Natural Fracture Systems in Carbonate Reservoirs

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Cambridge Carbonates Ltd

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Introduction

- Carbonate fields: typically >50% fractured, considerably more than in clastics
- Why the difference?
  - Not simply tectonic fracture mechanism
- Exploration
  - The presence of fractures or karst can influence the economics of a prospect
- Reservoir development
  - Well planning and location
  - Do you avoid or intersect fractures?
  - Methods of secondary recovery
- AIMS of presentation
  - Demonstrate the different fracture mechanisms in carbonates
  - Implications for reservoir geometries and reservoir quality

Origins of fractures in carbonate reservoirs

Tectonic

Karst collapse

Fracture-related dolomite (HTD)

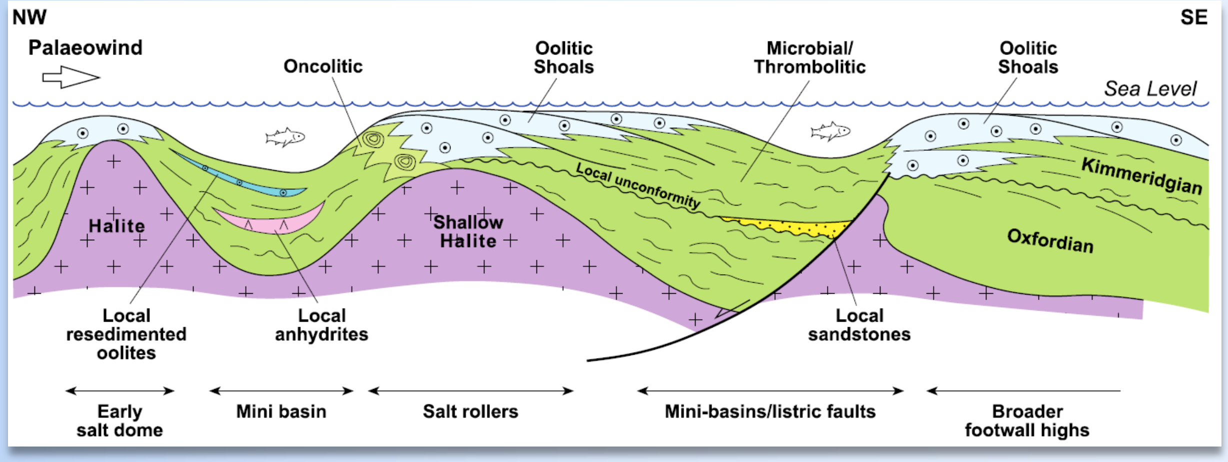
Evaporite collapse

Tectonic Fractured Systems

- Affect carbonate and clastic reservoirs
- Tectonic fractures relate to fold geometry
- Tectonic fractures usually fractal and ‘predictable’ in a statistical sense
- Type 1 and Type 2 reservoirs
- Variations and anomalies exist

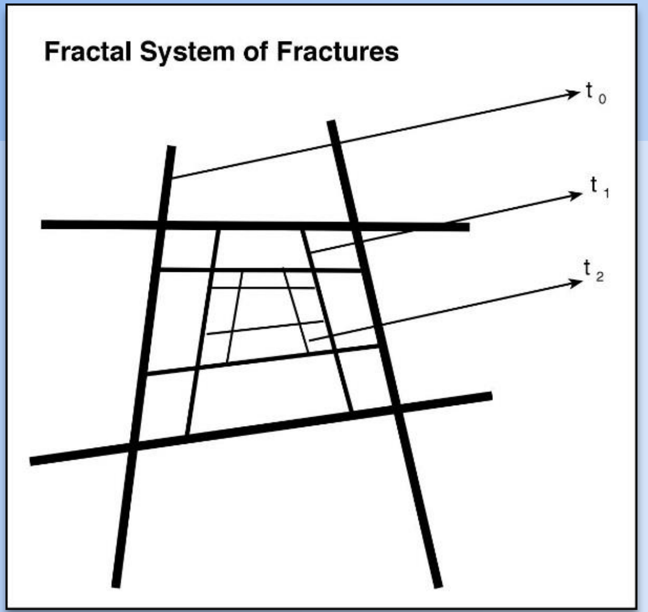
Mechanisms of tectonic fracturing

- Compressional tectonics
  - Thrust and fold belts
  - Foreland basins
- Salt tectonics
  - i.e North Sea Chalk
  - SE Mexico
- Transtentional settings
- Fracturing can affect any carbonate facies
  - Type 1 reservoirs (fractures, but no effective matrix porosity)
  - Type 2 reservoirs (fractures and matrix porosity – dual porosity system)

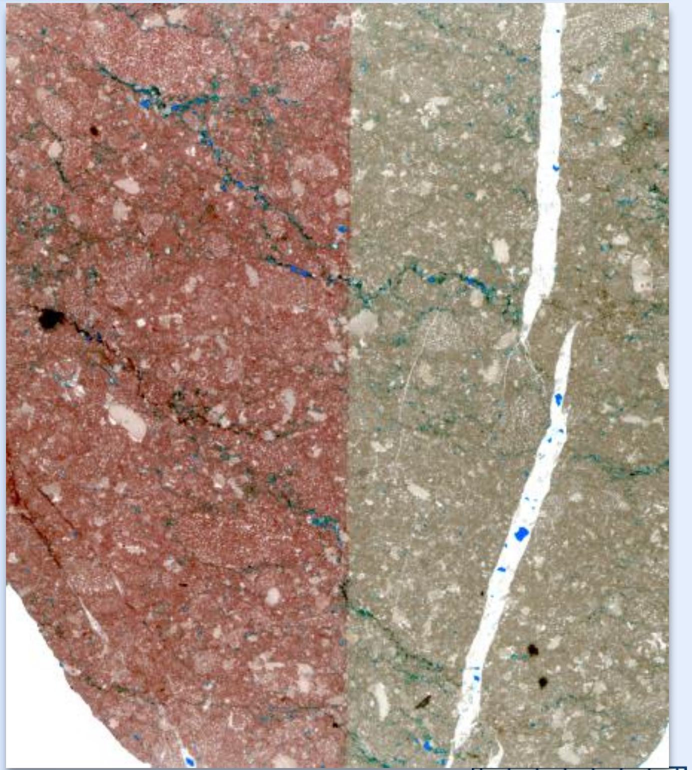


Tectonic fracture scales

- Fractures are typically fractal
- All scales important
- Meso-scale fractures
  - Important to identify – productive features
- Micro-scale fractures
  - Important because they connect non-fracture porosity to meso-scale fractures
  - Minor importance for storage and direct production
  - Can regard these as ‘matrix’ (i.e. Apennines)



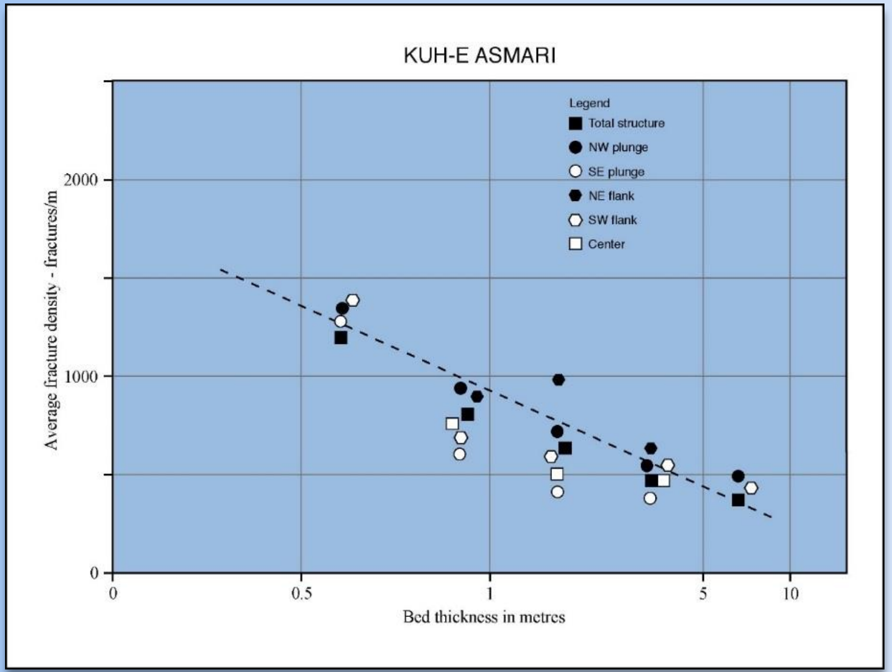
Wide (metre-)spaced fractures/joints, Stair Hole, Dorset, Southern England



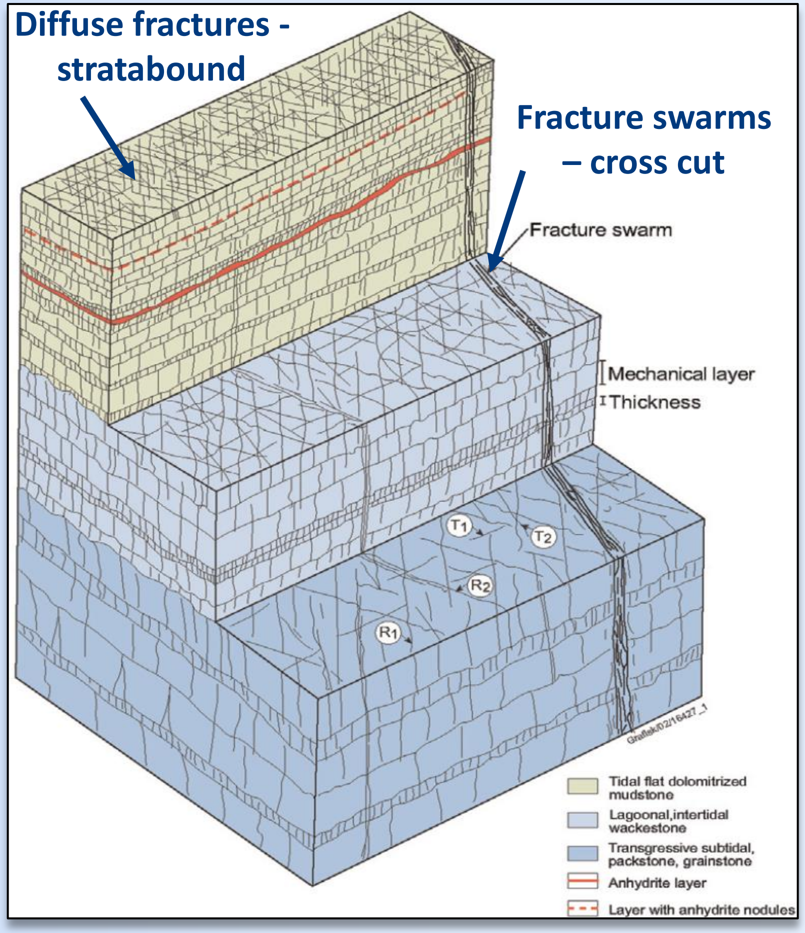
‘Typical’ en-echelon tectonic fracture from the Middle East

Tectonic fracture density and spacing

- Hierarchical scales particularly important in carbonates
  - fractures
  - cycles
  - bed thicknesses etc
- Fracture density and spacing controlled by
  - bed thickness
  - lithology
  - depositional facies
  - position on structure



