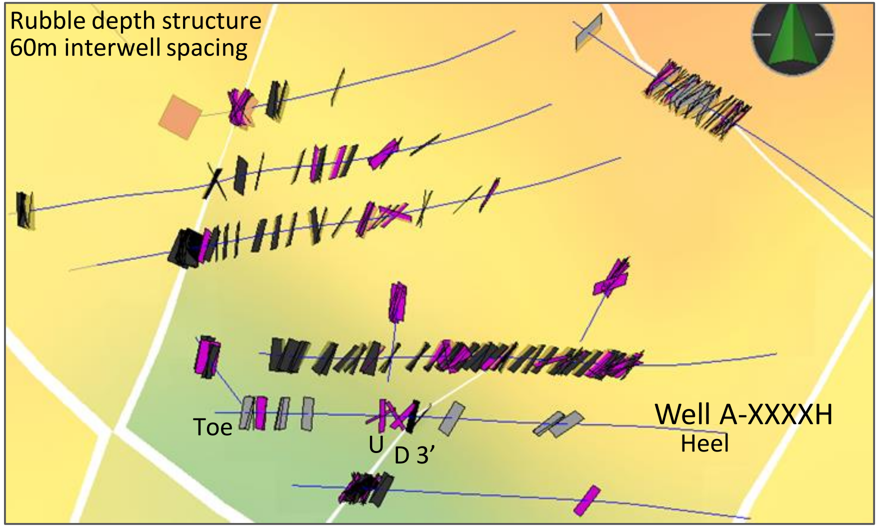
- joints
- graben fault associated fractures
- karst dissolution enhancing connections

Working Fault-Fracture-Karst Theory

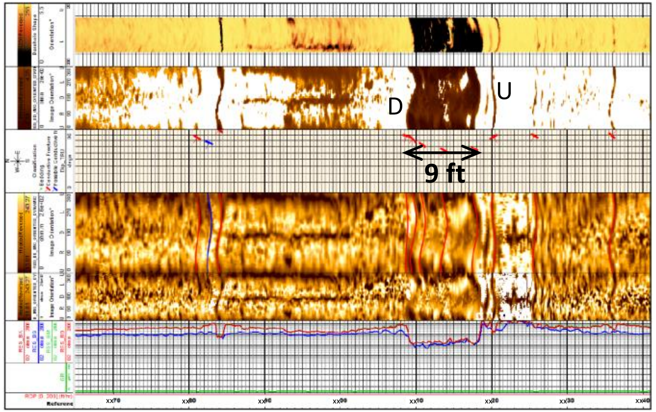


- Unaltered "host" limestone formation with erosional truncation along the top.
- Shale and argillaceous limestone layers (2-4 ft thick).
- Joints associated with initial structural flexing, originally vertical but now tilted with fault block.
- Normal (or strike-slip) fault, sometimes with gouge.
- Fault-associated fractures (damage zone wider for hanging-wall than foot-wall).
- Layer of carbonate debris (former soil) filling topographically low portion of Rubble limestone formation.
- Chemically altered "halo" associated with subareal exposure to meteoric water, percolating of water down exposed joints and faults, and leaching of carbonate skeletal grain rich layers.

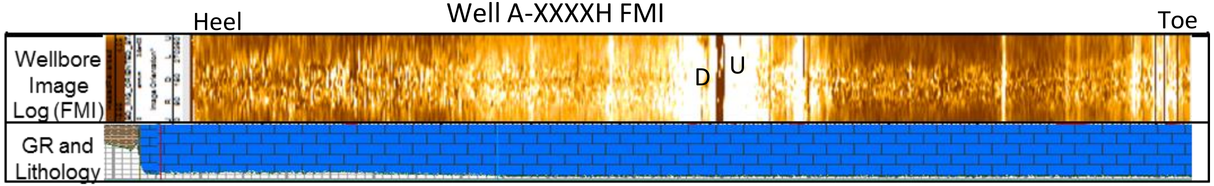
Impact of Faults and Damage Zones on Fluid Flow in Low Perm Rubble



