Finding Petroleum Meeting, 16th May 2017, Geological Society of London

Fractured Carbonate Reservoirs

A geological point of view

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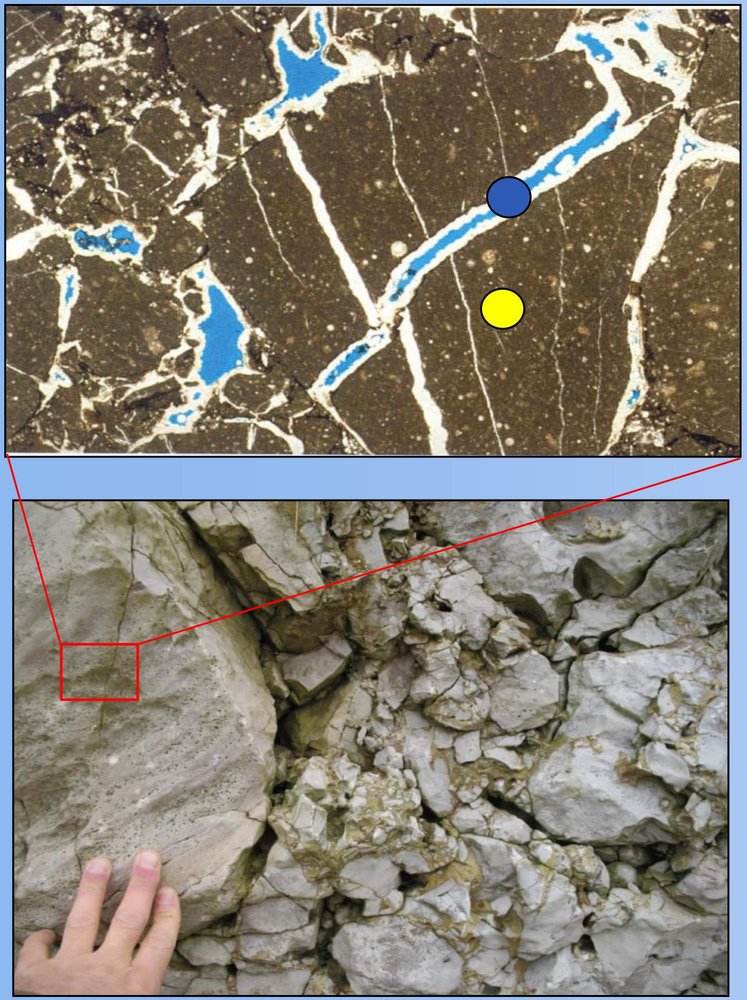
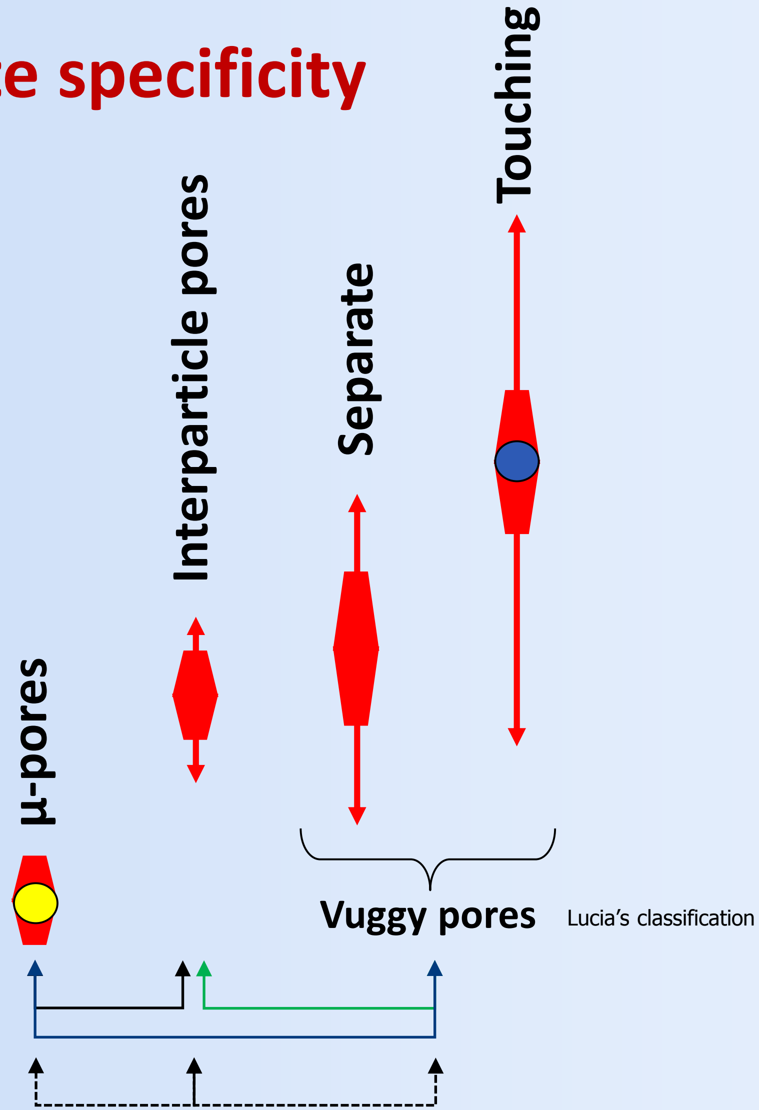
Cambridge Carbonates Ltd

INTRODUCTION

Introduction

Multiple pore types and scales = carbonate specificity





⇒ **3 kinds of dual pore network**

⇒ *extreme triple pore networks*

Introduction

- Carbonate reservoirs are often dual porosity systems with matrix (*s.l.*) and "megapores"

- This is not the case for clastic reservoirs
  - More than 50% of carbonate reservoirs are described as "fractured"
  - Less than 10% of siliciclastic reservoirs are described as "fractured"

- If fracture systems are purely structural there should be minor difference between carbonate and siliciclastic reservoirs
  - Karst reservoirs! → using fracture models only in carbonates may give the wrong answer a significant percentage of the time!

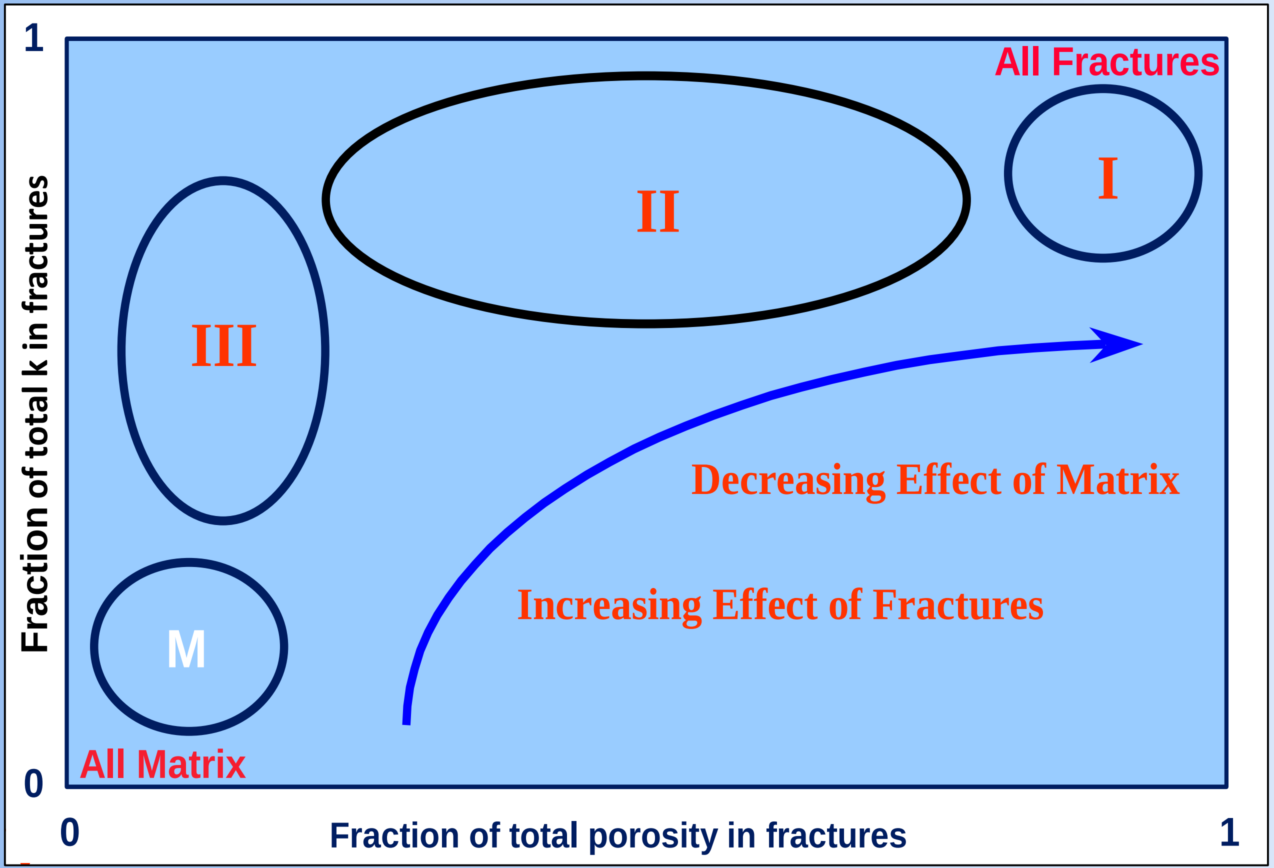
- But fractured carbonates do exist and represent challenging reservoirs

Tectonically fractured carbonates

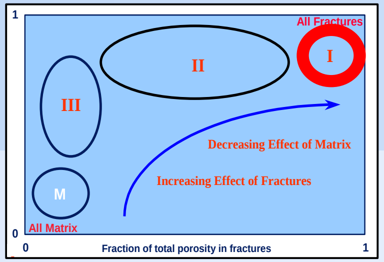
VARIOUS TYPES OF TECTONICALLY FRACTURED CARBONATE RESERVOIRS

A classification

- Fractured reservoirs (Nelson, 2001):
  - **Type I: Almost all porosity and permeability in fractures**
  - **Type II: Main porosity in matrix, main permeability in fractures**
  - *Type III: Main porosity and permeability in matrix, fractures enhances permeability*
  - *Type M: Main porosity and permeability in matrix, fractures causes anisotropy*

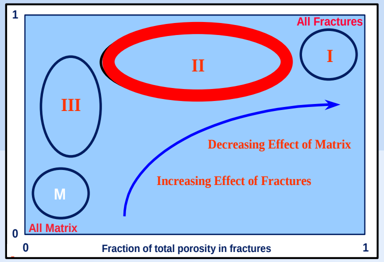


Type I – mostly deep water carbonates



- Storage and productivity of hydrocarbons restricted to fractures alone
- Very low permeability matrix to these reservoirs
  - Matrix is variably water-wet
  - Examples
    - Ain Zalah field (northern Iraq) = relatively light oil (31.5°API) + matrix is water-wet
    - Ebano-Panuco fields (Mexico) = heavy oils dominate (10-13°API) + matrix is variably oil saturated → “false” OWC’s with some intervals being 100% water-saturated within the oil leg
- Early water break-through = fine tuning of production rates
- Distribution of fractures is often not straightforward + connectivity clearly dependant on structural history and nature of the host rocks
  - The crest of the structure is NOT ALWAYS the location of the highest density of fractures
  - Ain Zalah field: highest productivity is offset from the crest due to multi-stage structuration
- Fracture porosity <1%

Type II – mostly shallow water carbonates

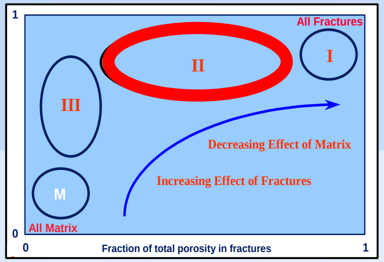


- Matrix porosities can be good **<u>BUT</u>** matrix permeabilities tend to be poor
  - Fractures are required in order to attain good production rates and maintain long-term production