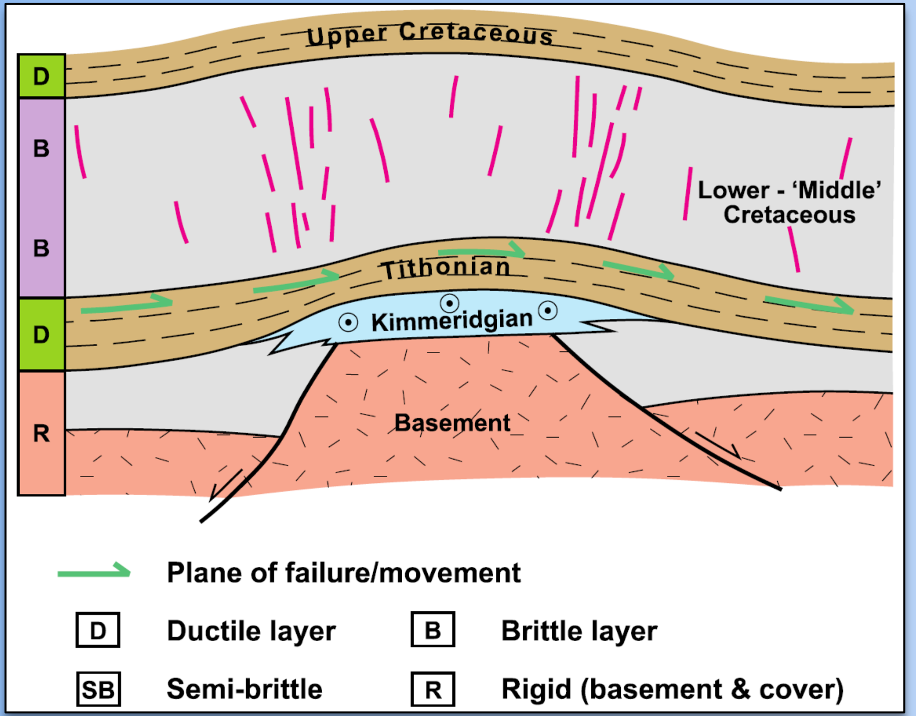
Bed thickness control on fracturing in the Asmari in Iran (McQuillan, 1985)



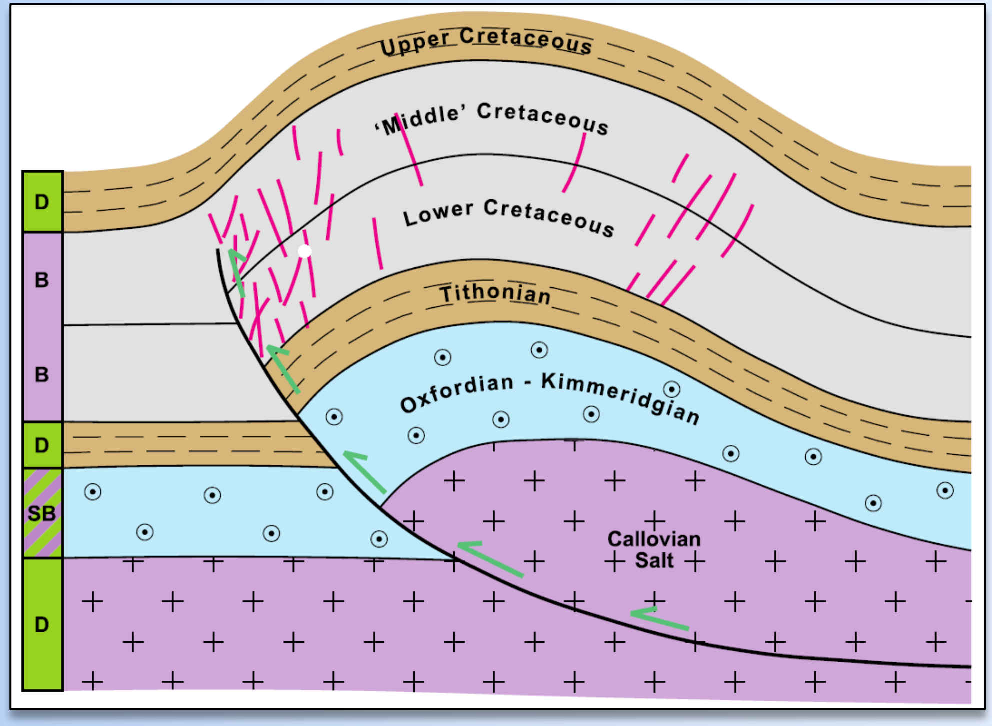
Shallowing-upwards cycle with typical fracture pattern, Zagros. Wennberg et al. (2007)

Tectonic fracture distribution

Tampico-Misantla, NE Mexico



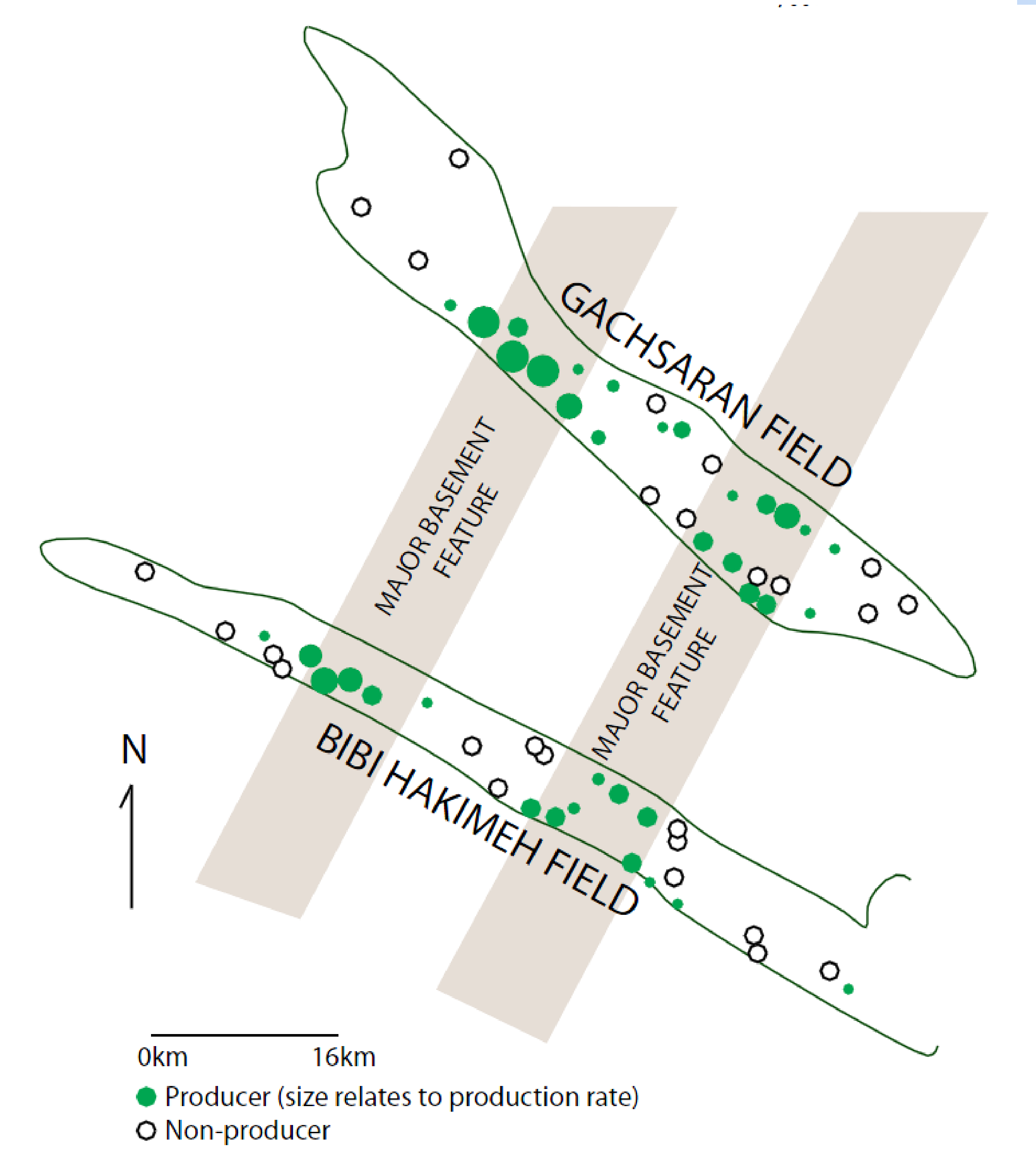
Sureste Basin, SE Mexico



- Tampico-Misantla Basin: fracture corridors that relate to deformation of the brittle micrites above an irregular basement topography. Internal "shearing" of a competent Lower Cretaceous slab.
- Sureste Basin: deformation of these same carbonates was primarily during the Miocene orogenesis, where fracture development is closely tied to folding of the NW-SE oriented anticlines.

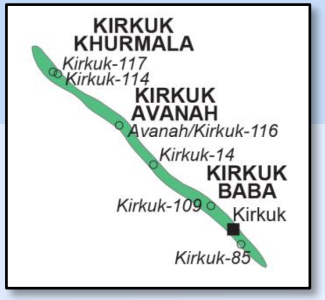
Heterogeneous productivity

- Gachsaran and Bibi Hakimeh fields - location of major productivity
- Productivity defined by major basement features
- Gaschsaran wells produce 60,000 BOPD

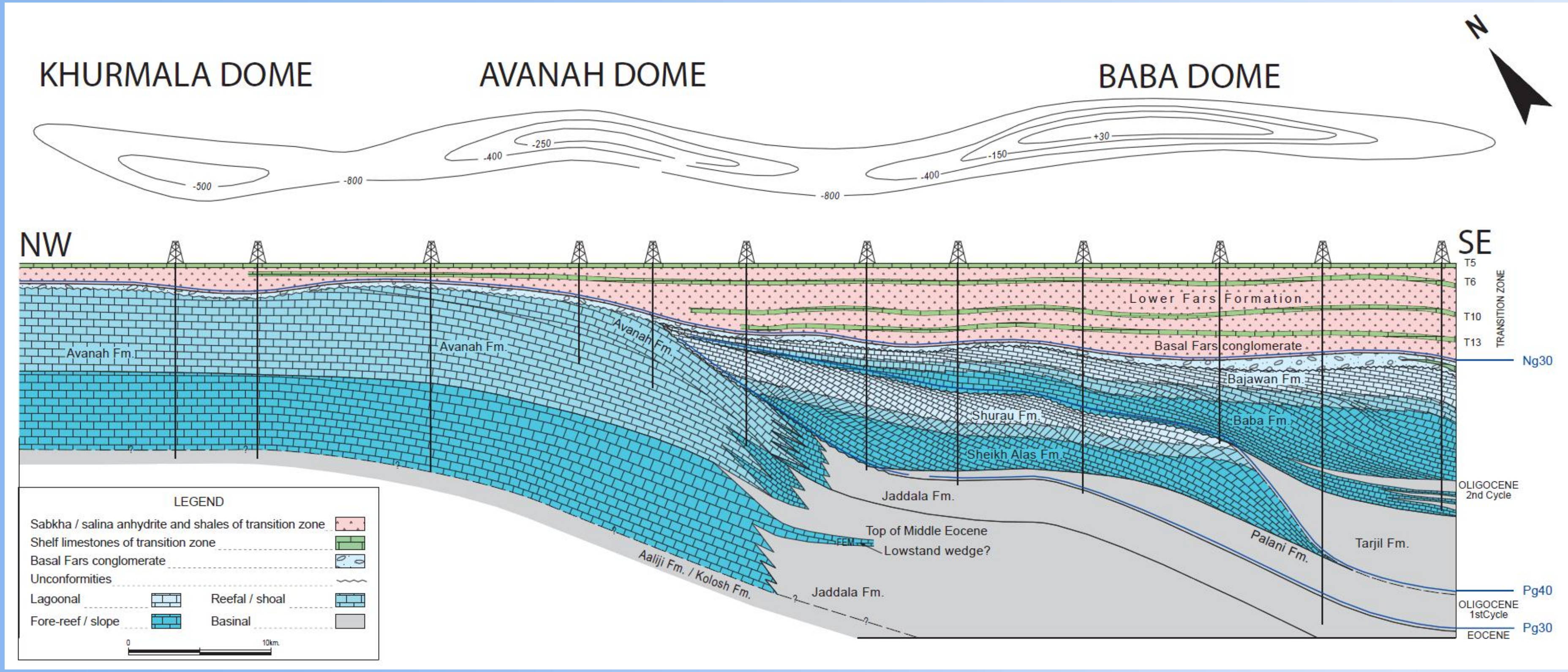


Redrawn from McQuillan (1984)