Well A-XXXXH FMI detail view of large feature



Well A-XXXXH FMI

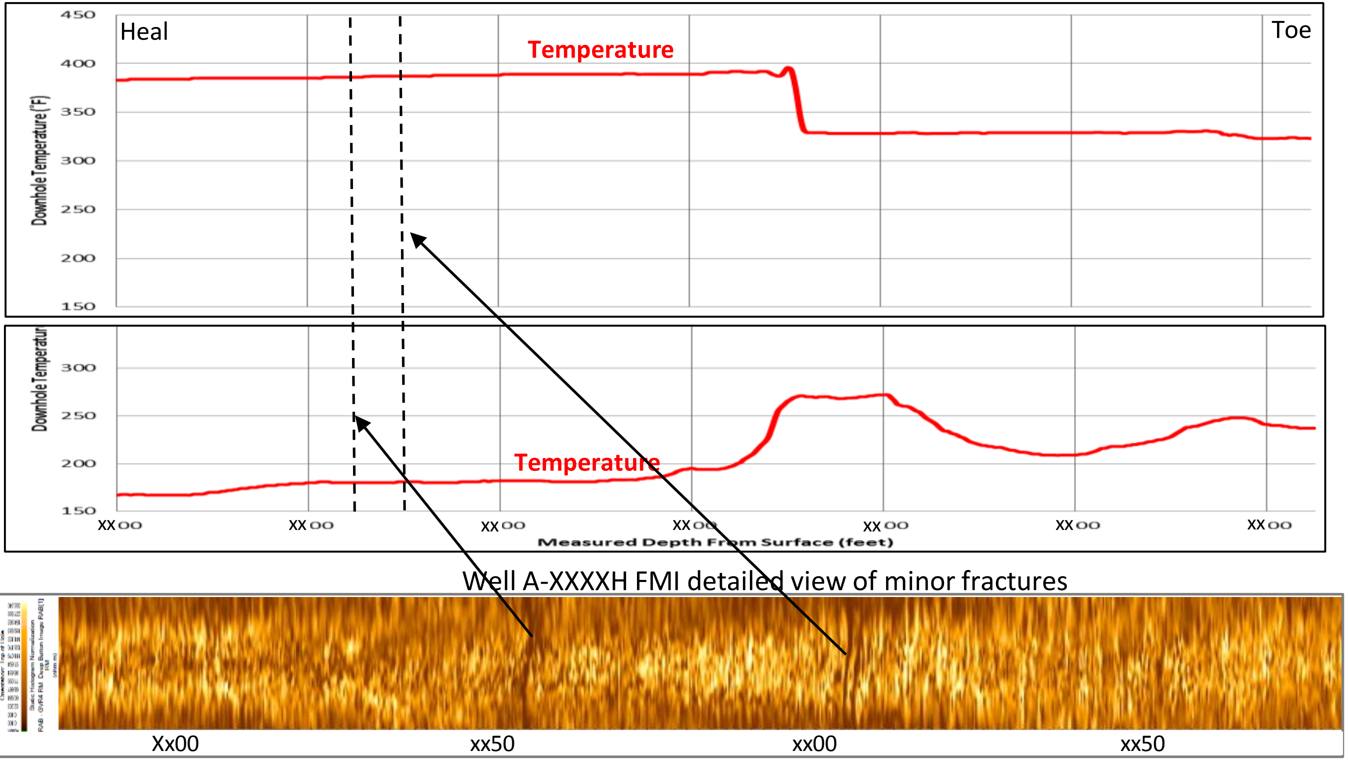


Jabel Hafeet, Oman (Holland, 2008)

No Steam Loss or Entry into Minor Conductive Fractures with No Halos

During steam injection horizontal well

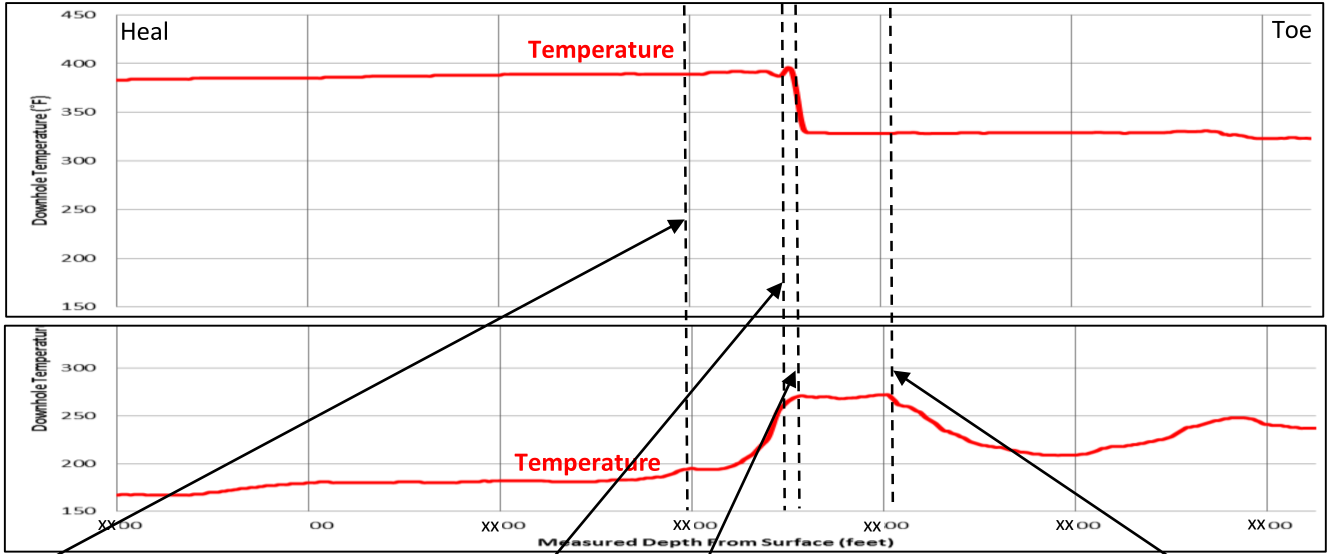
During production of same horizontal well