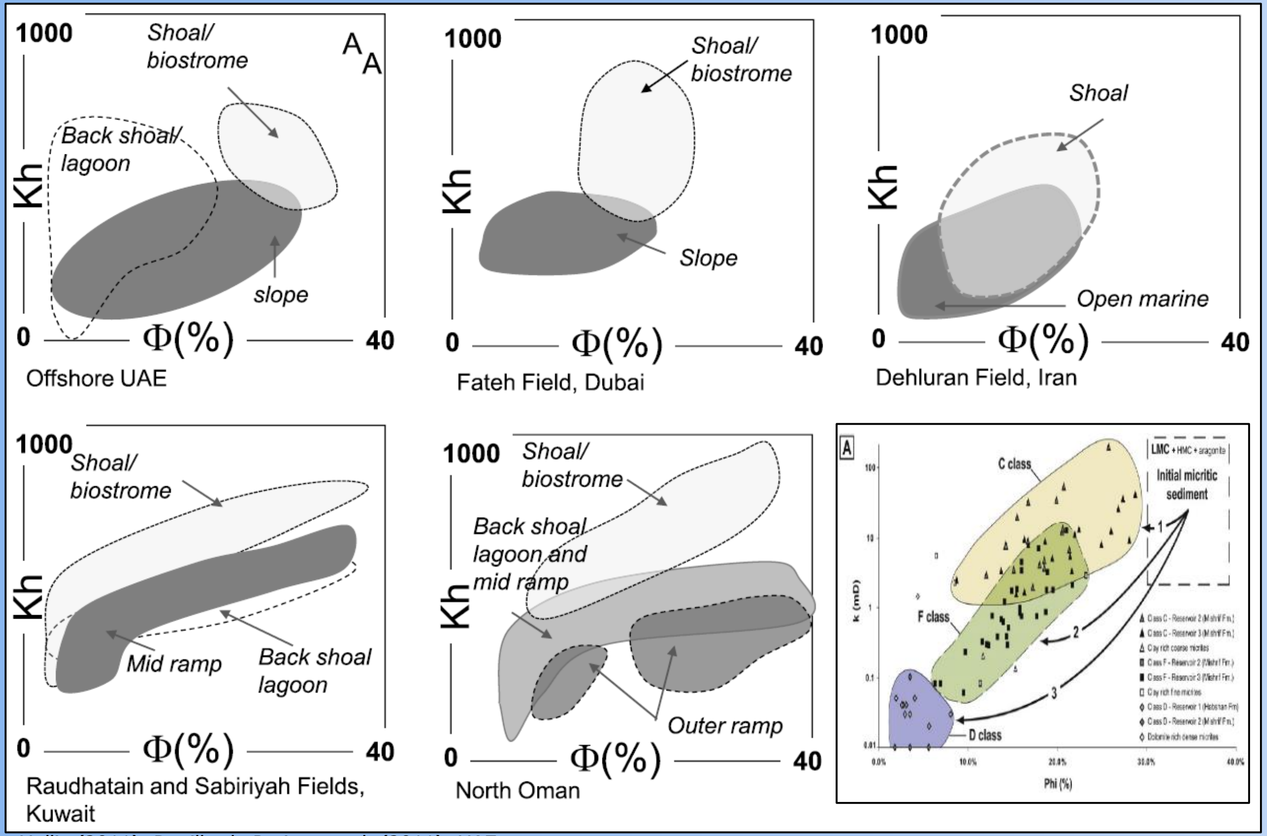
- Production can be heterogeneous or homogenous which depends on density and distribution of fractures
  - Kirkuk field = reservoirs so highly fractured and well-connected that pressure drops over the field (100km long structure) = instantaneous
  - However, other fields exhibit differential fracturing, and well productivity is far more heterogeneous (Masjed-e-Sulaiman, Iran; Gibson, 1948)
    - Shutting-in wells with high water-cut may allow the matrix to recharge the fracture system, and water-free production can be resumed (*i.e.* Masjed-e-Sulaiman field, Iran)

- Fracture porosity commonly <0.5%

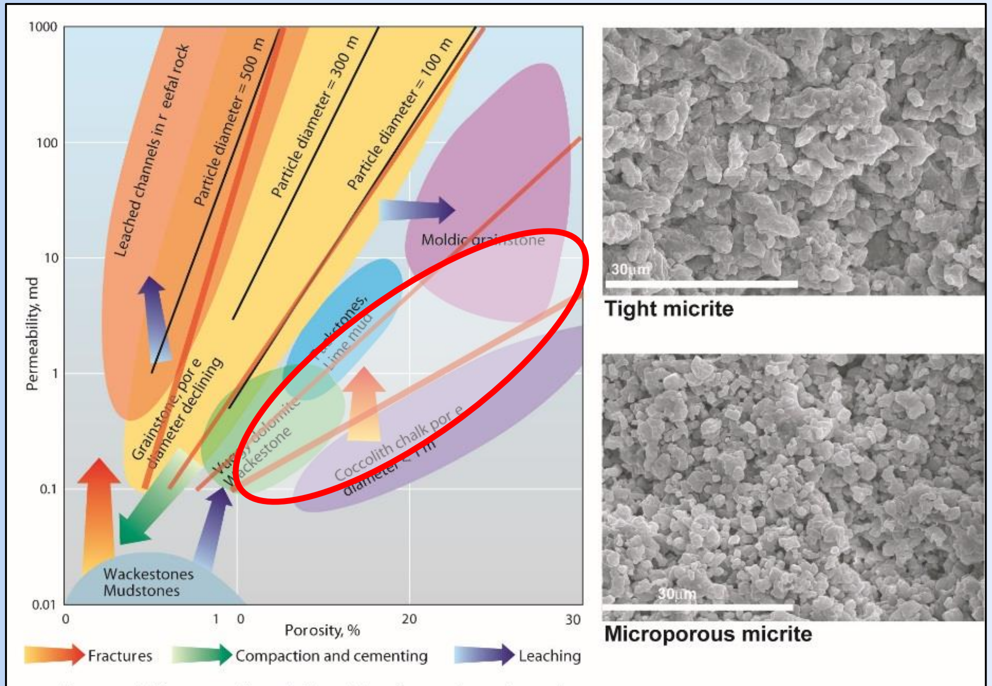
Type II



- Fractured chalk reservoirs are an important example of TYPE II reservoirs = high porosity (typically >30%) **BUT** microporosity with small pore-throats → Oil is stored in both the matrix and fractures
  - Fracturing is required to produce the oil at economically sustainable rates



Hollis (2011); Deville de Periere et al. (2011); UAE

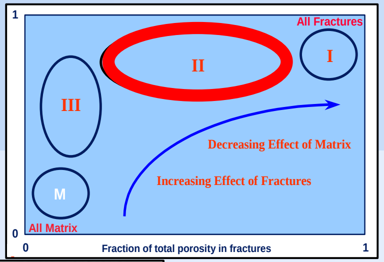


Permeability-porosity relationships for carbonate rocks (Dunham classification; Nurmi, 1986).

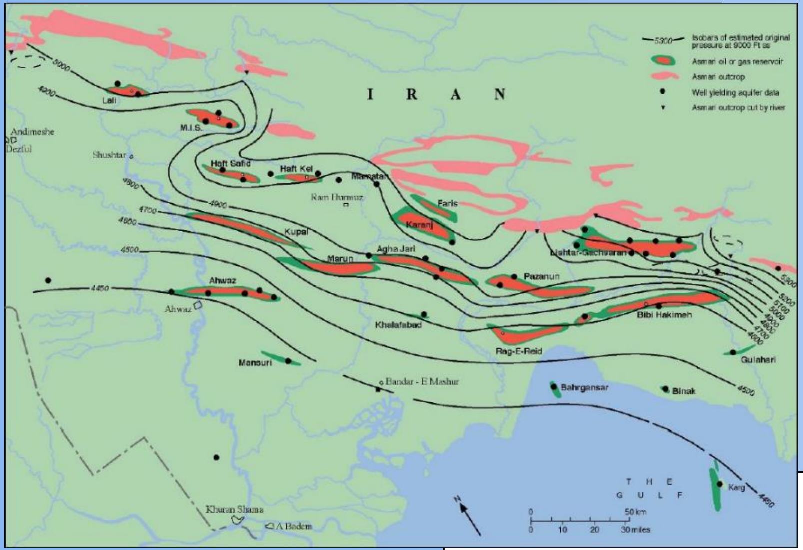
Red lines correspond to Lucia's classes

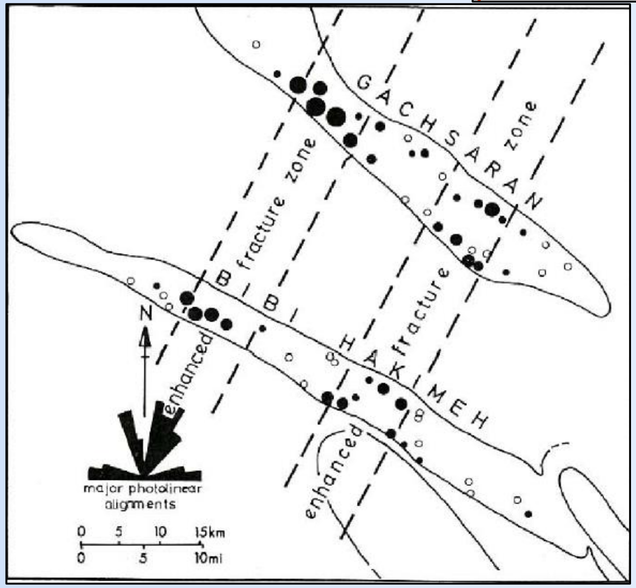
Type II

- Commonly a facies control on reservoir quality, particularly if structures transcend facies belts (i.e. Cenozoic of Iran/Iraq)



Asmari (Oligo-Miocene), Iran





McQuillan (1984)

SE

Unpublished confidential IFP/NIOC

Fields with fracture component – Zagros FTB

Type of reservoir	Examples
Type I: no significant matrix porosity (or water wet)	Ain Zalah, Butmah, Kirkuk (1), Souedie, Karatchok, Gbeibe and Jebissa
Type II: dual porosity systems	Kirkuk (2), Masjed-e-Suleyman, Gachsaran, Bibi Hamikeh, Agha Jari, Haft Kel, Naft-e-Shah (Iran and Iraq)

Late Cretaceous (deep water carbonates)

Cenozoic (shallow water carbonates mostly)

Important parameters and some numbers

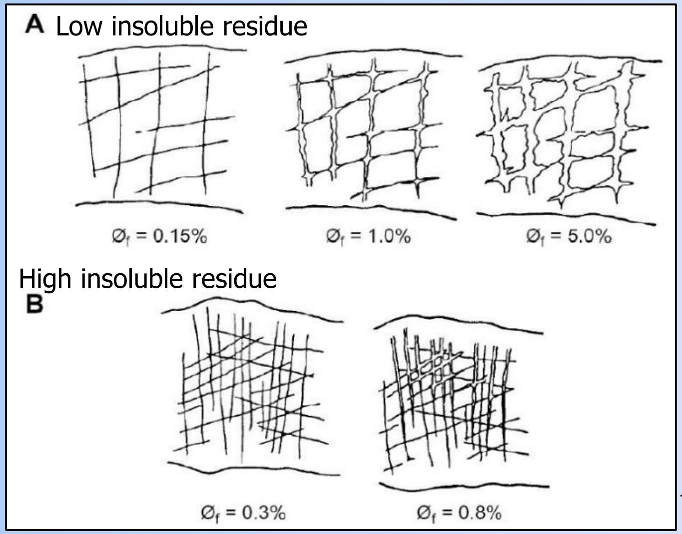
PROPERTIES OF FRACTURED CARBONATE RESERVOIRS

Fracture porosity

Field	Fracture porosity
Agha Jari	0.22%
Haft-Kel	0.21%
Masjed-e-Suleyman	0.20%
Masjed-e-Suleyman (Asaib sector)	3% of total porosity

Collated by CCL based on Gibson (1948); Weber and Bakker (1981)

- Usually very low fracture porosity **BUT**
  - Major faults can be associated with breccia zones and ‘tectonic caves’ (porosities of cave-size within fault systems)
  - Solution-enlarged fractures
  - Porosity locally increased up to 5%

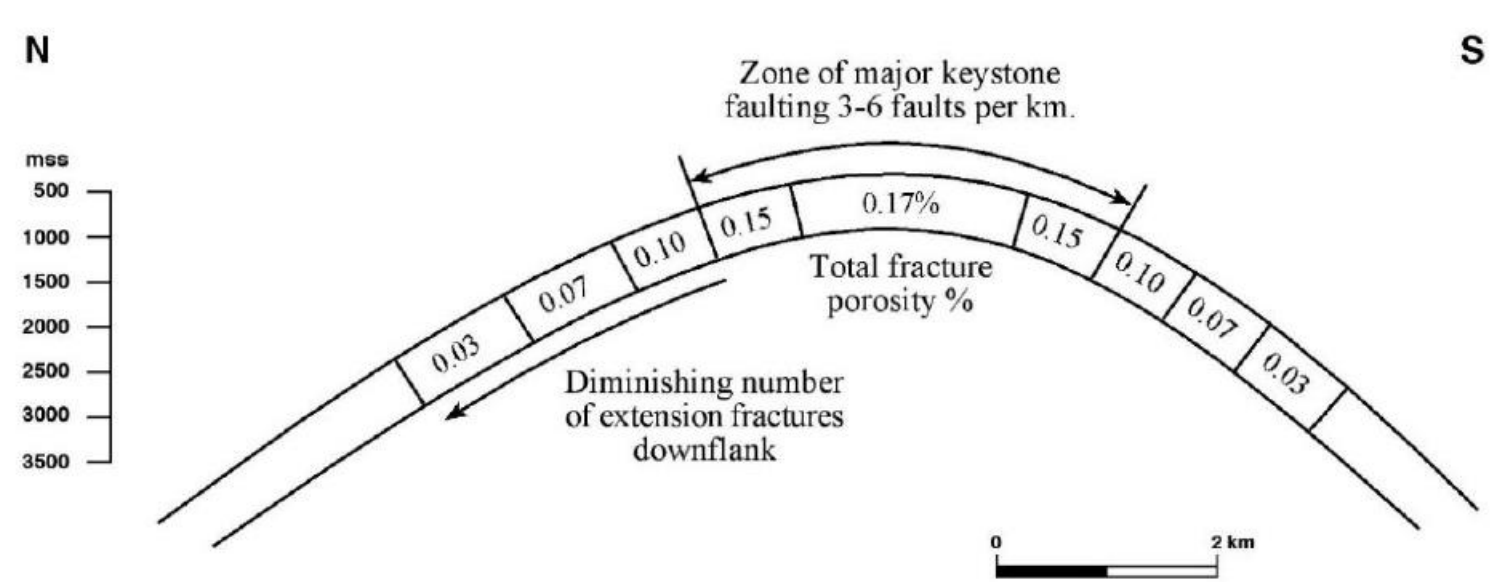


Tkhostov et al. (1970)