Type 2 vs Type 1 tectonic fractured reservoirs



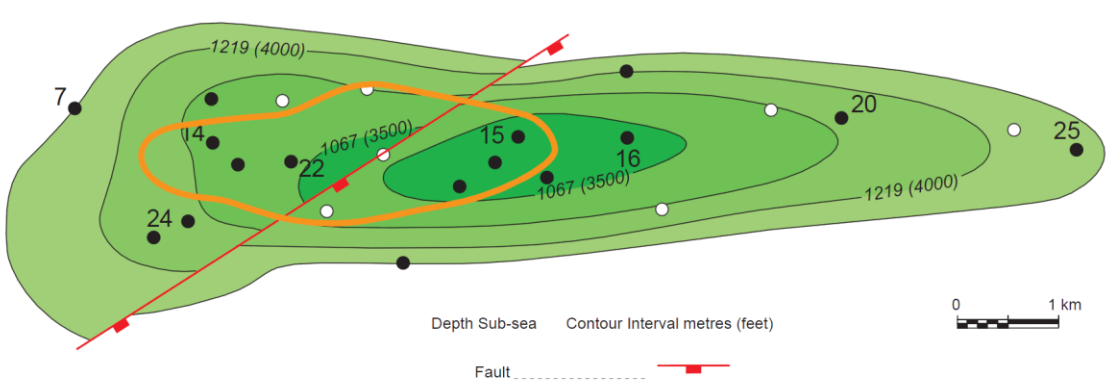
- Cenozoic Asmari fields, Zagros – dual porosity reservoirs (Type 2)
- Hydrocarbon storage capacity is given by micro and vuggy matrix porosity systems, whilst deliverability is provided by networks of fissures.
- If it were 100% matrix, the reservoirs would not flow, and if it were 100% fractures, production would be short term.



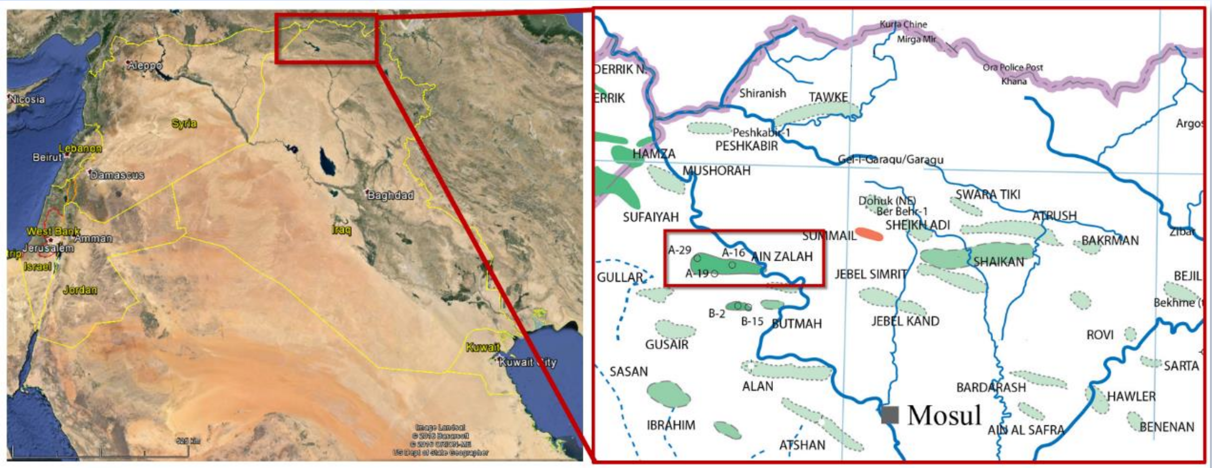
- Facies influence reservoir quality
- Extensive fracture network – estimated that the 104km structure drained only from SE culmination.
- Flow rates 20,000 to 30,000 BOPD

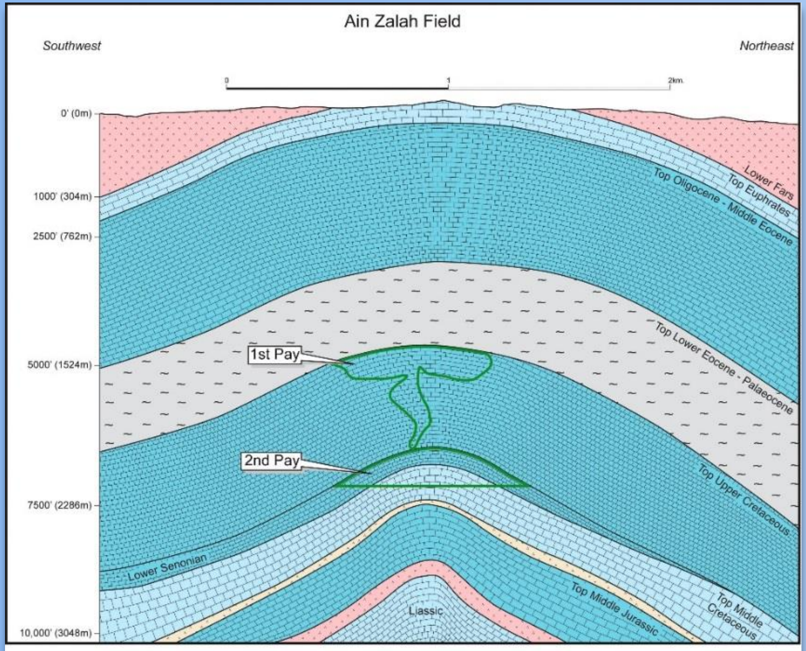
Reservoir zones along the Kirkuk structure, after Daniel (1954)

Type 1 tectonic fractured reservoir, Ain Zalah Field



Aqrawi et al. (2010) after various sources





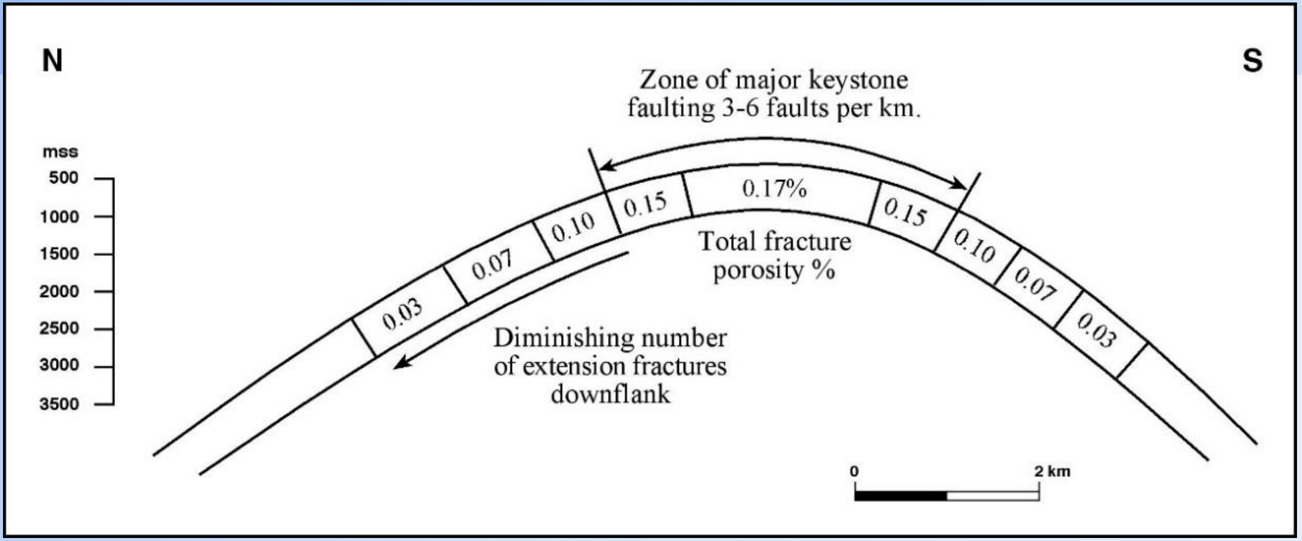
Aqrawi et al. (2010) after various sources

- 1st pay reservoir - Late Cretaceous (Shiranish Formation) fractured marly carbonates. Fractures are oil bearing, matrix is water-wet.
- Fractures detected through mud losses. Fracture frequency is variable, up to 20-40 per metre of core.
- Fractures are well-connected – flows in wells influence pressures in other wells.
- Rapid recovery of bottom hole differential pressure when major producers are cut back
- Productive area is offset from crest of structure
- 2nd pay – pressure communication through faults
- Possible recharging of tectonic fractures

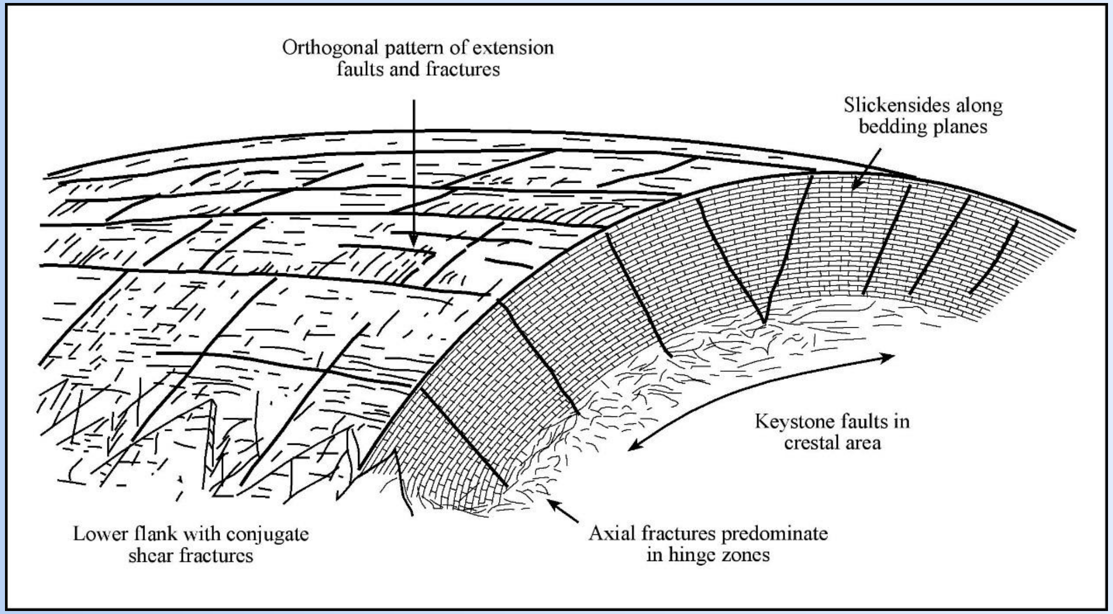
Tectonic fracture porosities

- Important to understand in Type 1 reservoirs
- Fracture porosities contribute on a minor amount – permeability is the key factor

Field	Fracture porosity (%)
Agha Jari, Iran	0.22%
Haft Kel, Iran	0.21%
Masjed-e-Suleyman, Iran	0.20%
Gachsaran, Iran	Up to 0.17%
Taq Taq, Kurdistan	0.24%
Shaikan, Kurdistan	0.3% to 0.4% (mid case)
Urdenata West, Venezuela	0.2%
West Kangean, Indonesia	0.68%
Valhall, Norway	0.2%
Nido, Philippines	2-3%
Gela, Italy	3-5%



Distribution of fracture porosity across the Gachsaran structure. Weber and Bakker (1981).