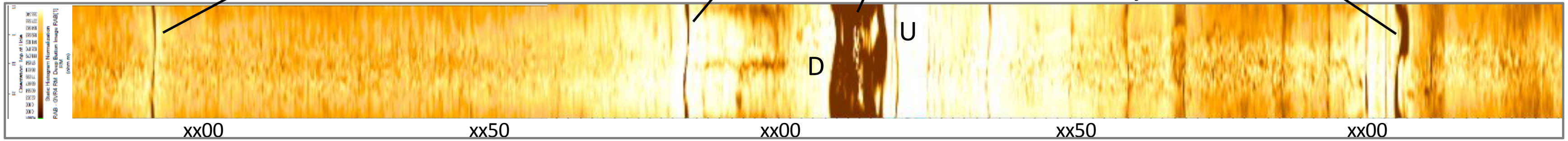
Steam Loss and Entry into Conductive Faults and Fractures with Halos

During steam injection horizontal well

During production of same horizontal well

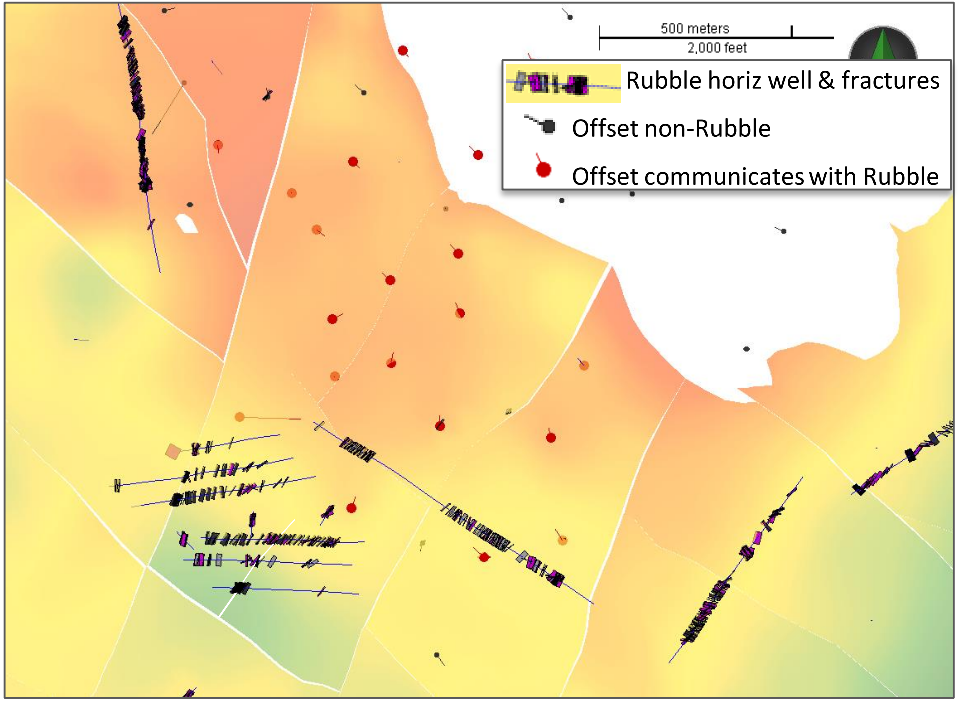


Well A-XXXXH FMI detailed view of fault and major fractures

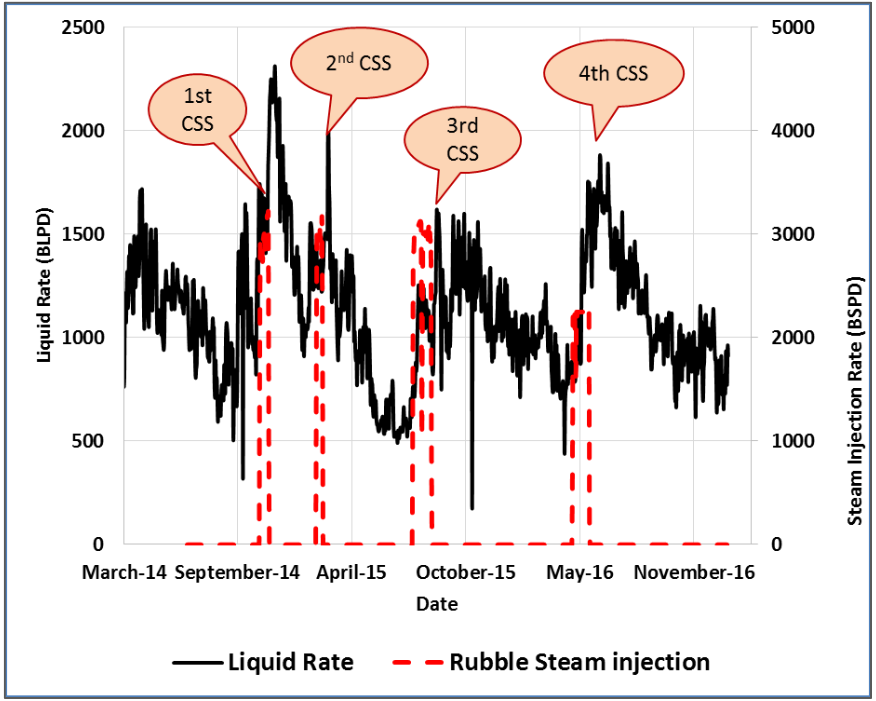


Fluid Communication with Underlying Reservoir

Rubble structure, wells with FMI fractures, and offset non-Rubble wells

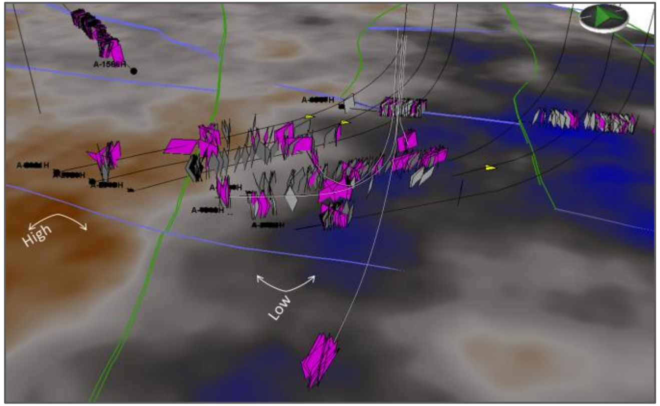


Fluid production response of non-Rubble wells to Rubble injection



Independent Dynamic Fracture Fluid Levels and Contacts

- Historic production data and recent “mapping experiment” within the axial graben.
- Although almost all joints and fractures trend NNE-SSW within the axial grabens, there is a range in azimuths such that joints and fractures intersect at some point.
- Because the joints, faults, and fractures were subareally exposed prior to Blue Shale deposition, karst dissolution has enhanced the connections between fractures, accelerating interwell communication.
- A common fluid level rises within the fracture network during steam injection and falls during fluid production.



Wennberg et al, 2016

Conclusions and Recommendations

- Faults and fractures within the Rubble limestone have enhanced interconnectedness and conductivity due to karst dissolution and brecciation.
- Common fluid levels occur in fracture networks independent of the reservoir matrix contacts. They rise during steam injection and fall during fluid production.
- Rubble fracture networks differ along the axial crest versus the east and west flanks.
- A predictive conceptual fracture and karst model is necessary to optimally manage a thermal EOR project within a low matrix permeability reservoir.
- Detailed integration of every dataset you can think of is recommended:
  - 3D seismic attributes
  - Core and outcrop analogs
  - Drilling operations data
  - Wireline data, including images
  - Injection data (PLTs, DTSs)
  - Production data, trends
  - Offset well response
  - Cartoon conceptual sketches