Cretaceous, Italy

Fracture porosity

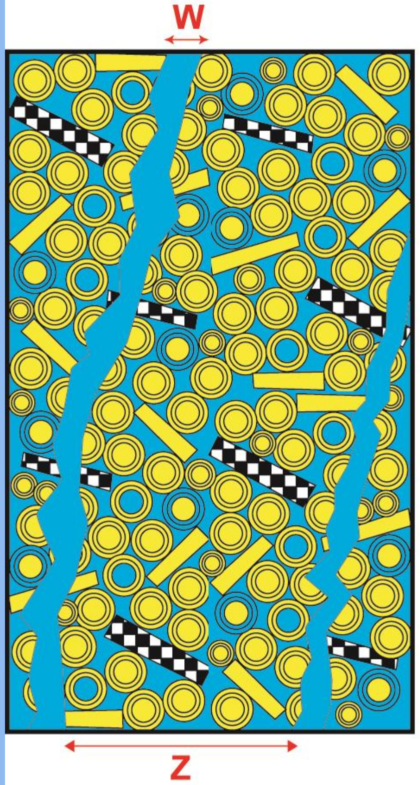
Distribution of fracture porosity across the Gachsaran structure



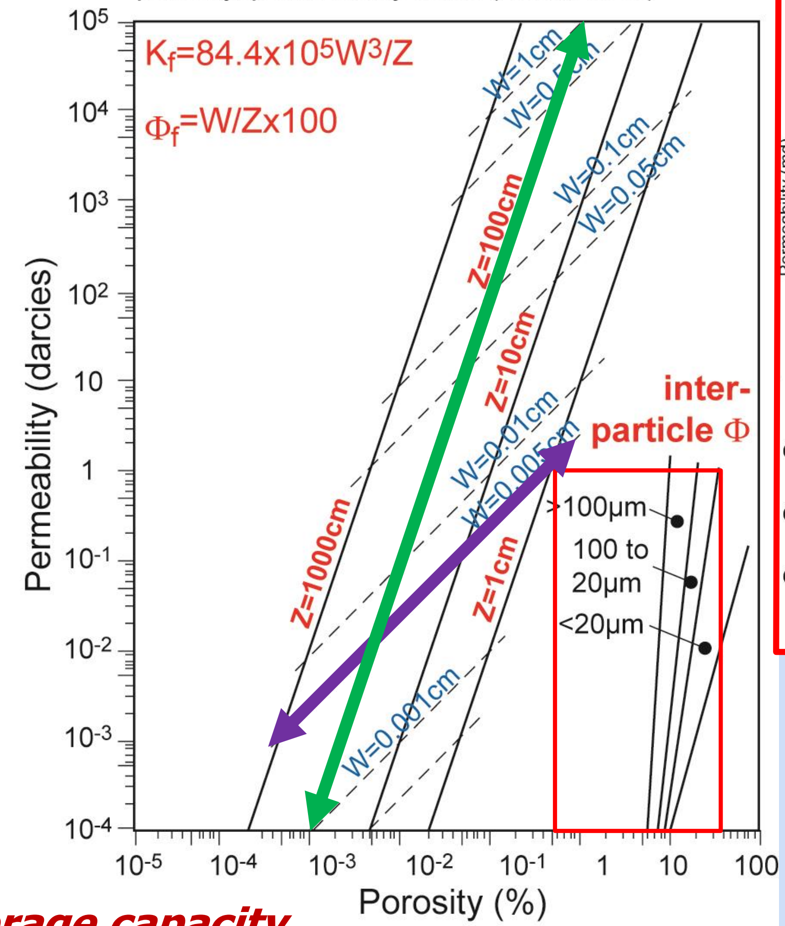
From Weber and Bakker (1981)

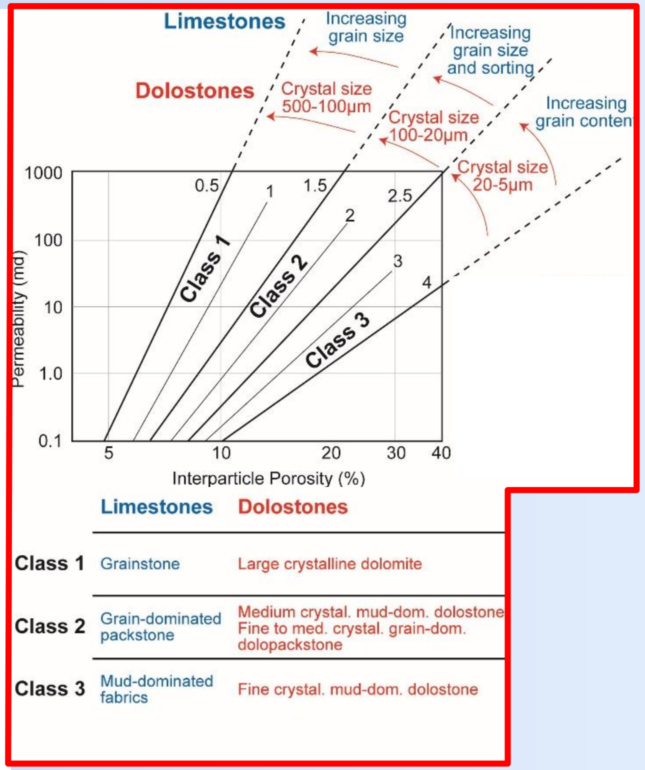
- Locally up to 0.4% in other structure in the Zagros (Weber and Bakker, 1981)

Poroperm properties



Theoretical fracture air permeability-porosity relationship compared to the Lucia's rock-fabric porosity, permeability fields (Lucia, 1983)





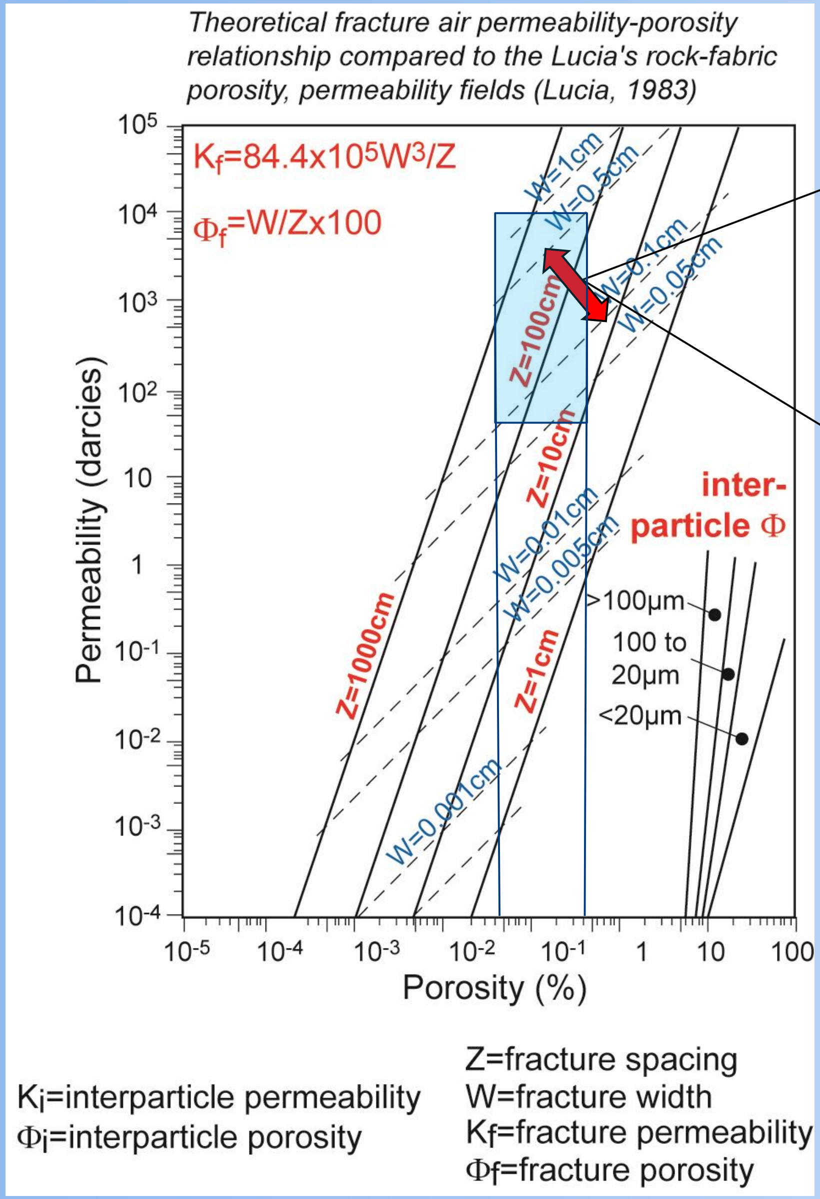
$\Phi_f << \Phi_i$ ***Low storage capacity***

$K_f >> K_i$ ***High flow capacity***

K_i=interparticle permeability
Φ_i=interparticle porosity

Z=fracture spacing
W=fracture width
K_f=fracture permeability
Φ_f=fracture porosity

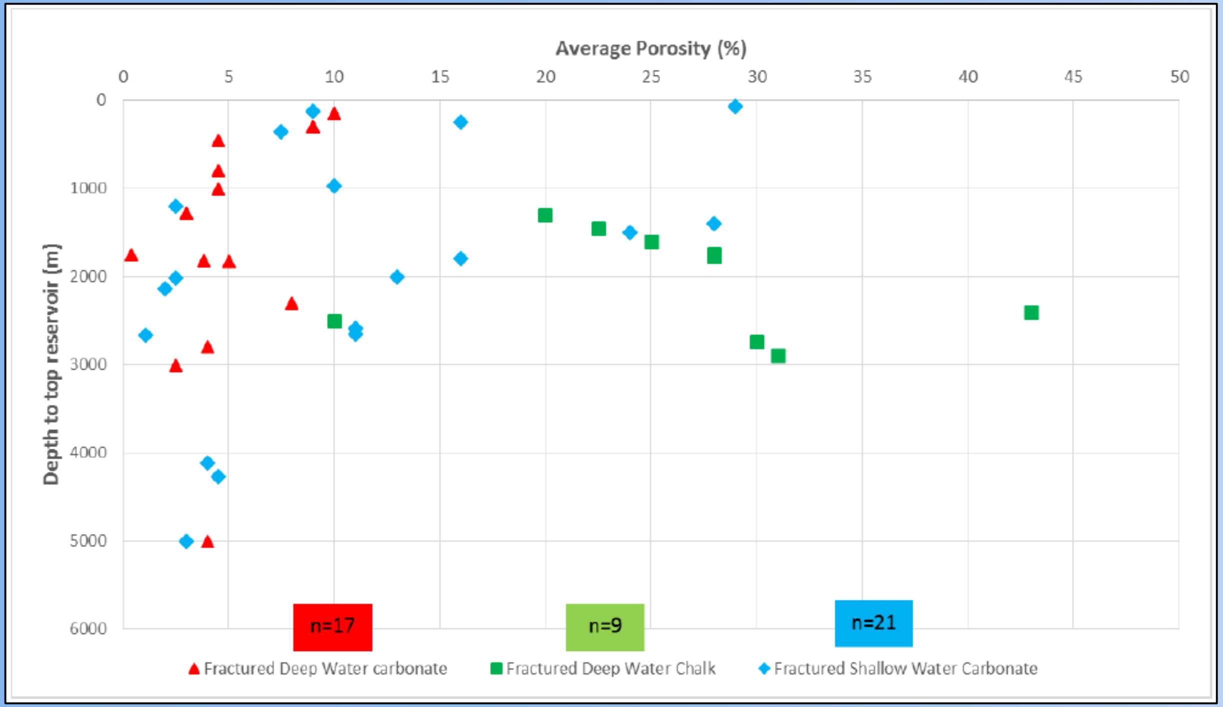
Poroperm properties

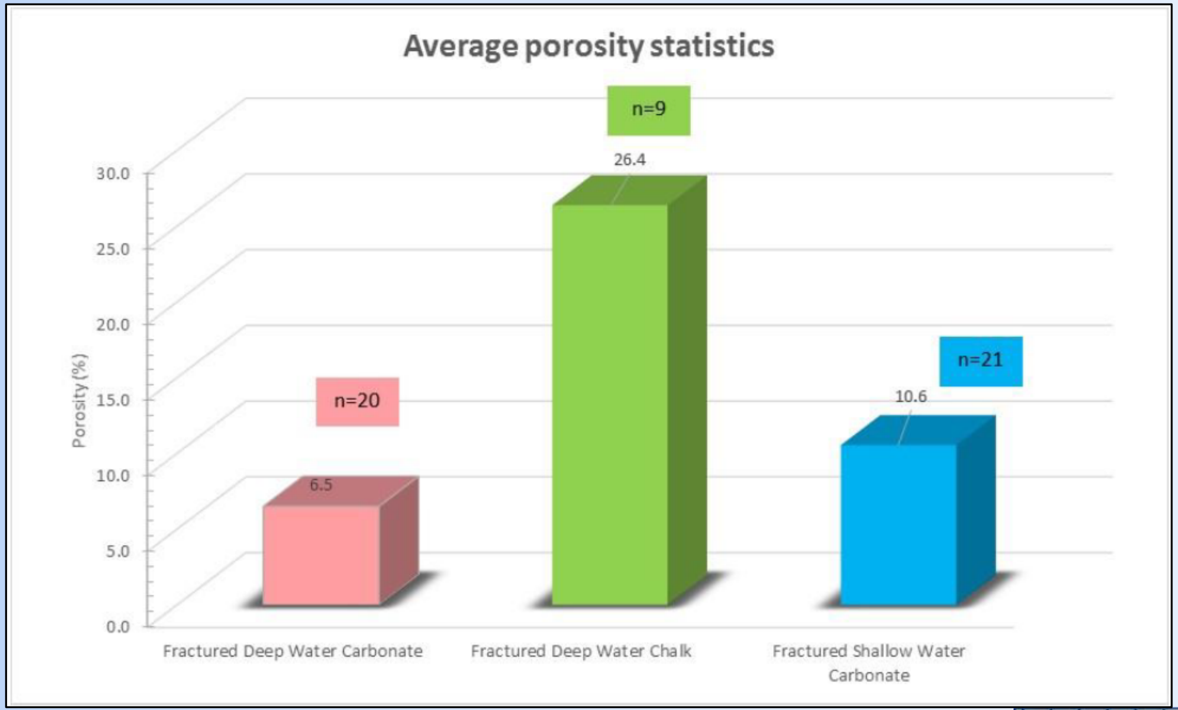


- W=1-2.5mm
  - Masjed-e-Sulaiman, Iran (Gibson, 1948)
  - Experimental work based on production data
- W=0.1-0.5mm
  - Weber and Bakker (1981)