Tectonic fracture systems - summary

- Tectonic fractures relate to fold geometry and deeper lineaments
- Tectonic fractures usually fractal and ‘predictable’ in a statistical sense
- Type 1 and Type 2 reservoirs
- Variations and anomalies exist
- Need a good understanding of structuration/ fracturing/ diagenesis
  - Highest fracture concentration not always at crest of structure
- In tectonic fractured reservoirs, fractures can be recharged

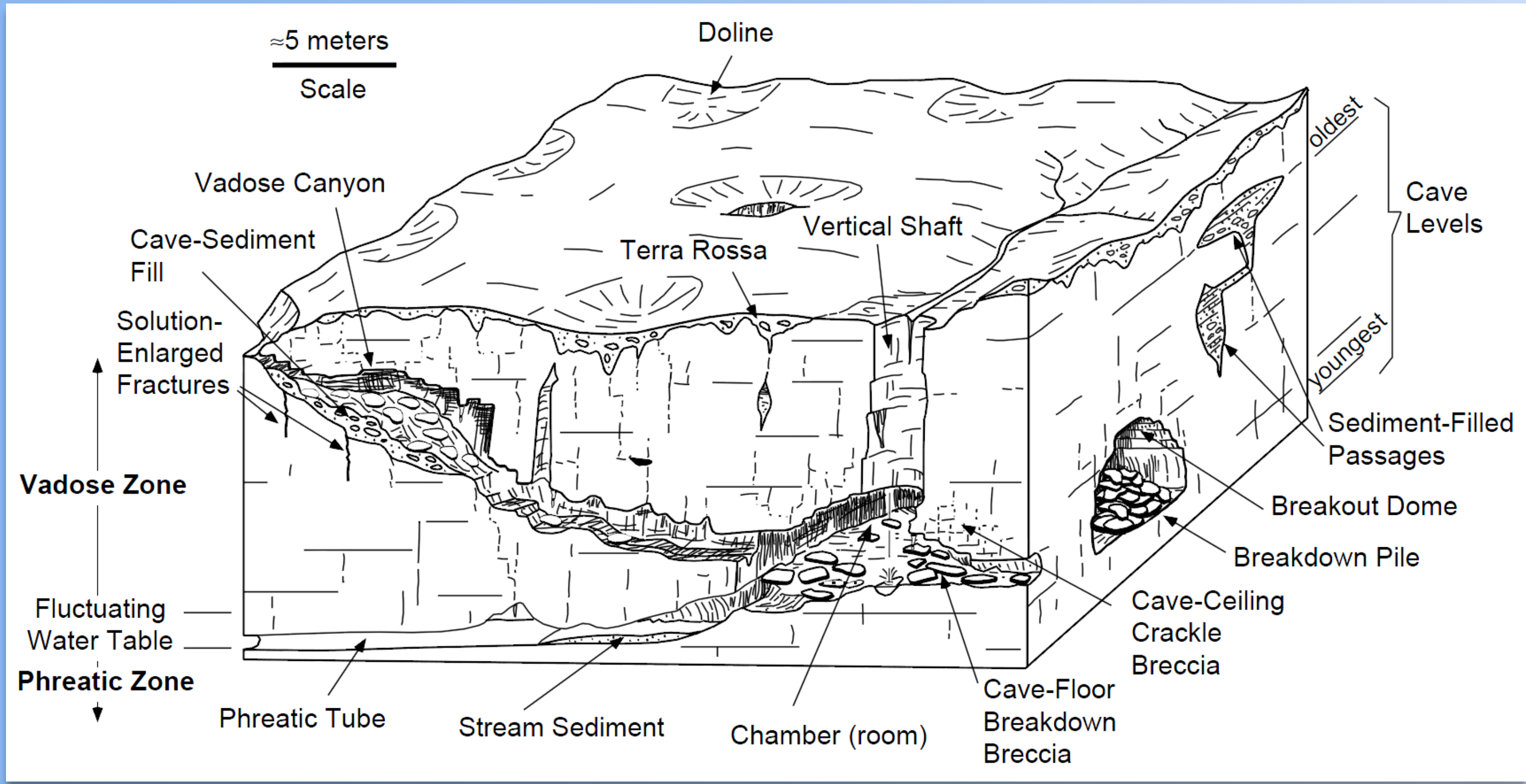
Karst Fracture and Breccia Systems

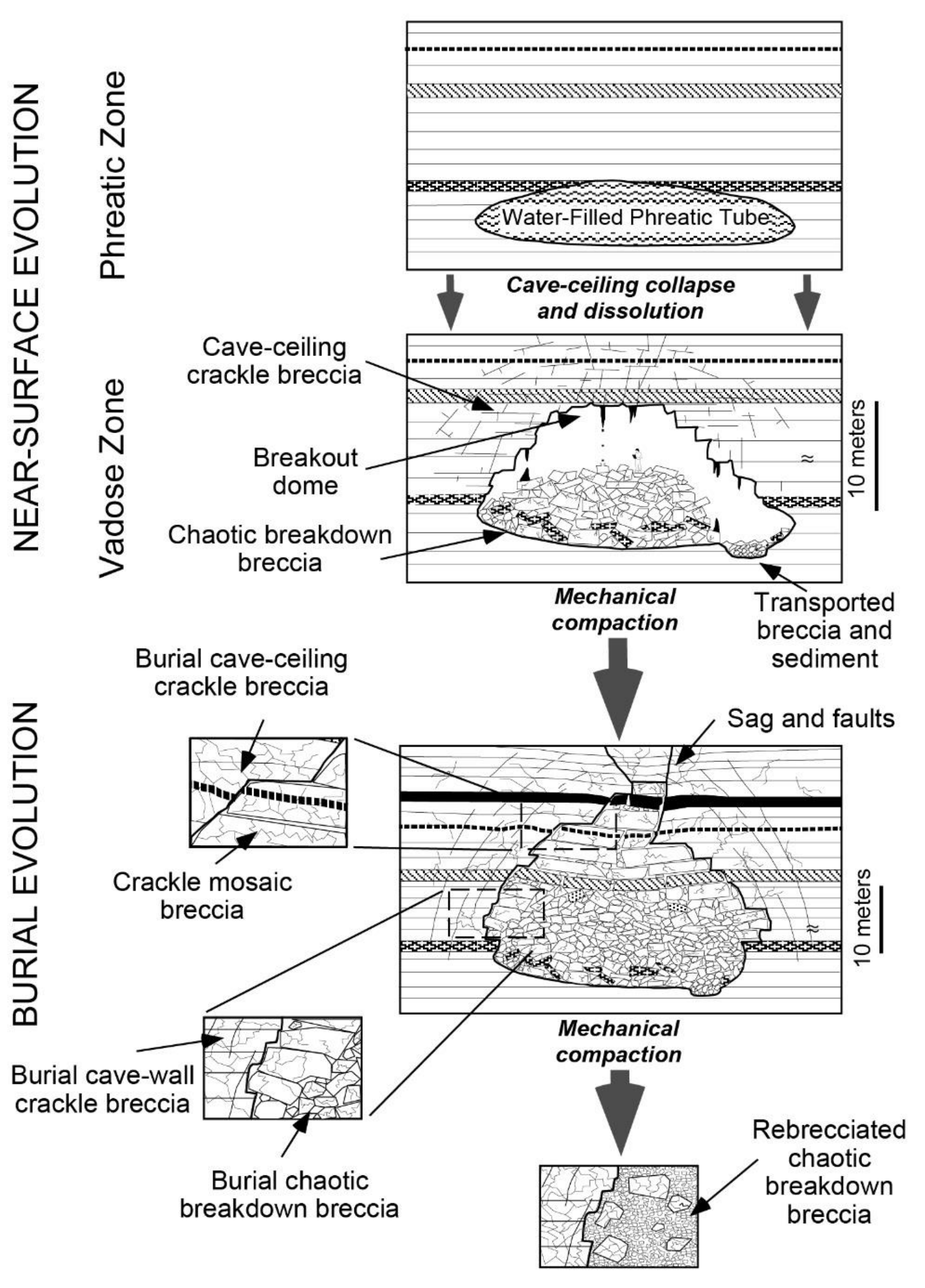
- Form via collapse of caves
- Result in stratiform, heterogeneous fracture systems
- Fracture propagation into roof, wall rocks
- ‘Nested’ caves increase lateral and vertical extent of fracture/breccia zone

Karst reservoirs

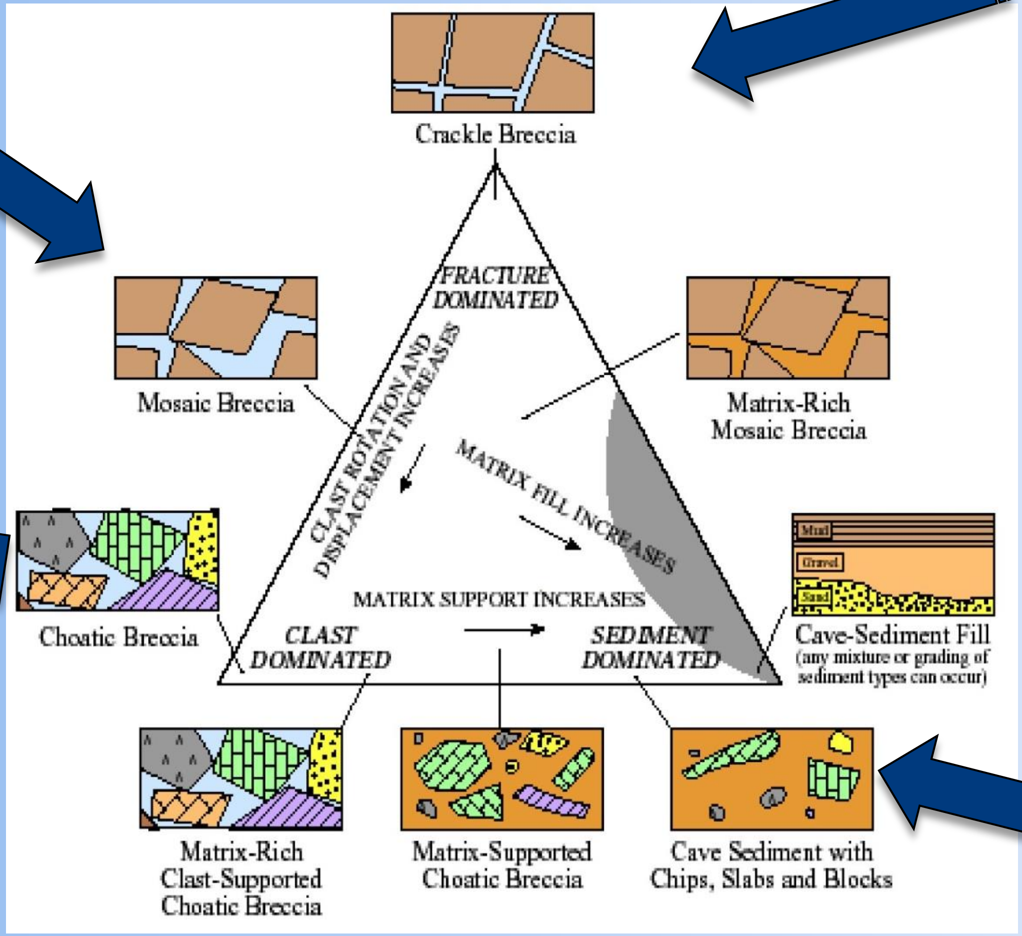
- Palaeocave systems formed during SEQUENCE BOUNDARIES AND LOWSTANDS
- Dual porosity system that formed by dissolution of carbonate host rocks in meteoric-derived water

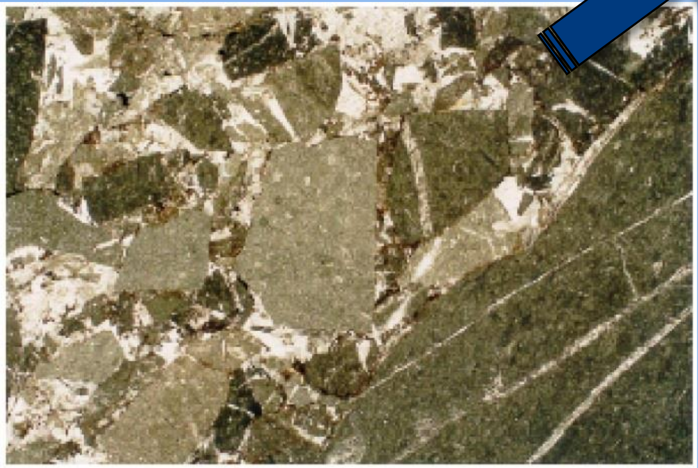
Loucks (1999)

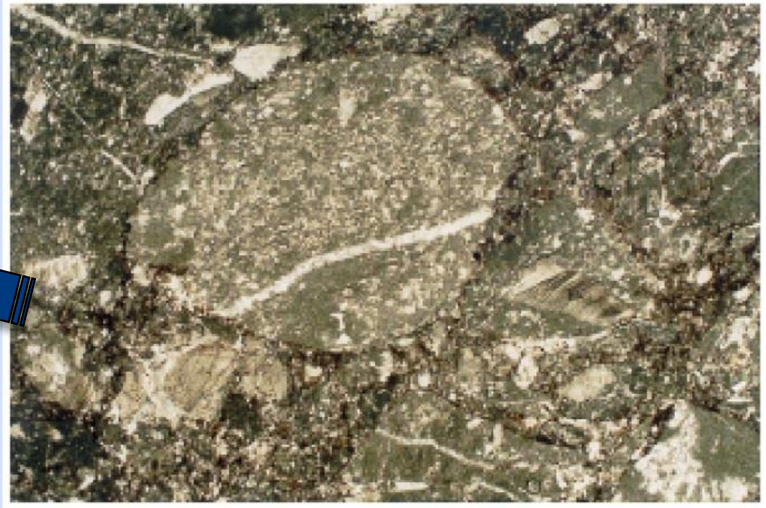




Karst reservoirs in the subsurface







Microtextures associated with karst collapse, from Loucks (1999); examples from Italy

Karst collapse breccia reservoir

Base of collapse breccia 1919.7m

Dolomite breccia with inverted geopetal, 1902.6m

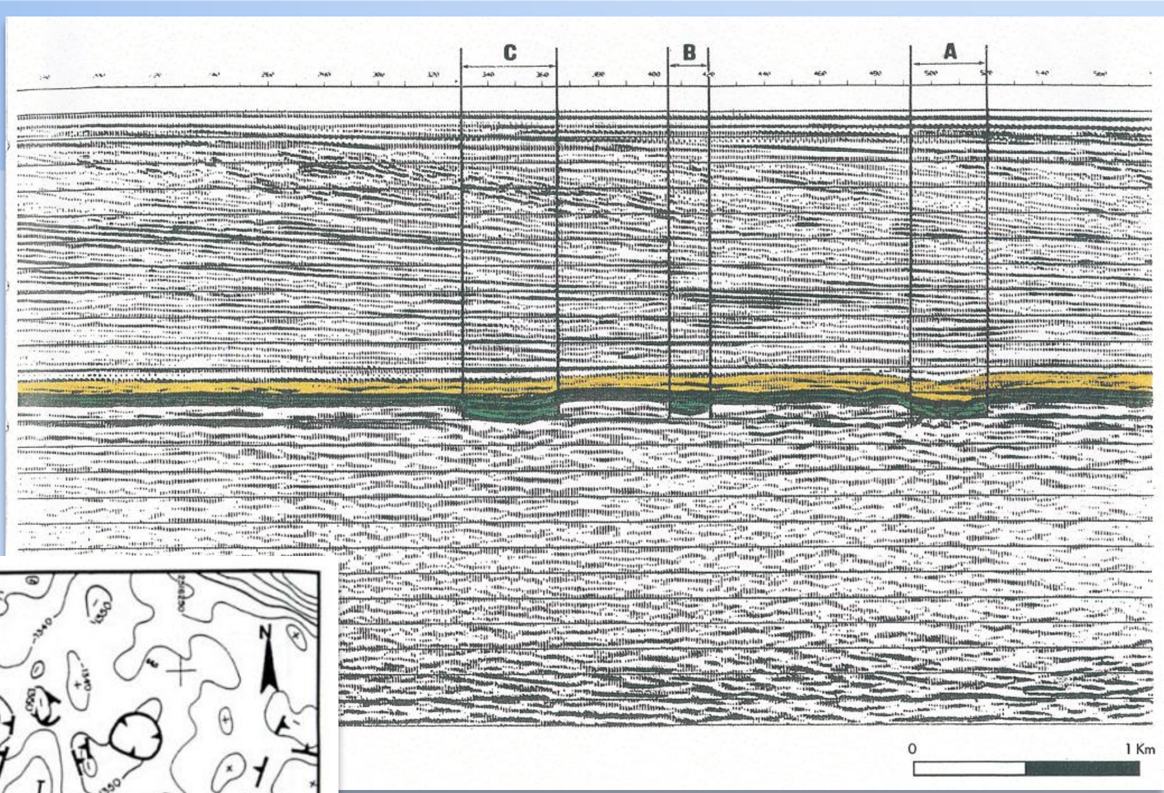
Dolomite breccia with granulation seam 1860.4m

Dolomite breccia with bryozoan bioherm clast 1890.3m

Clast at top of collapse breccia 1849.3m

- 70m collapse brecciated dolomite forms stratiform high permeability layer in karst reservoir

Rospo Mare field – karst example

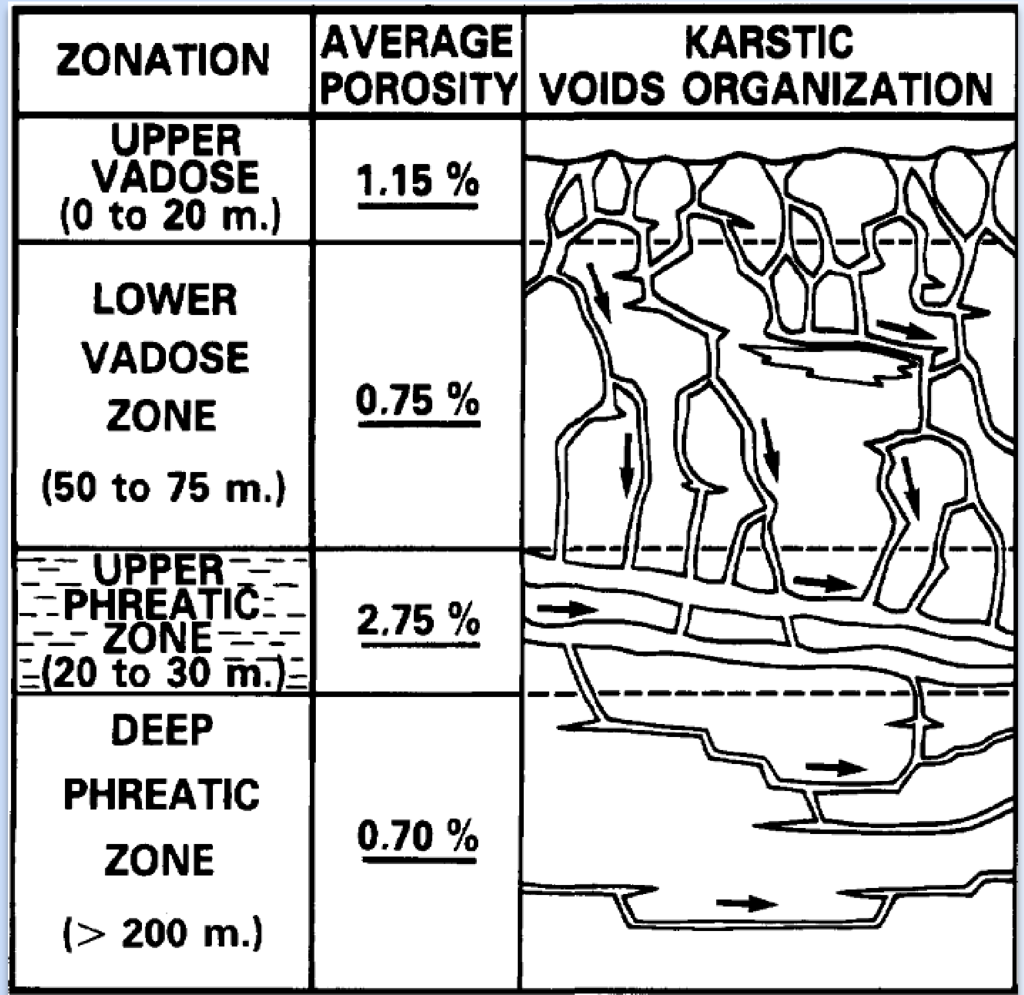


- Karsted lower Cretaceous carbonates
- Overlain by Tertiary mixed carbonate-clastics

Dolines on top carbonate, Rospo Mare Field.
Heritier et al. (1991) and Soudet et al. (1994)