General characteristics

- Fractured shallow-water carbonate fields (Type II) and fractured deep-water carbonate fields (Type I) follow a standard porosity envelope curve of decreasing porosity with depth
  - Fractured deep-water carbonates (Type I) = low total porosity (always below 10%)
  - Fractured shallow-water carbonates (Type II) = considerable variation in porosity
  - Fractured chalk fields = characteristically high porosities (up to >40% average)





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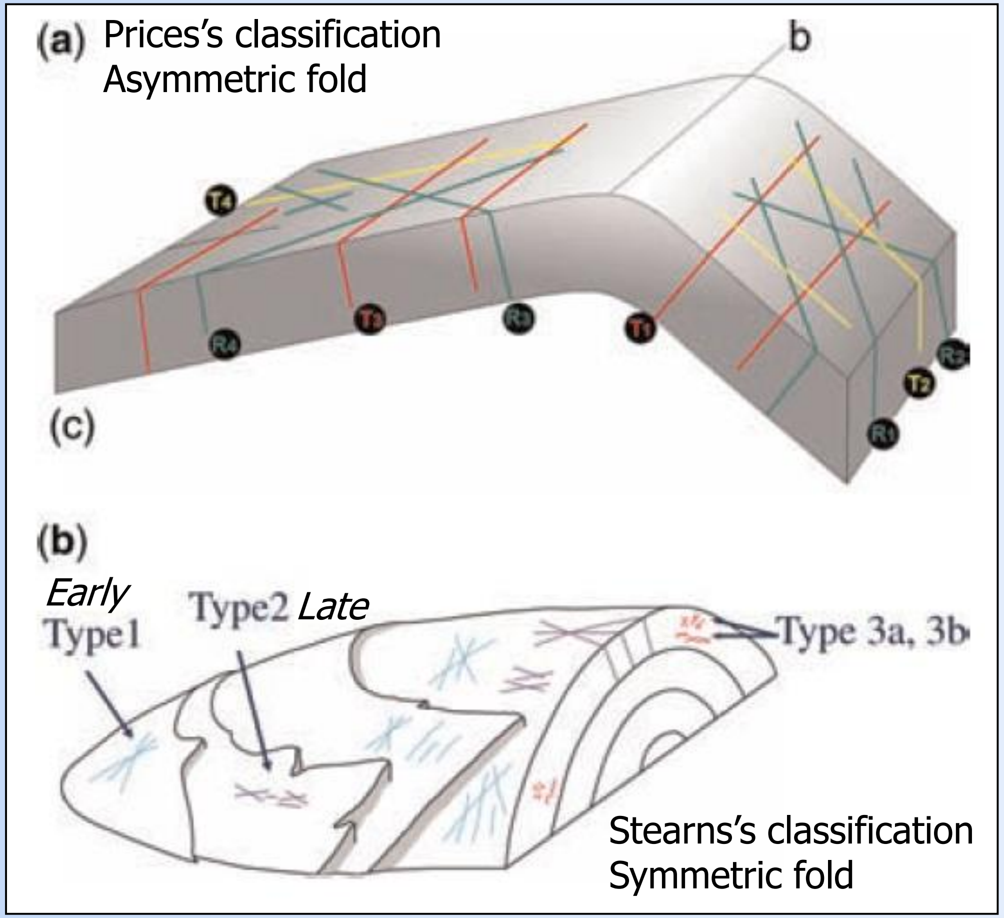
Controlling factors and impacts on reservoirs

FRACTURE DISTRIBUTION AND DENSITY

Controlling factors – Fracture types and distribution

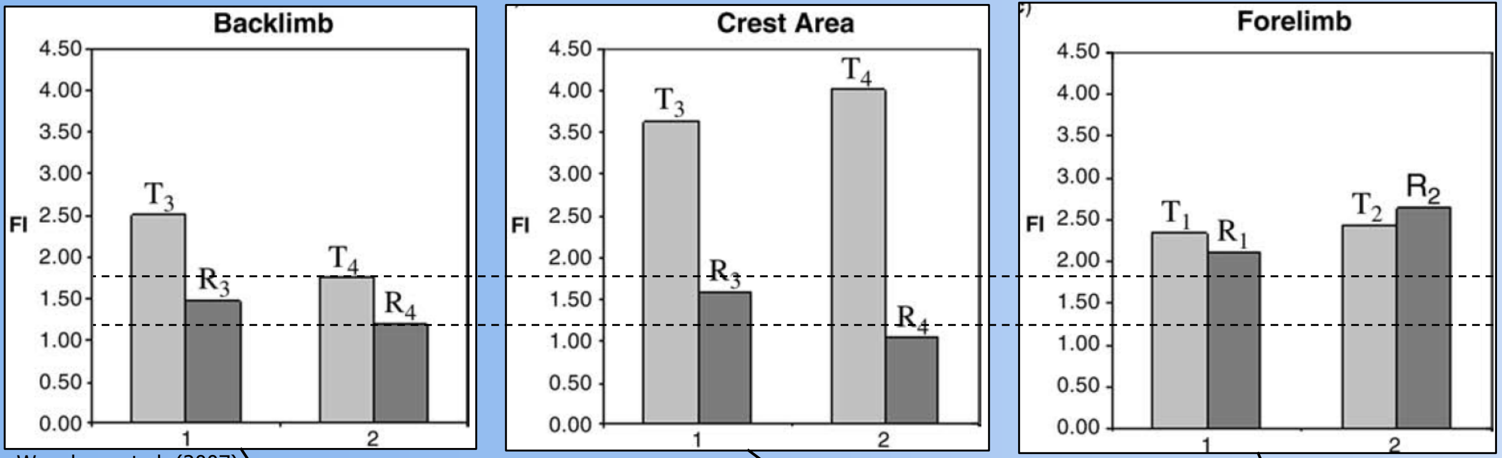
- Fractures and faults form through deformation
  - Follows some established classifications
  - Orientation(s) depends on stress direction(s)
- Sequence of fracture formation during fold development
  - T then R or Type 1 then Type 2
- Some pre-existing fractures may exist!
  - inherited



Wennberg et al. (2007)

Controlling factors – Folding and structural position

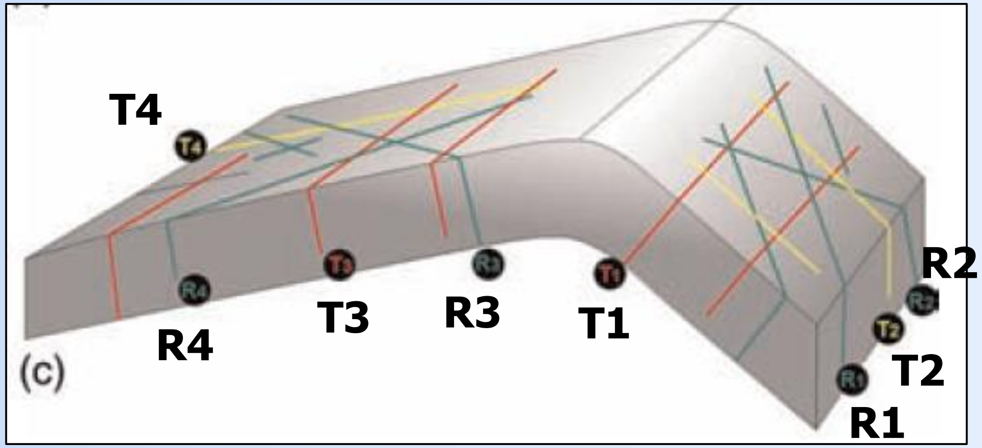
- Fracture intensity/density is usually higher in **crest area** and **forelimb**

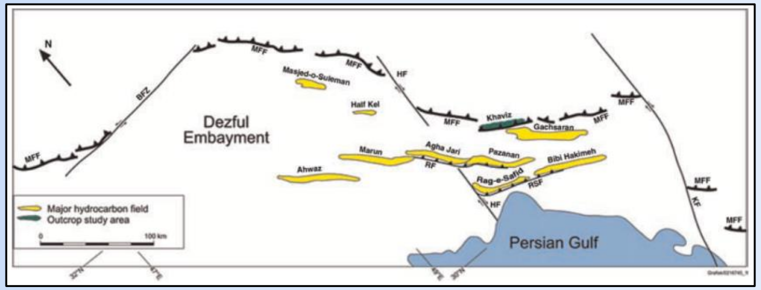


Wennberg et al. (2007)

FI (Fracture intensity)=Number fractures/metre line length

FI=1/S_{mean} (average fracture spacing)





Khaviz anticline, Asmari Formation (Oligo-Miocene), Iran

Controlling factors – Folding and structural position

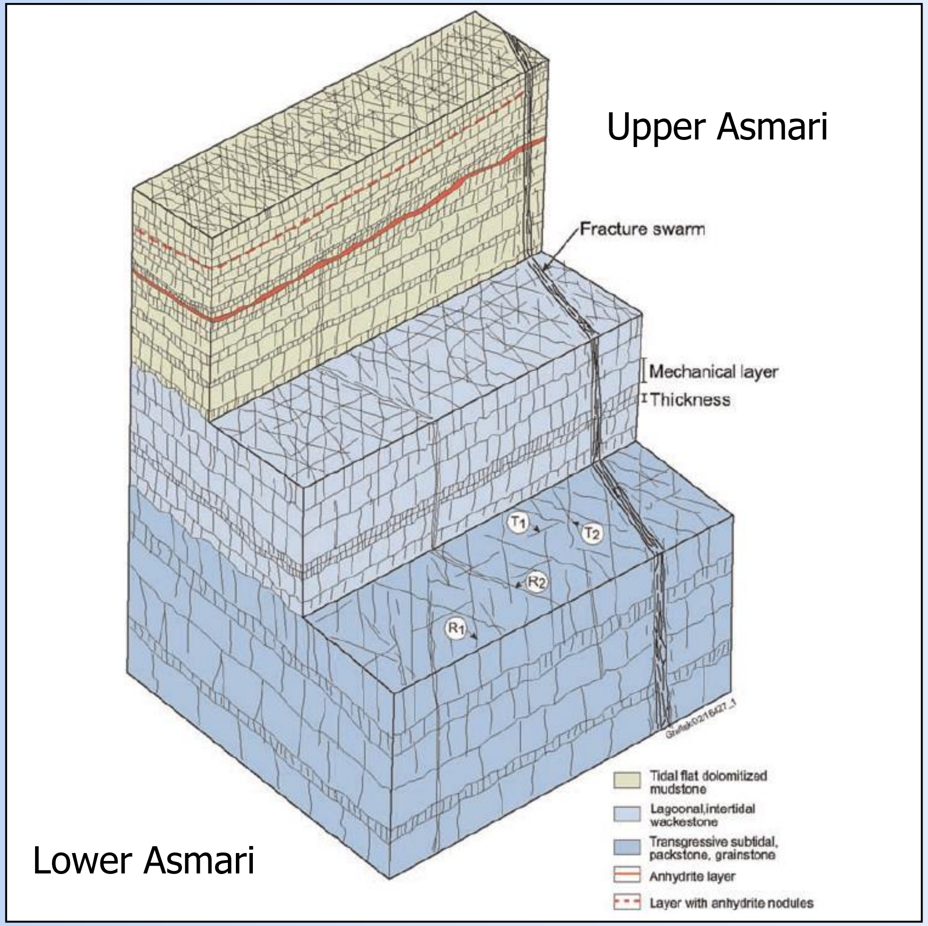
Sheep Mountain anticline, Madison Formation (Mississippian), USA
(outcrop analogue to oil/gas fields Wind River and Big Horn basins)