Reservoir geometries/properties

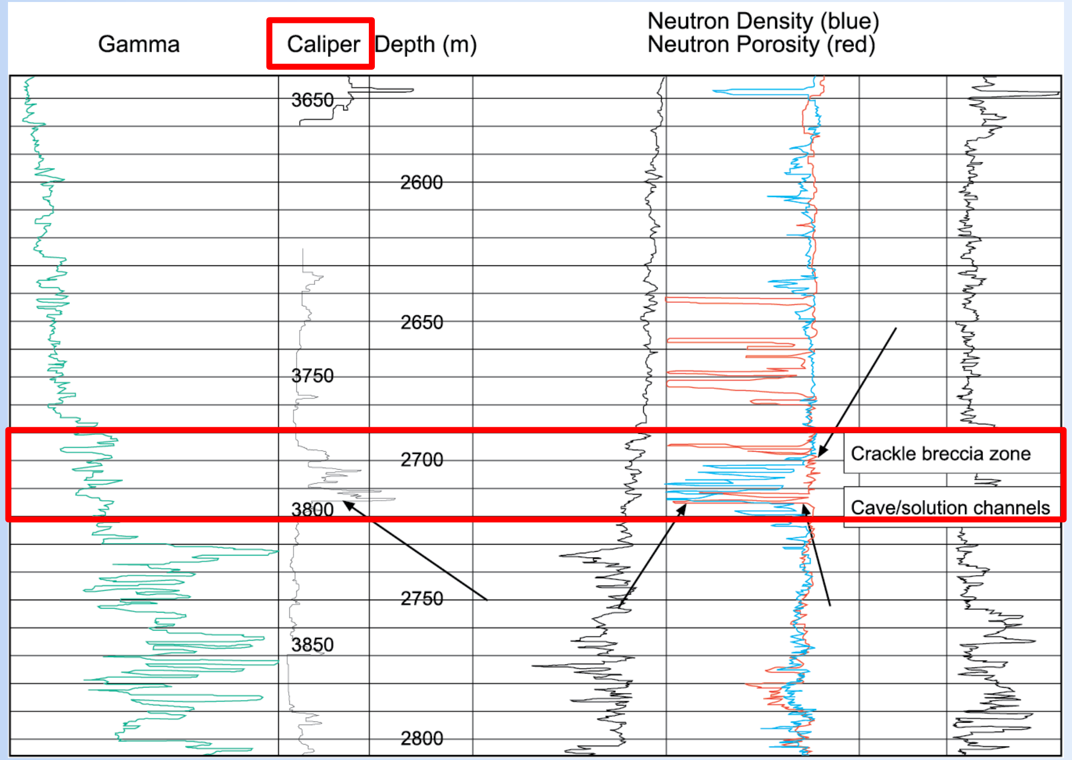
- 600m thick karstified zone
- Layered (compartmentalised) reservoir structure
  - Vadose zone: vertical fissures widened by dissolution
  - Phreatic zone: vugs and partially filled caverns – horizontal drainage system
- Pore system
  - Minimal matrix porosity
  - Pore system: fractures, vugs, sinkholes, breccias
  - Karst macrovugs contribute 8 %
  - Fracture density 15 per metre
- Horizontal wells
  - 3000-8000 BOPD (no water cut)



From Andre and Doulcet (1991)

Karst fractures/breccia reservoirs - summary

- Stratigraphically defined – related to subaerial exposure
- Connected high volume macropore system
  - High volume mud losses
  - Bit drops/positive breaks
  - Caliper and density anomalies often indicate VERY large pores
- Very heterogeneous reservoirs, vertically and laterally
- Well productivity unpredictable – some wells produce >50,000 BOPD, others do not flow
- Seismically resolvable with good data



Cretaceous fractured and karst carbonates (S Italy)

Evaporite Collapse Fracture/Breccia Systems

Mechanism of formation

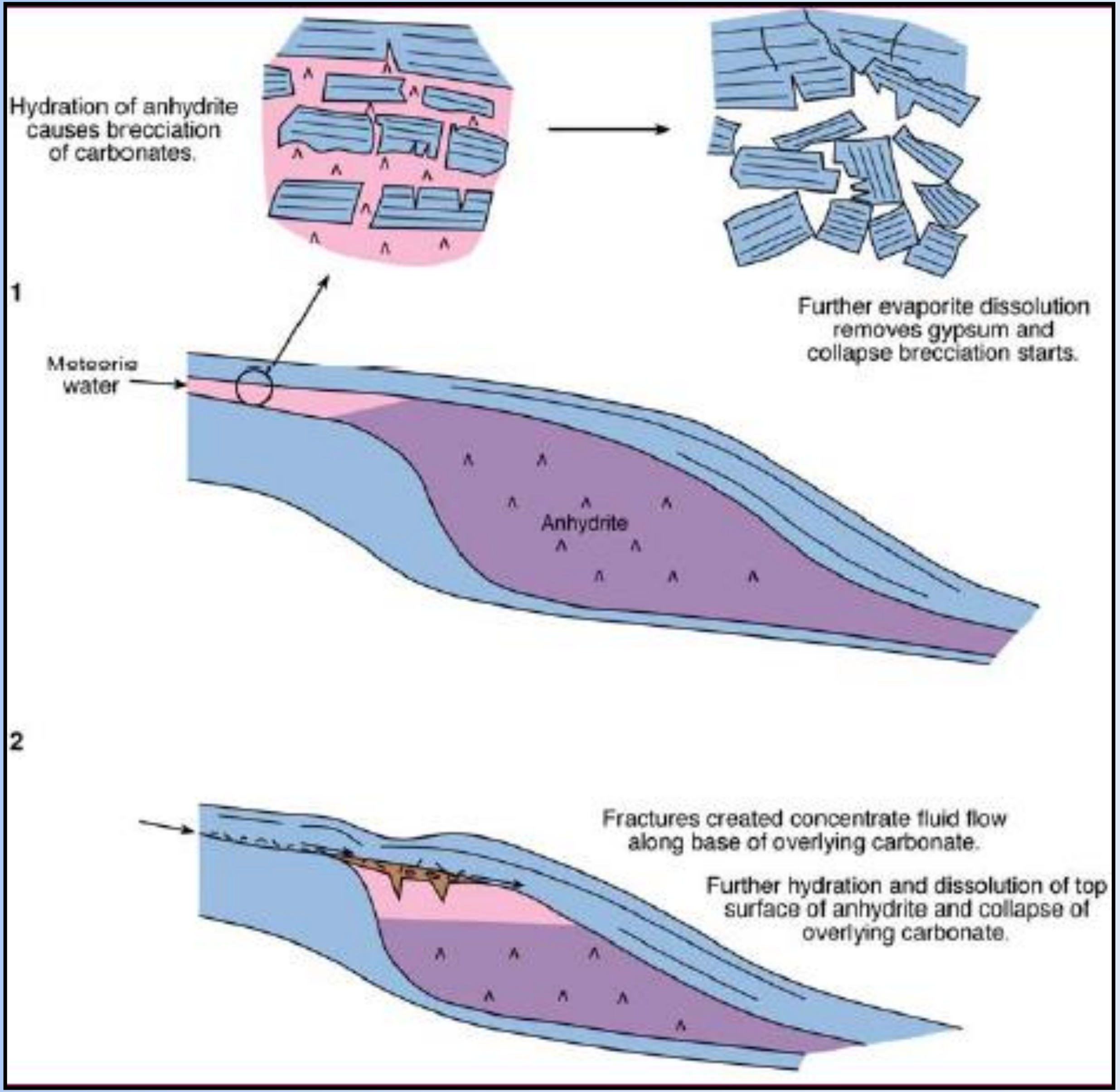
- Collapse breccia reservoirs occur
  - Dissolution of evaporites at basin margins
  - In intrabasinal fault blocks that have been exposed and sealed

- Meteoric water enters up dip part of system

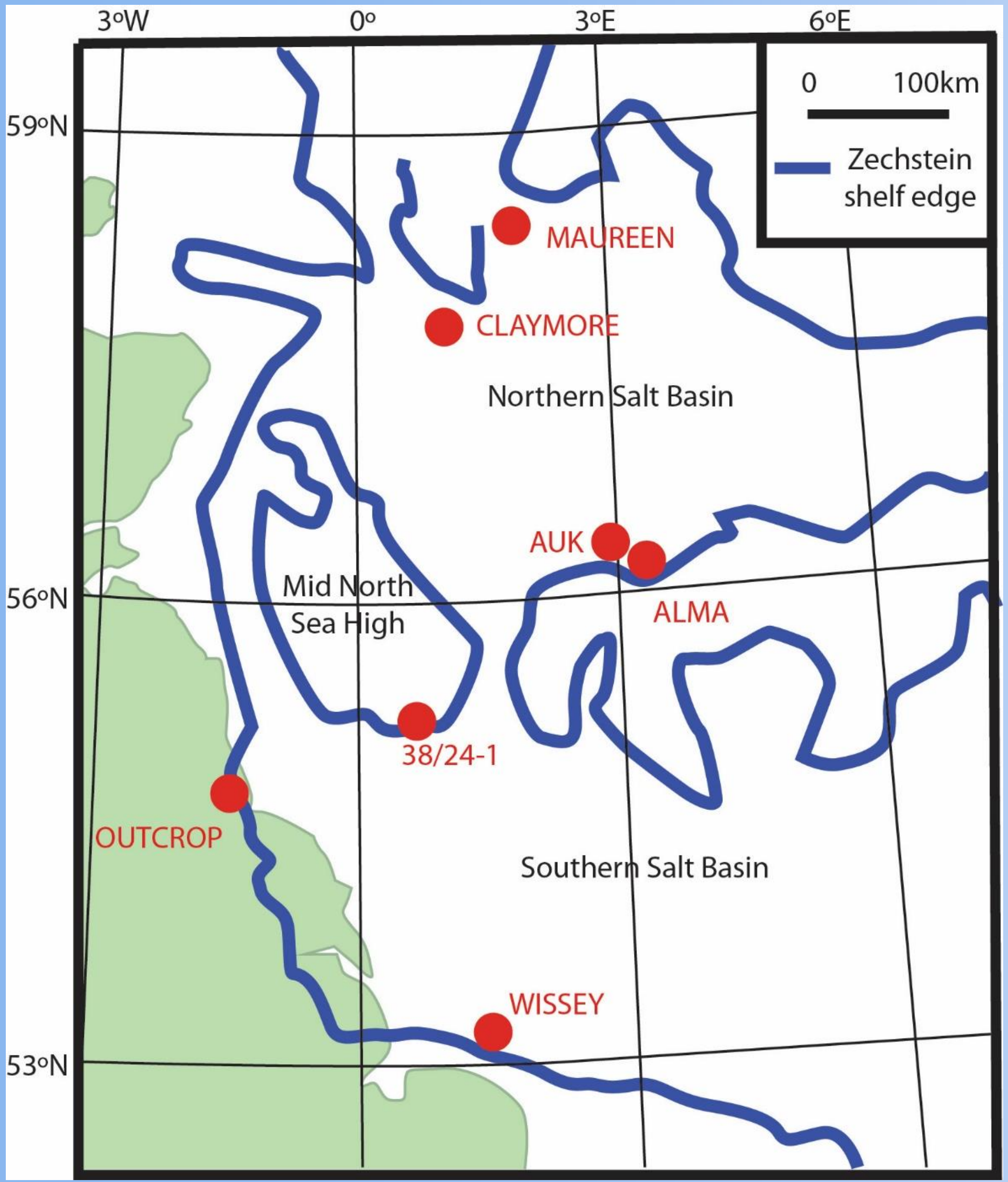
- Hydration of anhydrite to gypsum causes fracturing 64% volume increase