Controlling factors – Mechanical stratigraphy

- Two types of fractures are commonly recognised in fractured carbonate reservoirs/structures
  - **Diffuse fractures**
    - Stratabound
    - Controlled by **mechanical stratigraphy**
      - mechanical unit thickness
      - material properties (depositional facies, diagenesis)
      - strength of the interfaces between units = inter-unit shearing

    Corbett et al. (1987); Gross et al. (1995); Cooke and Underwood (2001)

  - **Fracture swarm** (fault damage zones or narrow zones of intense fracturing; Wennberg et al., 2007)
    - Cut through the units

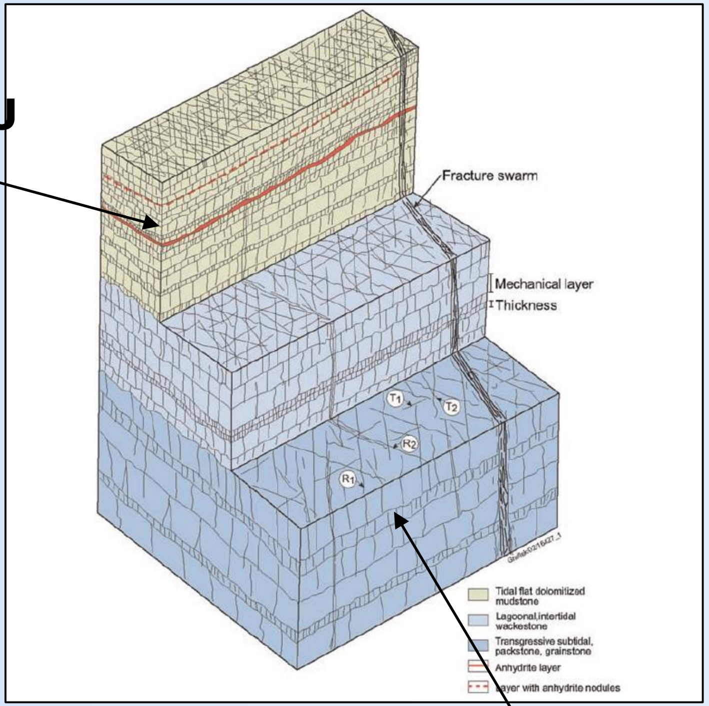


Wennberg et al. (2007)

Controlling factors – Mechanical stratigraphy

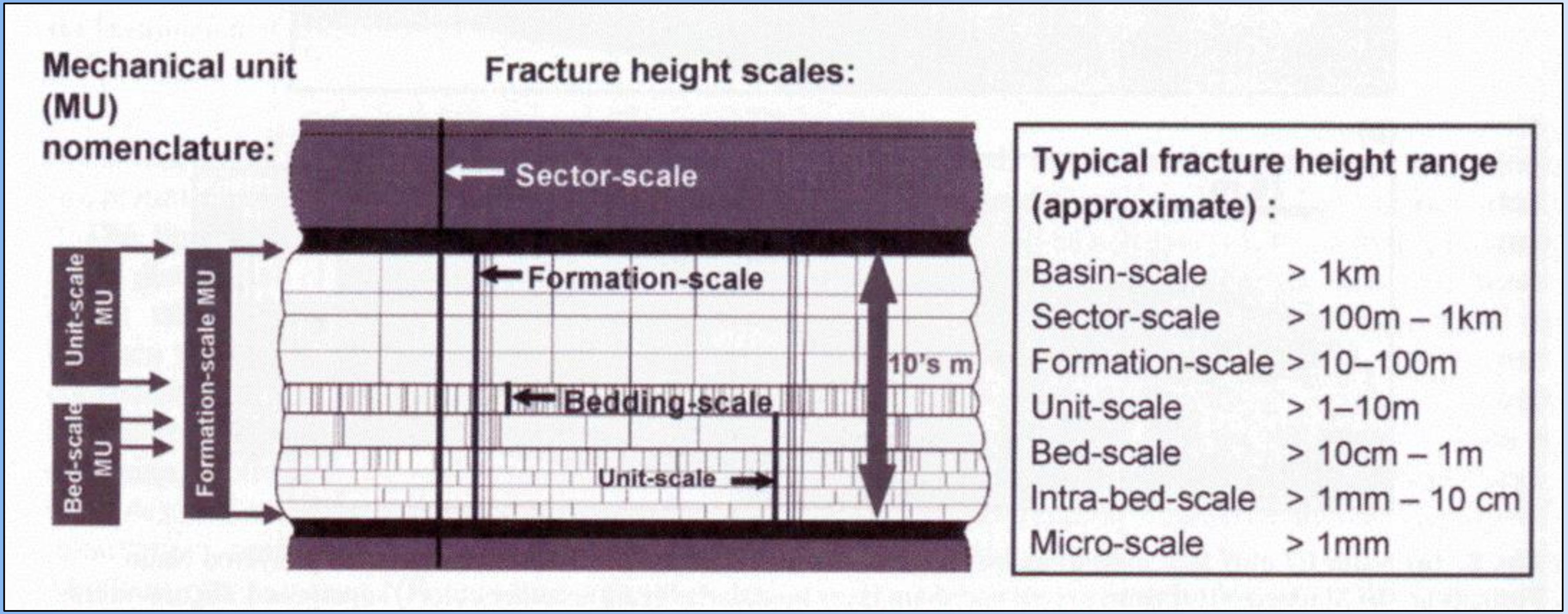
- Mechanical units can have different scales
  - Thin to medium bedded succession = bed scale
  - Thick-bedded succession = unit (bed-sets) or formation scale

Bed-scale MU



Wennberg et al. (2007)

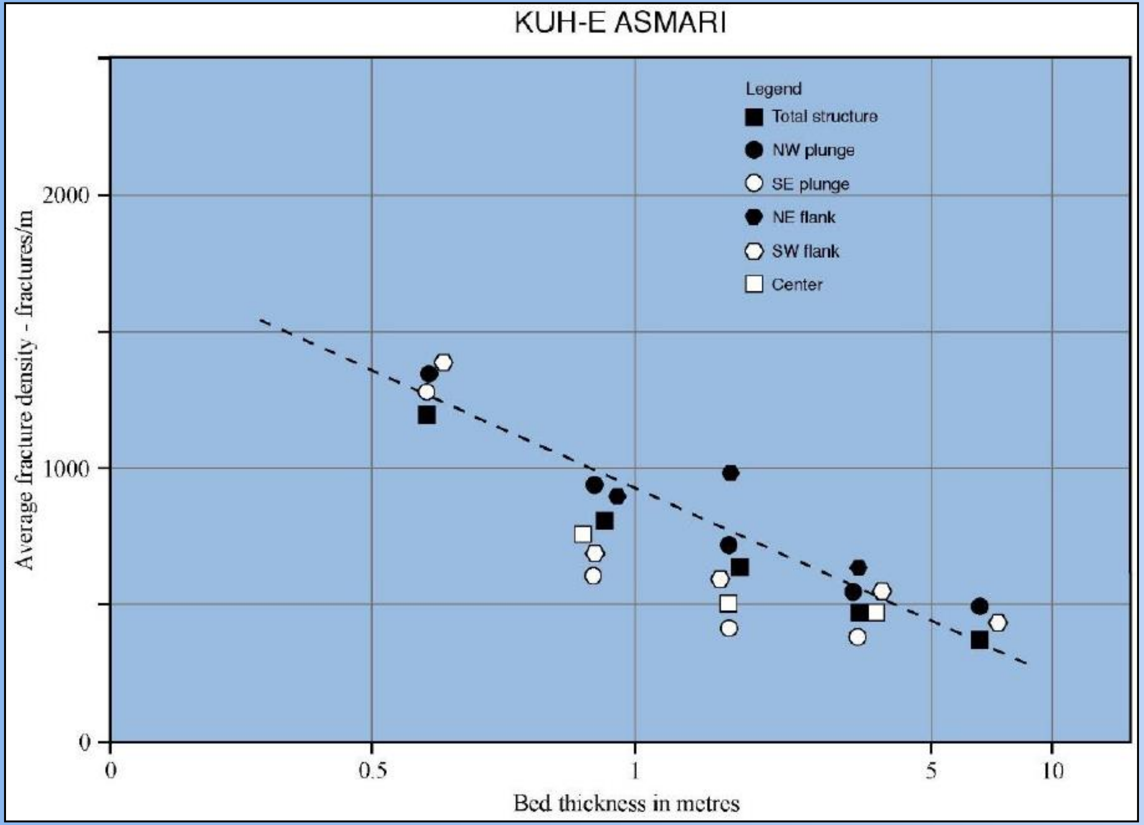
Unit-scale MU



De Keijzer et al. (2007)

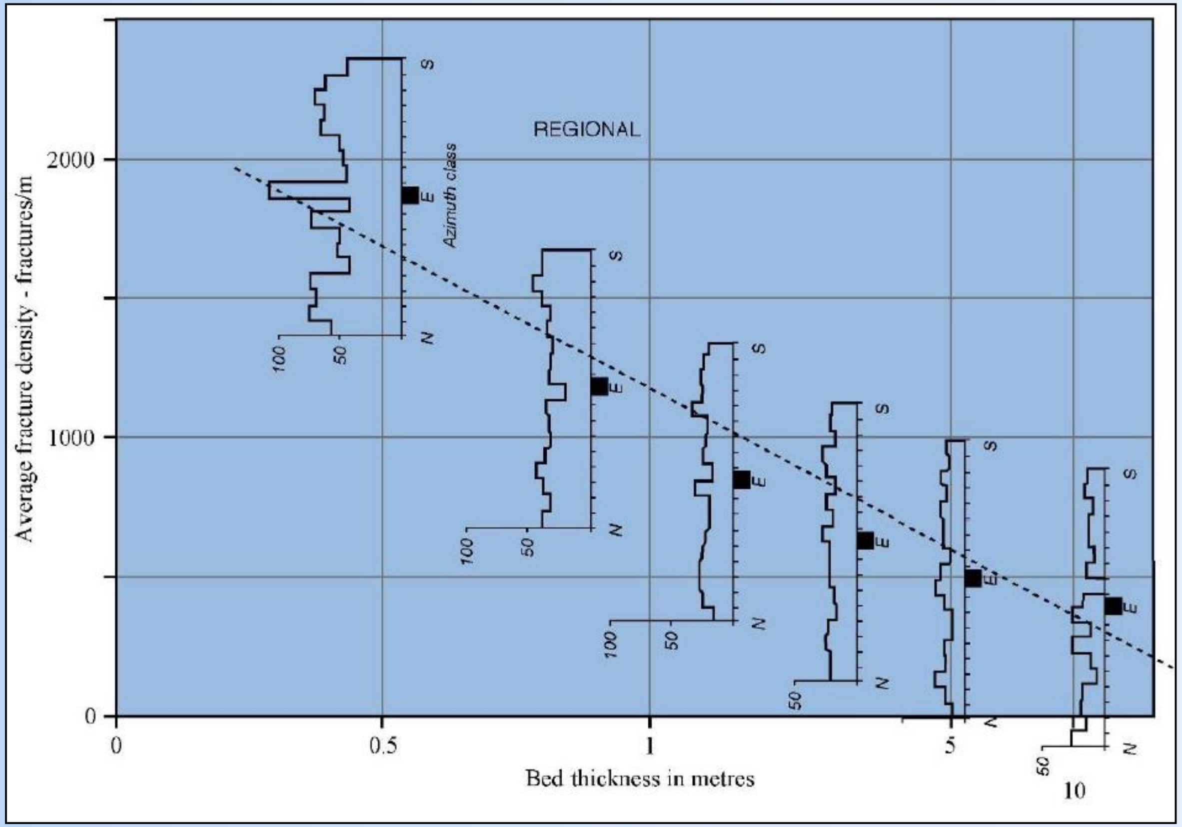
Controlling factors – Mechanical unit thickness

Relationship between bed thickness and average fracture density <u>from the Kuh-e-Asmari anticline</u> outcrop study in Iran



From McQuillan (1984)

Relationship between bed thickness and density of small scale fractures <u>from anticlines selected from a large area of Zagros foothills</u>



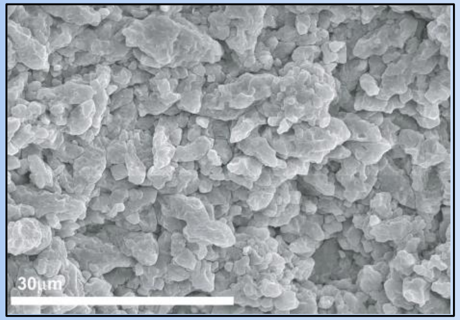
Histograms show fracture density distributions by azimuth classes

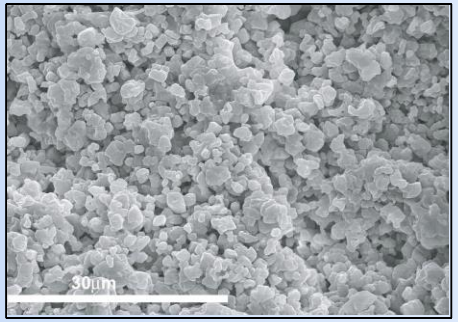
Controlling factors – Mechanical unit thickness + material properties

- For a given unit thickness
  - Higher fracture intensity for mudstone textures
  - More brittle?
  - Less interfaces (grains-matrix) for development of shearing?

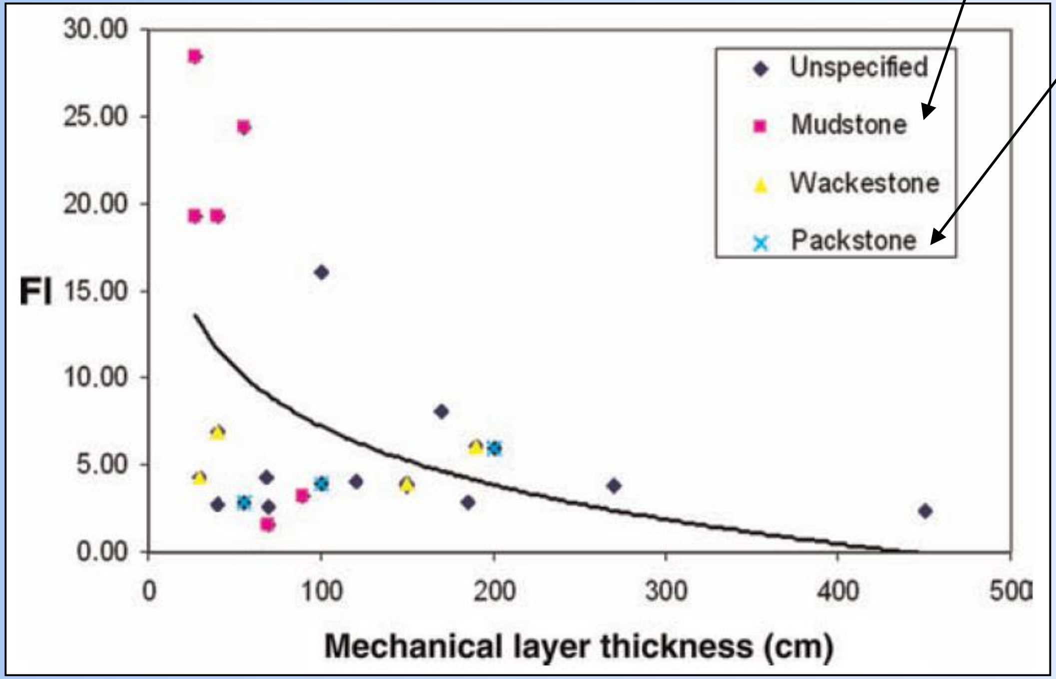
- Tight mudstone and porous mudstone may react differently to stress
  - Greater potential for accommodation of deformation in porous material

Tight micrite

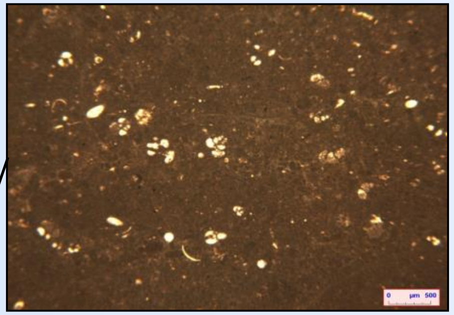


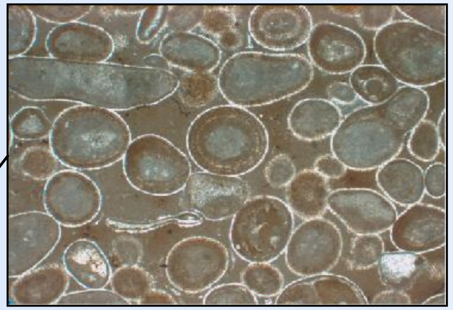


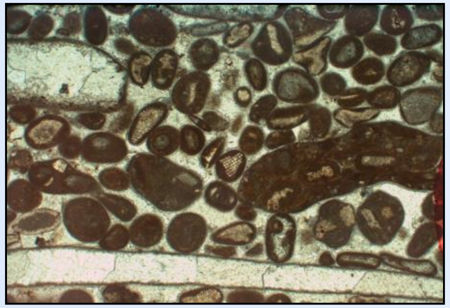
Porous micrite



Wennberg et al. (2007)



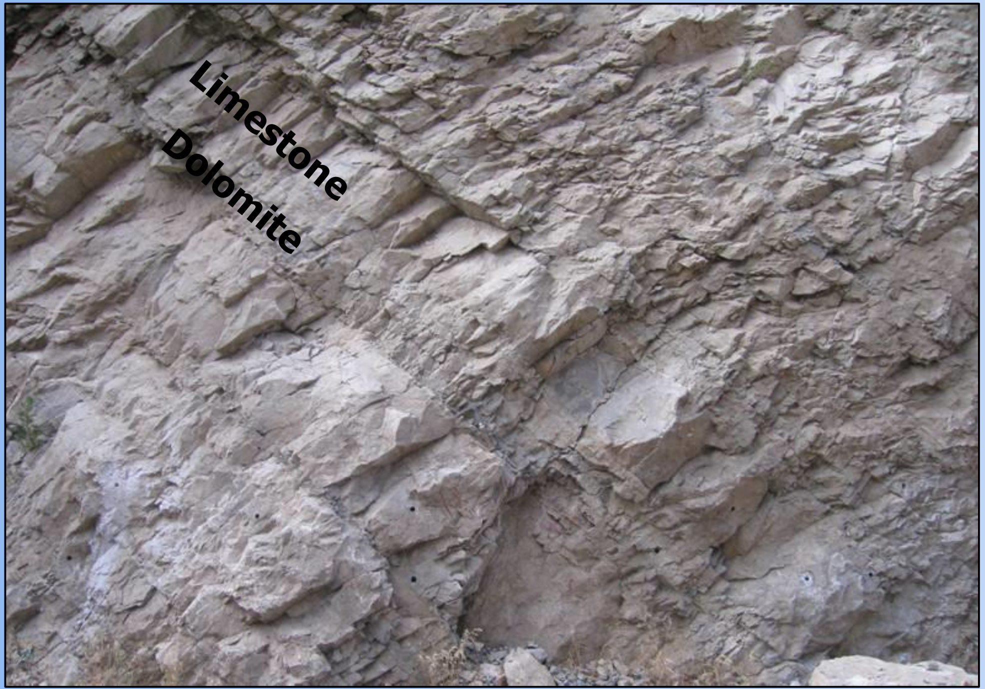


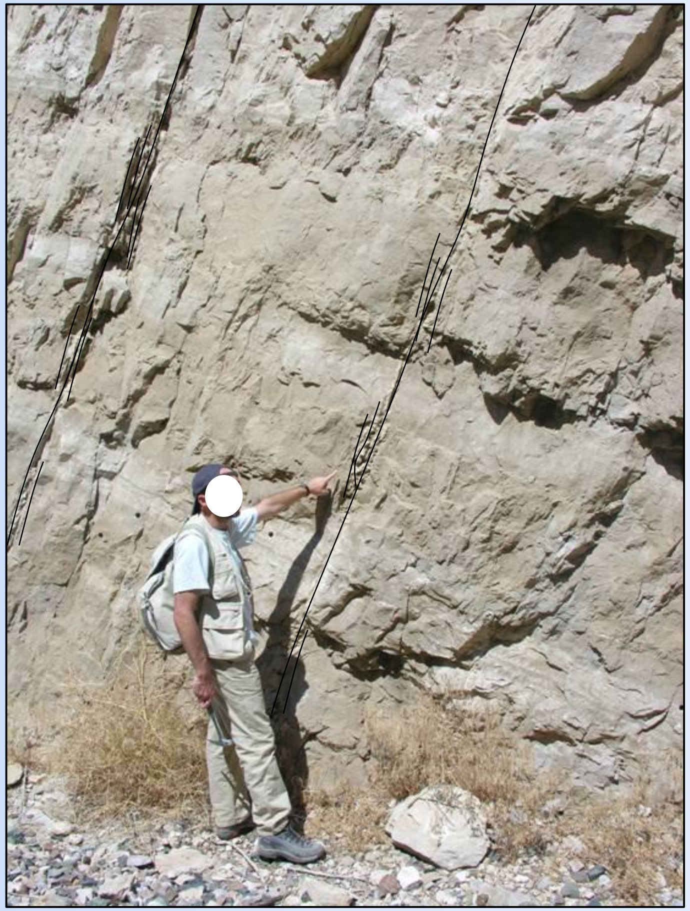


Controlling factors – Material properties

- **“Dolomite tend to develop fractures more readily than limestone”** (Purser et al, 1994; Nelson, 2001; Ortega and Marrett, 2001; Gale et al., 2004; Philip et al., 2005; Ortega et al., 2006…)

- Diffuse fracturing is more pronounced in dolomite





Guillet et al. (2007)

Sheep Mountain anticline, Madison Formation (Mississippian), USA

Impact on reservoirs

- Asmari fields (Wennberg et al., 2007)
  - Diffuse fractures
    - very important in linking fault damage zones
    - form a well-developed background fracture network which may facilitate high production over a significant time (draining a porous matrix or not)
  - Large-scale lineaments
    - connect fissures, joints and caverns occur over a wide area
    - major influence of fluid circulation
    - associated with early water and/or gas break through