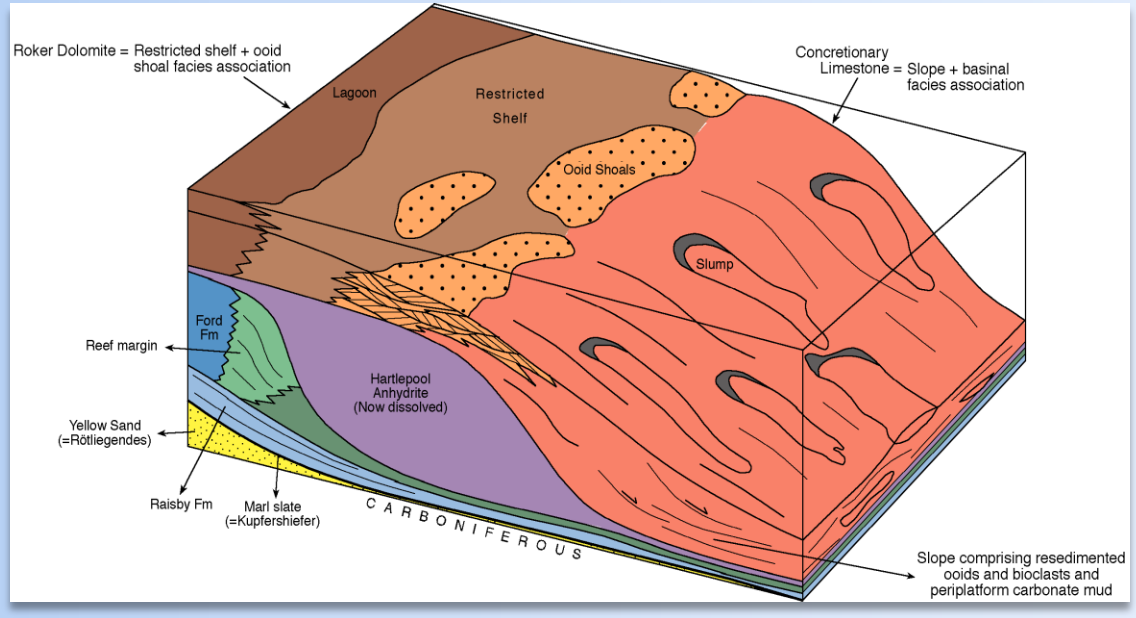
- High permeability pathway created

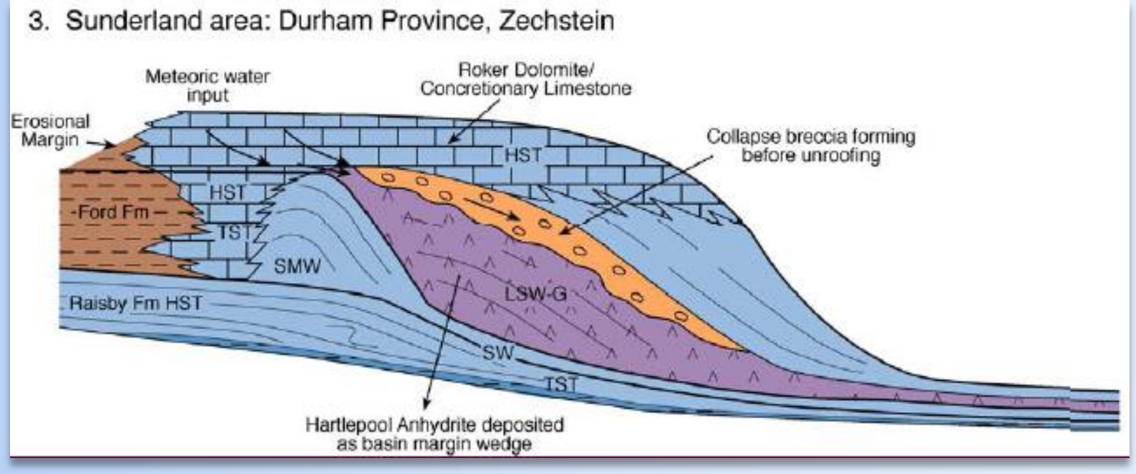
- Further dissolution of gypsum causes collapse



Zechstein collapse breccias; North Sea

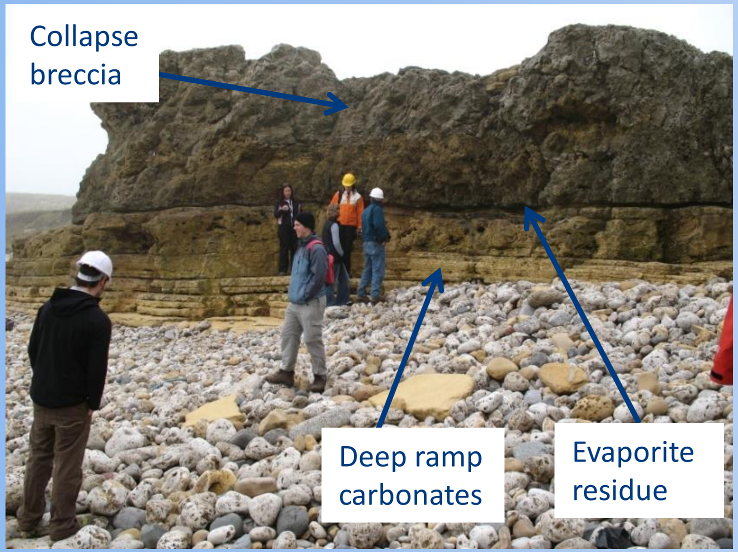


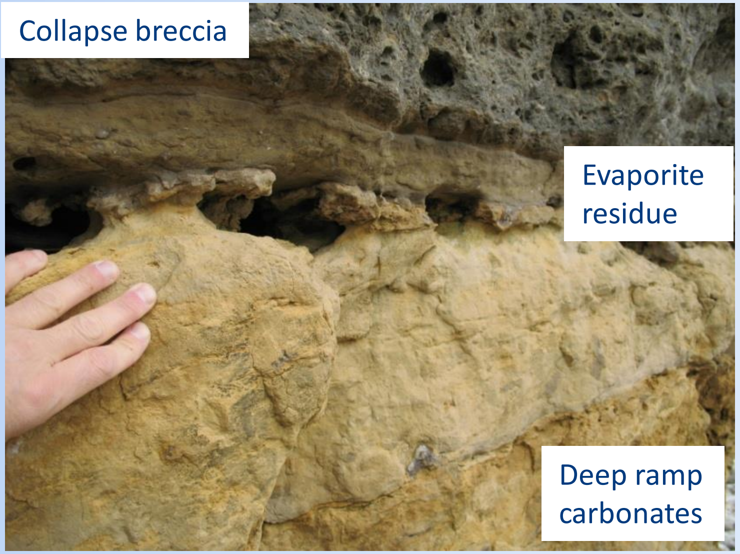




Palaeogeography of the North Sea (simplified from Glennie, 1998)

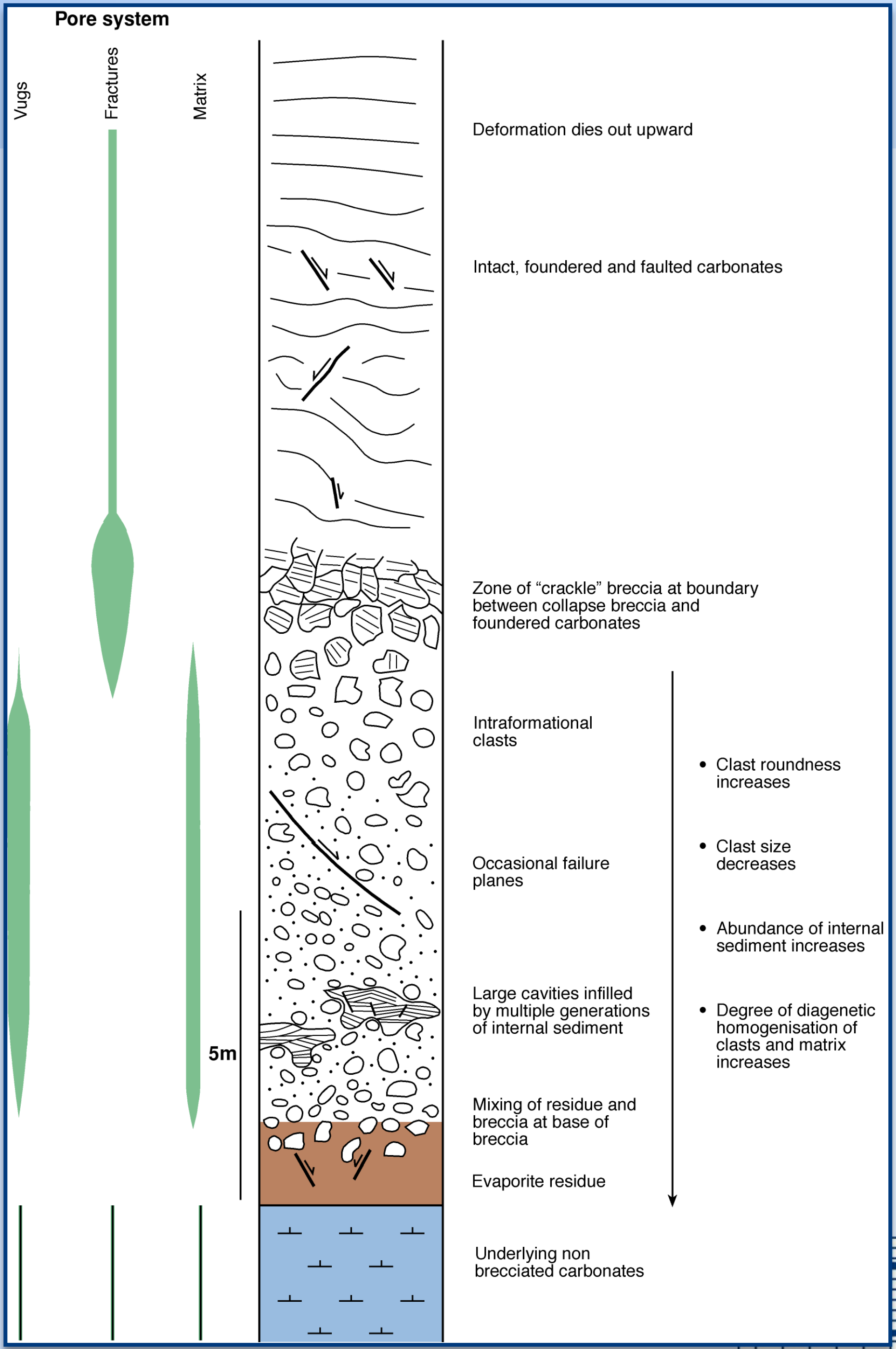
Permian collapse breccia, northern England

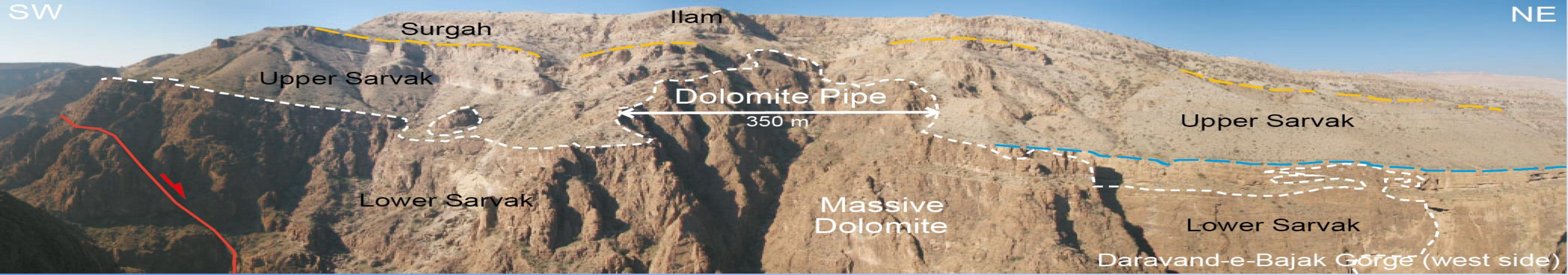




Summary - evaporite collapse breccias

- Dissolution of evaporites interbedded with carbonates
- Stratiform with fractured and foundered roof
- Pore types: breccias, fractures vugs
- Collapse breccia reservoirs occur
  - Dissolution of evaporites at basin margins
  - In intrabasinal fault blocks that have been exposed and sealed