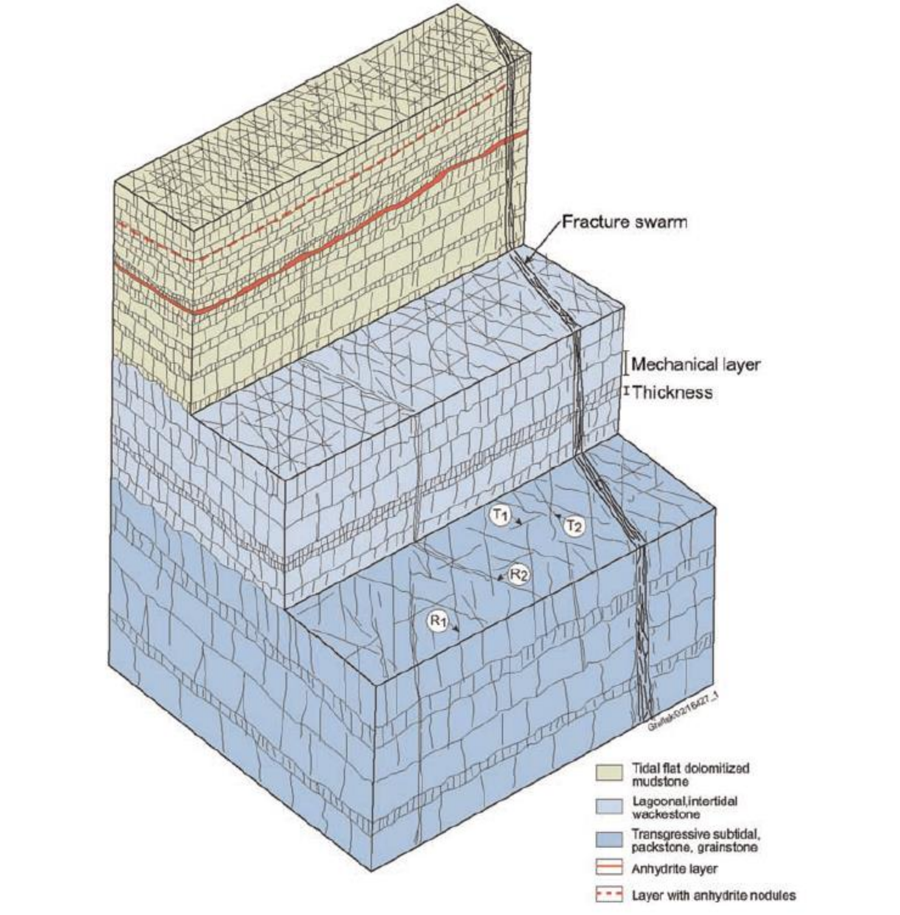


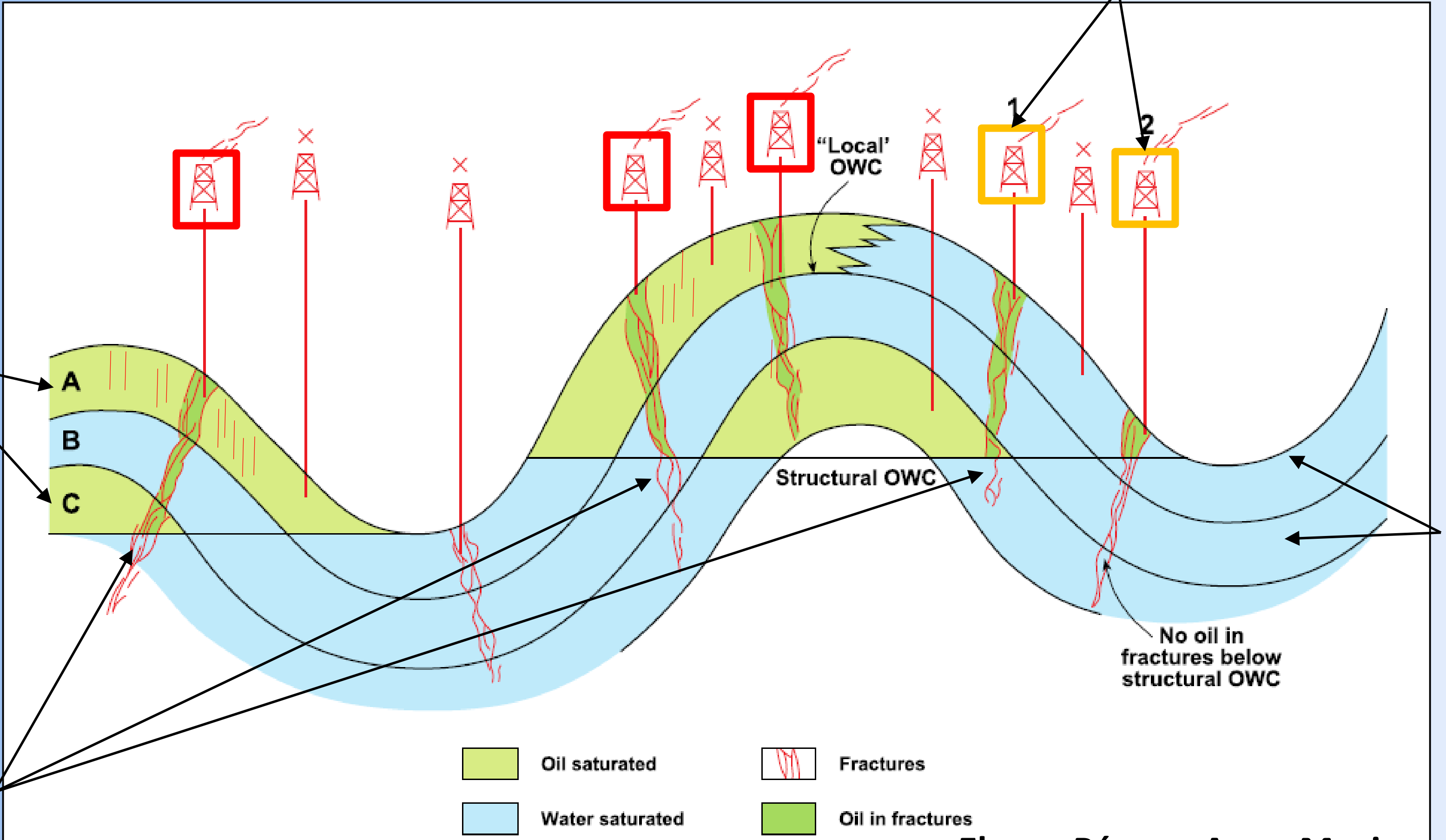
Fig. 6. An ideal shallowing up cycle of the Asmari Formation with a typical fracture pattern in a forelimb of a Zagros anticline.

Wennberg et al. (2007)

Impact on reservoirs

"flank faulted pools" (Muir, 1936)

Porous matrix with storage but no flow capacity
C and A (left)



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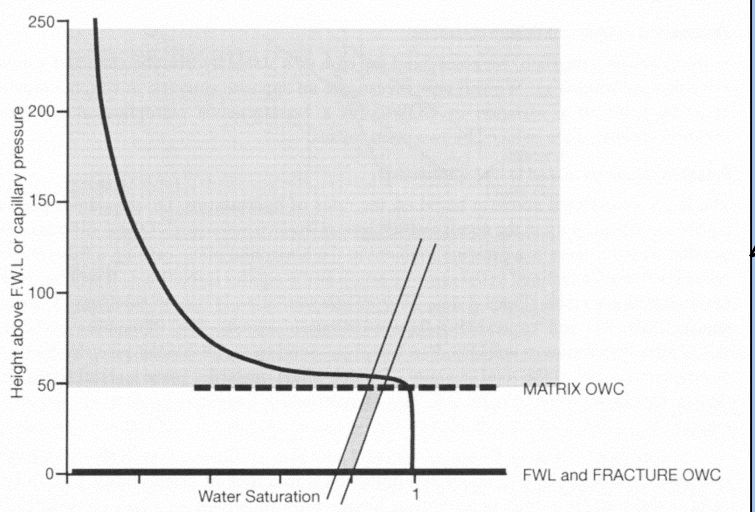
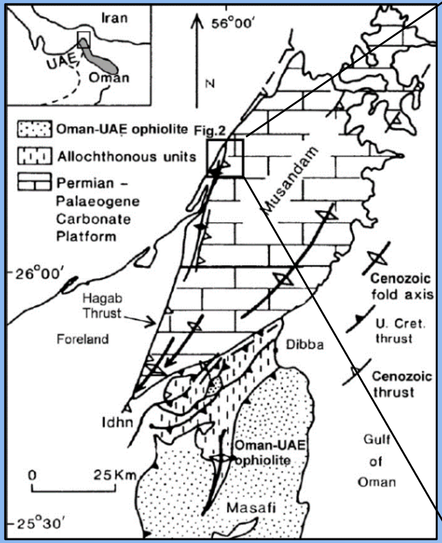
Ebano-Pánuco Area, Mexico

Tight matrix B and A (right)

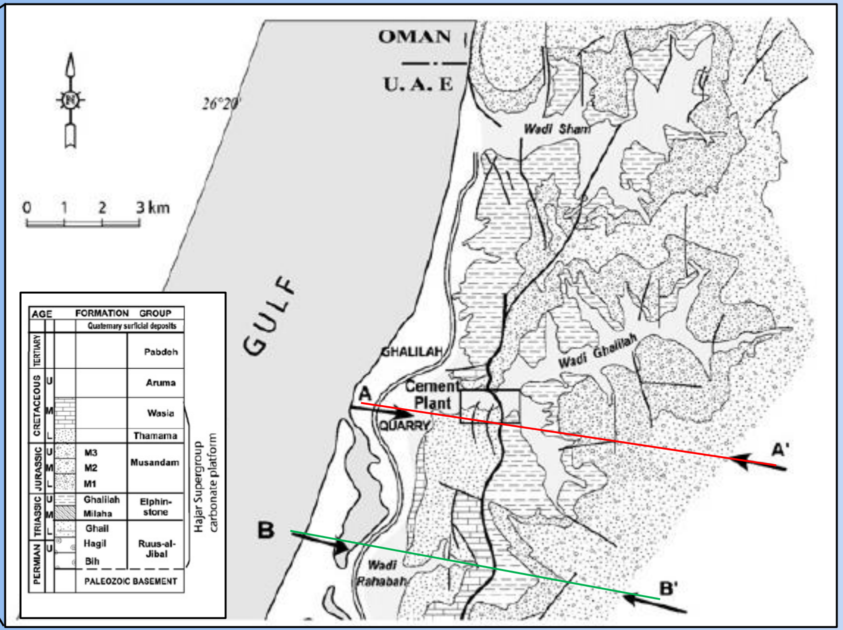


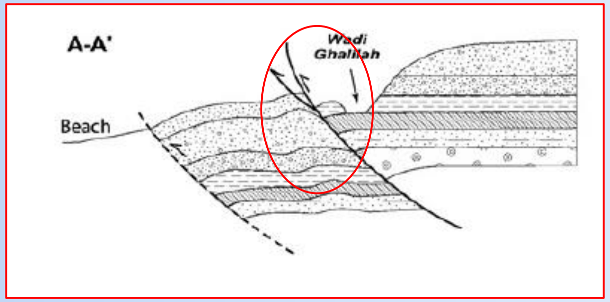
Zinszner and Pellerin (2007)

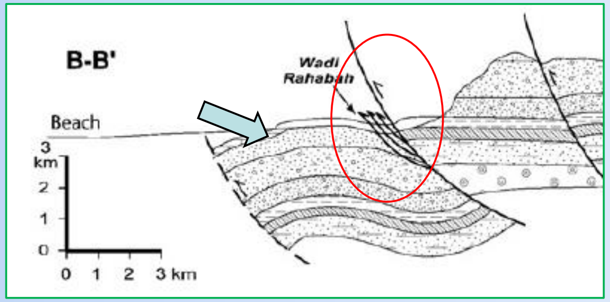
Impact on reservoirs

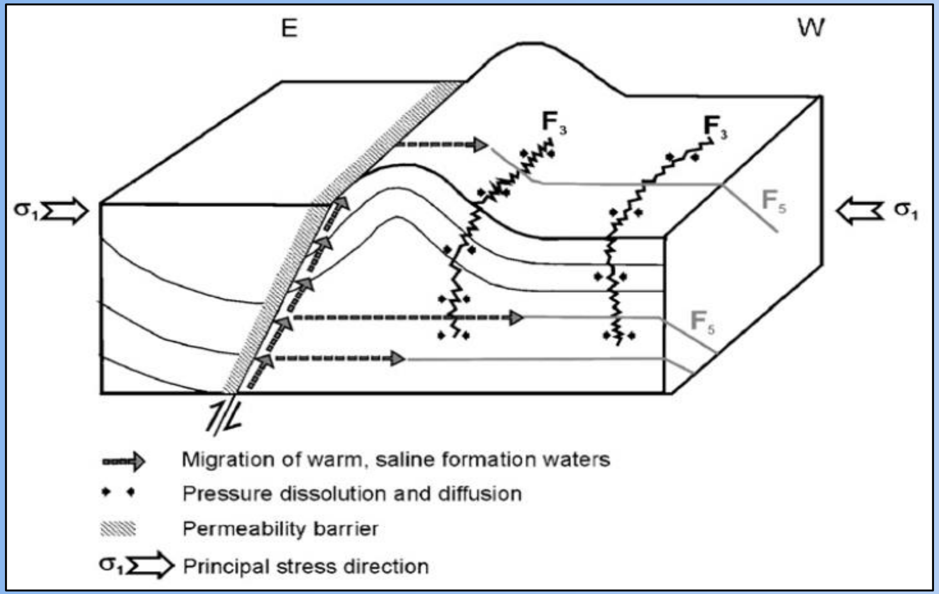


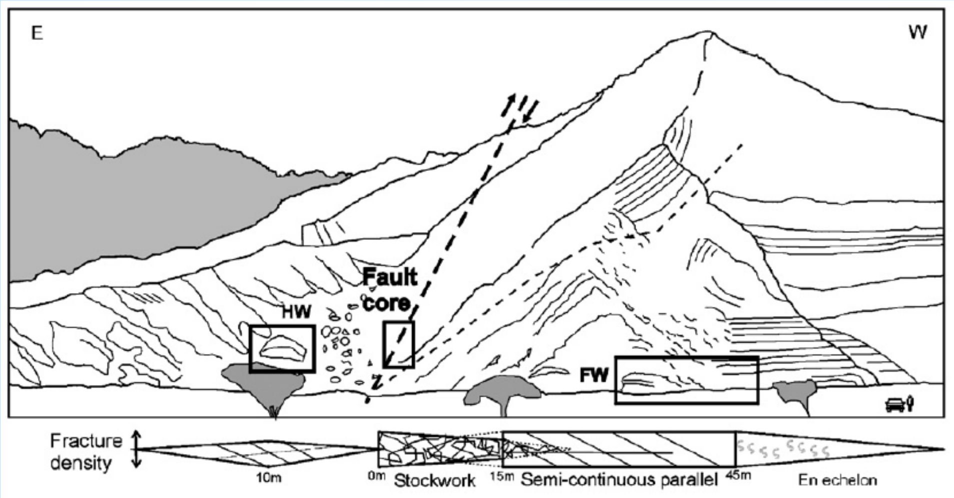
Breesch et al. (2008)







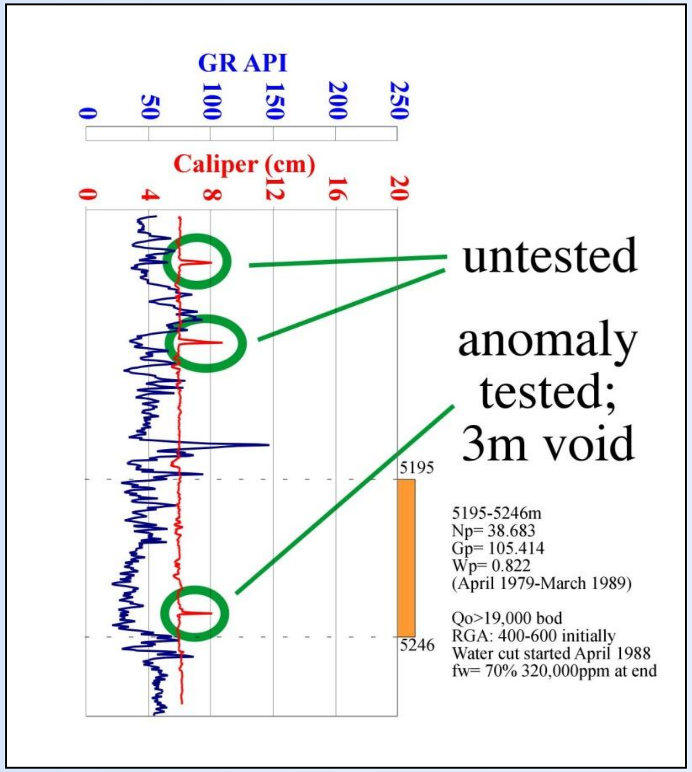




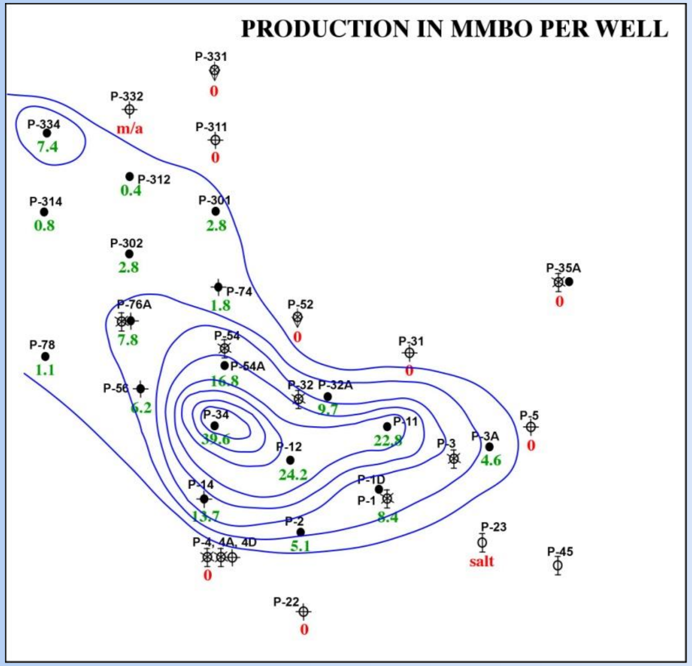
IDENTIFYING TECTONICALLY FRACTURED CARBONATE RESERVOIRS

Fractured reservoirs – Identification

- Fracture indicators
  - Open natural fractures are seen in core or on borehole image logs
  - $K_{test} >> K_{matrix}$
  - Reservoir heterogeneity (production)
  - Correlation between PLT and fracture occurrence
  - Mud loss (but large non-curable mud losses likely indicate karst systems)
  - Rapid water/gas breakthrough



Jurassic, Southern Mexico
Higher productivities associated with caliper anomalies



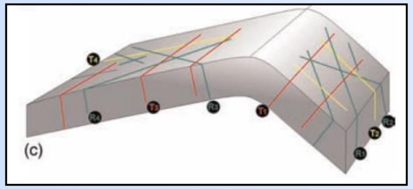
Fracture analysis from image logs

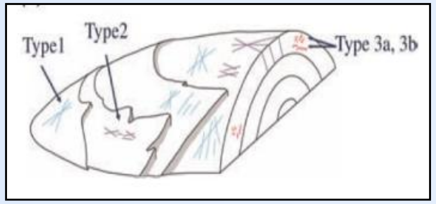
SUMMARY – TAKE AWAY POINTS

Structural model

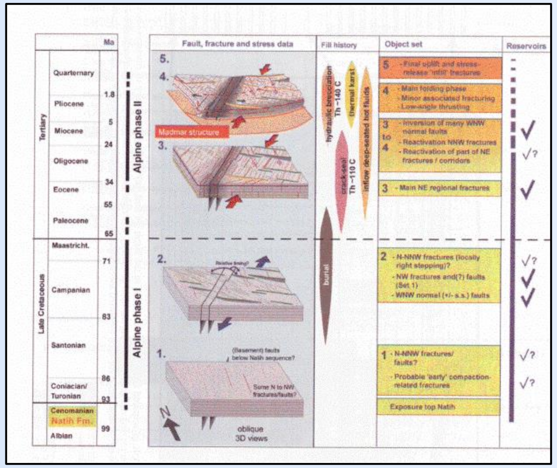
- Fractured reservoir identification
  - Dual porosity system may have another explanation (karst)
- Fracture analysis
  - Type of fractures: diffuse vs. swarm-large-corridors
  - Timing
  - Distribution and density of fractures: mechanical stratigraphy
- Structural model
- Subsurface reservoir (FMI+all other tools) **AND/OR** outcrop analogue

Type of structure

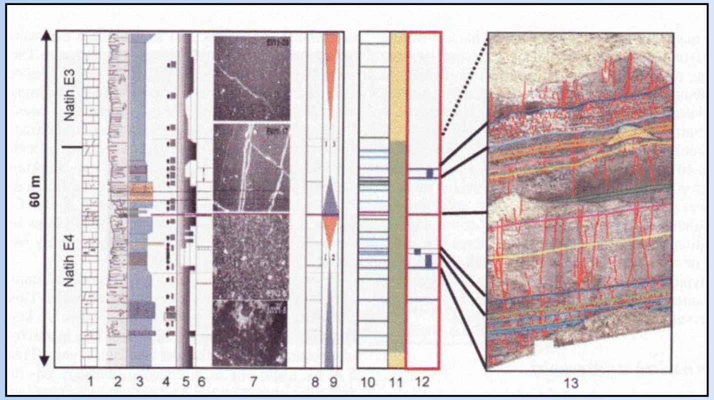




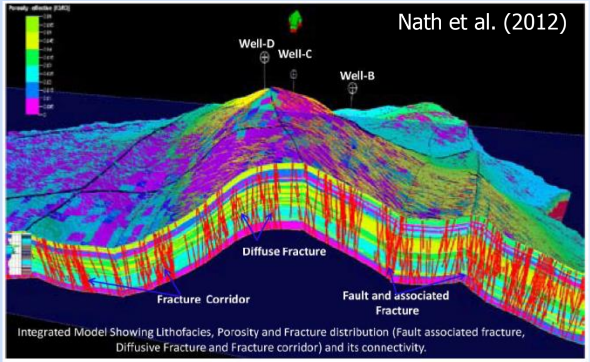
Tectonic agenda



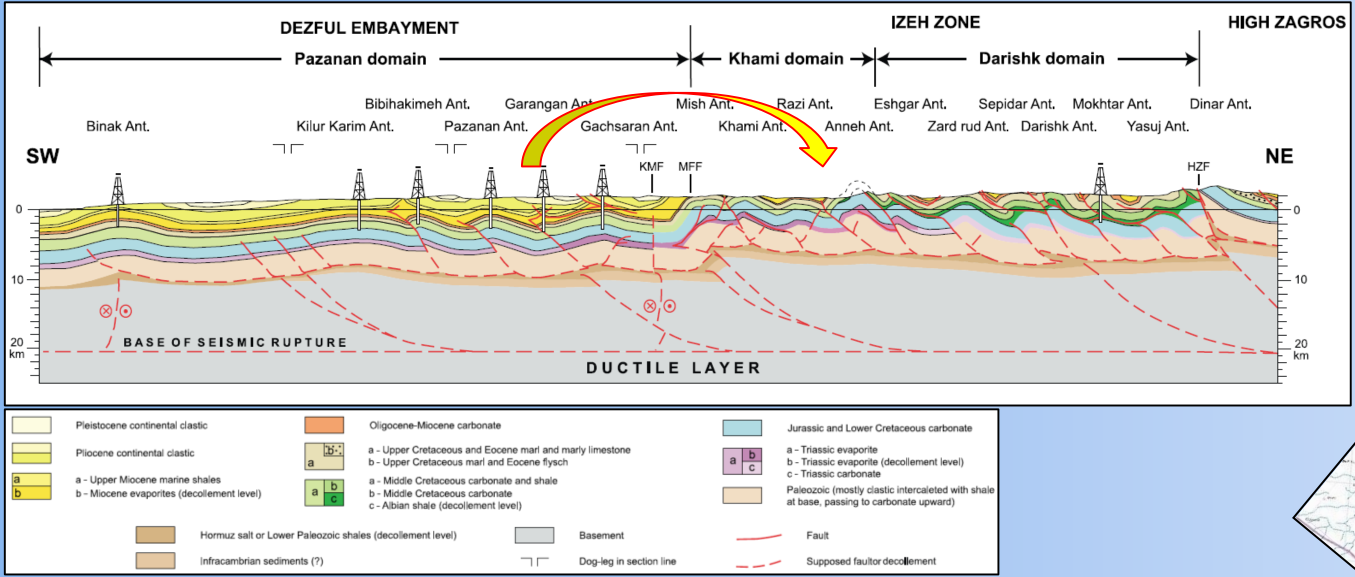
De Keijzer et al. (2007)



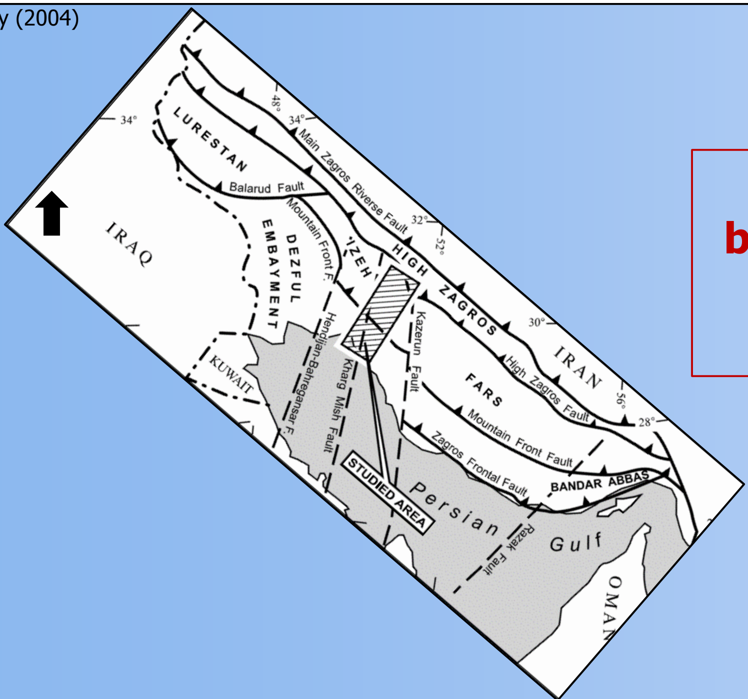
Mechanical stratigraphy



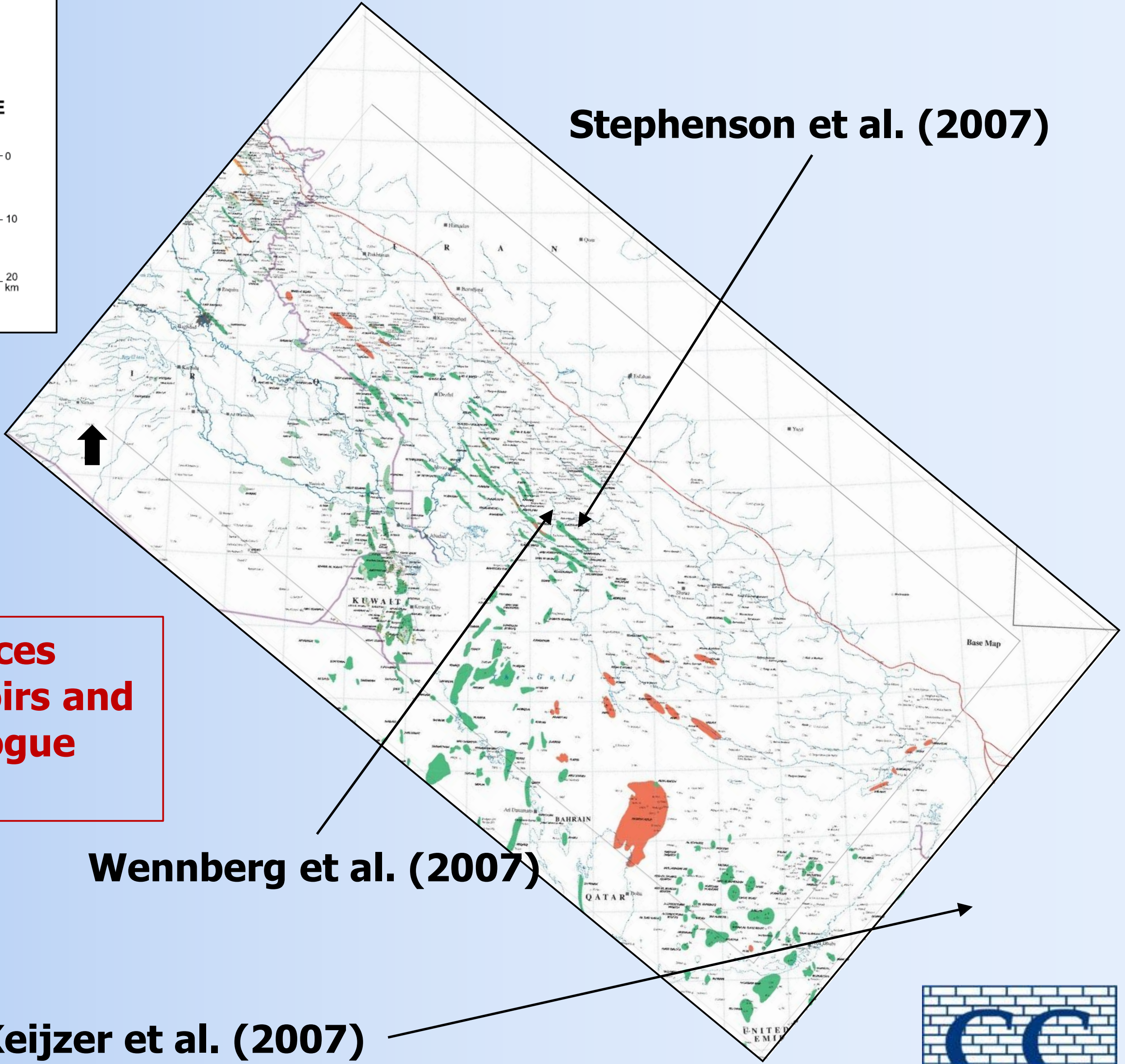
Importance of analogues in the Zagros FTB



Sherkati and Letouzey (2004)



Short distances between reservoirs and outcrop analogue anticlines



Stephenson et al. (2007)

Wennberg et al. (2007)

De Keijzer et al. (2007)

Some removed images and data are from:

“Fractured Carbonate Reservoirs - A Synthesis of Analogues”

Cambridge Carbonates Ltd. multiclient report

http://www.cambridgecarbonates.com/

http://www.cambridgecarbonates.com/key-products.html

(expert reports, fractured reservoirs)