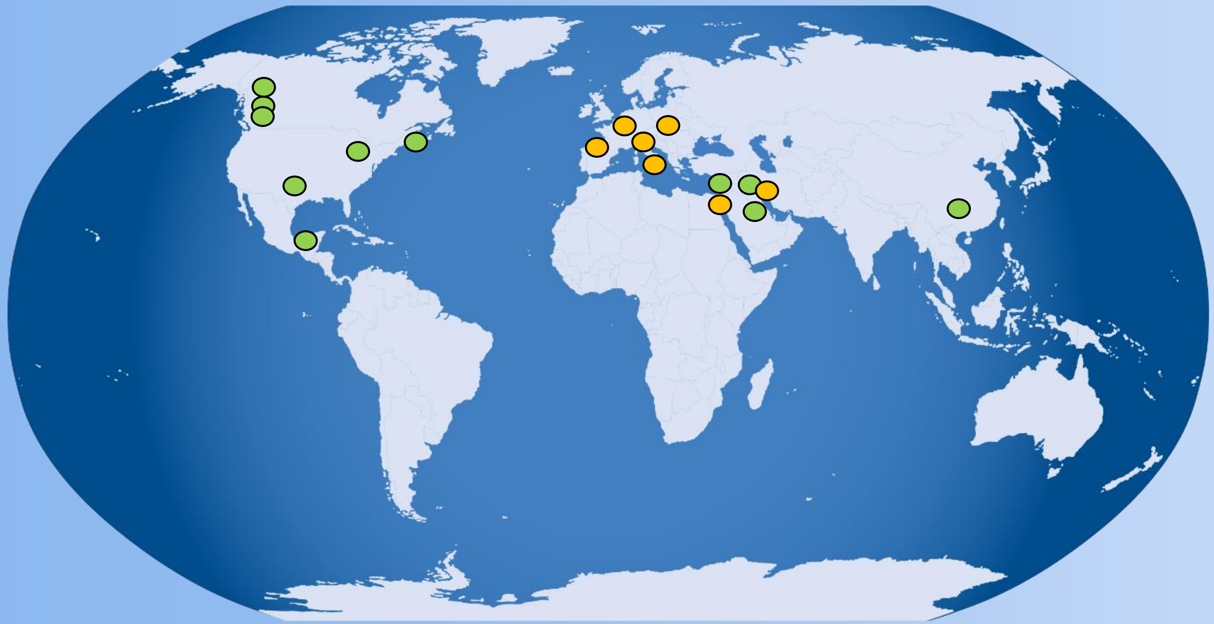


Fracture-related dolomite bodies – Hydrothermal dolomites

Image from Lapponi et al. (2011)

Fracture-related (hydrothermal) dolomite bodies

- Hot Mg-rich fluids move upwards through fractures, dolomitising surrounding carbonates. Generally sealed by tight limestones.
- Hydrothermal dolomites can **add additional matrix porosity** to what would traditionally be considered a **fractured reservoir.**
- Dolomites cross cut stratigraphy, but geometry also a function of original facies permeability
- Established play type in North America, becoming recognised more and more in Mexico, Middle East. Occurs in all tectonic settings.



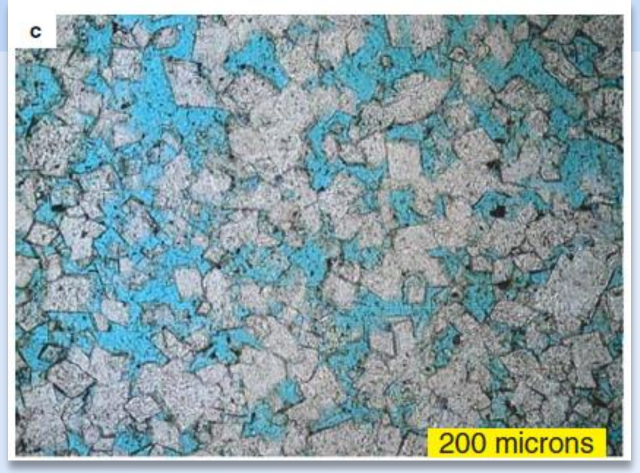
HTD, Canadian Rocky Mountains. Photo courtesy of Dave Hunt and Ian Sharp, Statoil

Fracture-related dolomite bodies

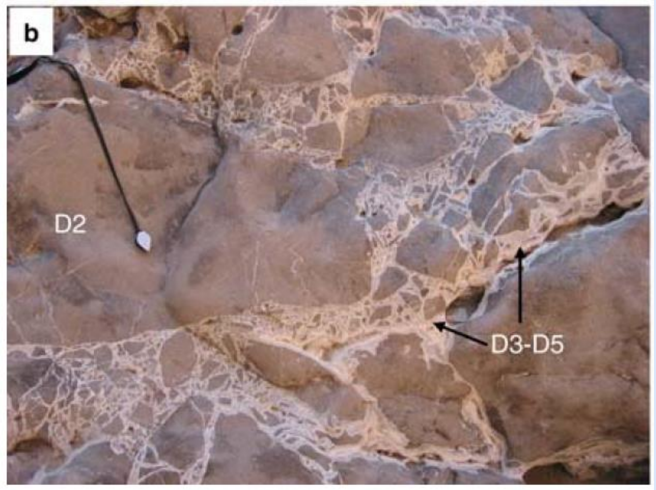
- Reservoir quality occurs in intercrystalline dolomites
- Saddle dolomites, breccias, zebra dolomites
- Known dolomite bodies up to 6.5km wide (generally ~1km), 10's km long

Field	Dimensions
Northville (Michigan Basin)	1 km x 10.5 km
Albion-Scipio (Michigan Basin)	1.6 km x 56 km
Stoney Point (Michigan Basin)	12 km2
Crystal (Michigan Basin)	1.6 km x 0.32 km
Vernon (Michigan Basin)	2 km x 9.5 km
Goldsmith/Lakeshore (Appalachian Basin)	0.400 - 1.2 km x 14 km
Glodes Corners field (Appalachian Basin)	0.7 km x 10 km
Ladyfern (WCSB)	15 km x 6.5 km
Rosevear (WCSB)	2 x 2 km x 11 km
Reinecke (Midland Basin)	2.2 km x 1.5 km

Subsurface, Middle East



Taq Taq field. Garland et al (2010)

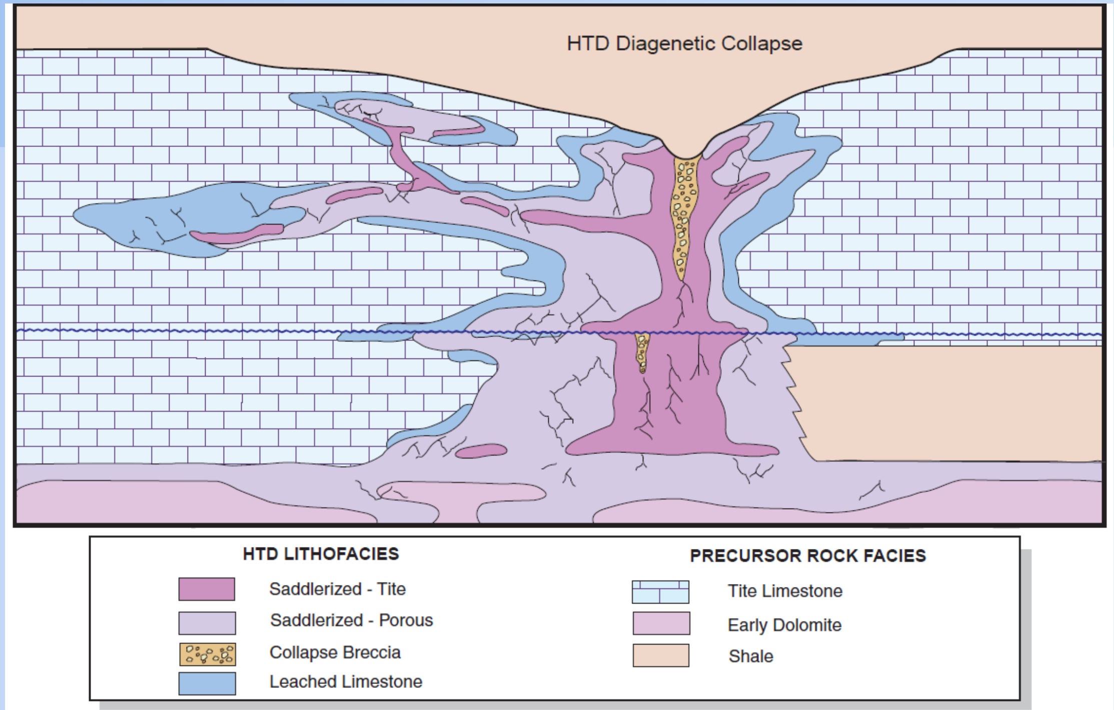


Chaotic breccias

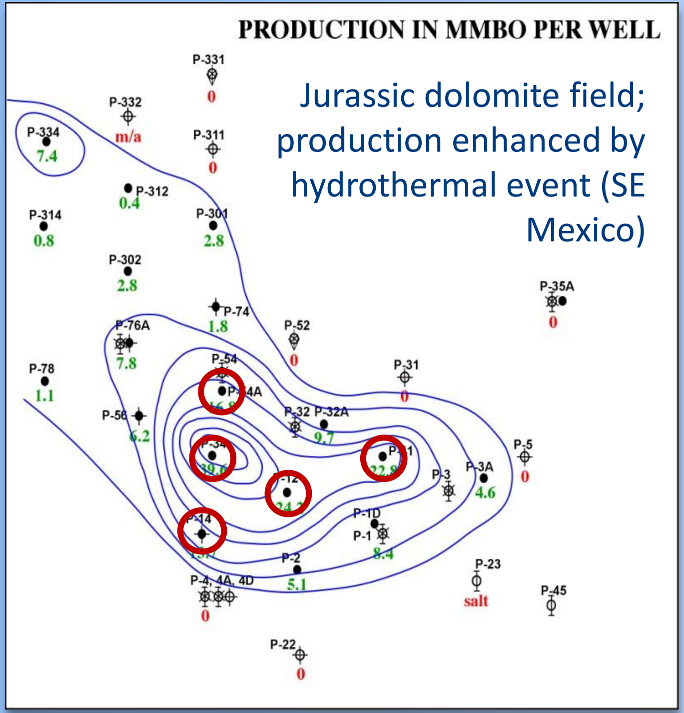
Large vugs occur in between zebra layers, Cretaceous, Ramales Platform, northern Spain

Reservoir properties

- Porosity and permeability are not homogenously distributed
  - fluid feeders are commonly cemented and tight
  - very porous and generally vuggy dolomite occurs in the upper part of the dolomite bodies
  - sucrosic dolomites form high permeability channels which impact on fluid flow during production
- Most of the production is delivered by a few wells



Ladyfern field, Reimer et al. (2001)

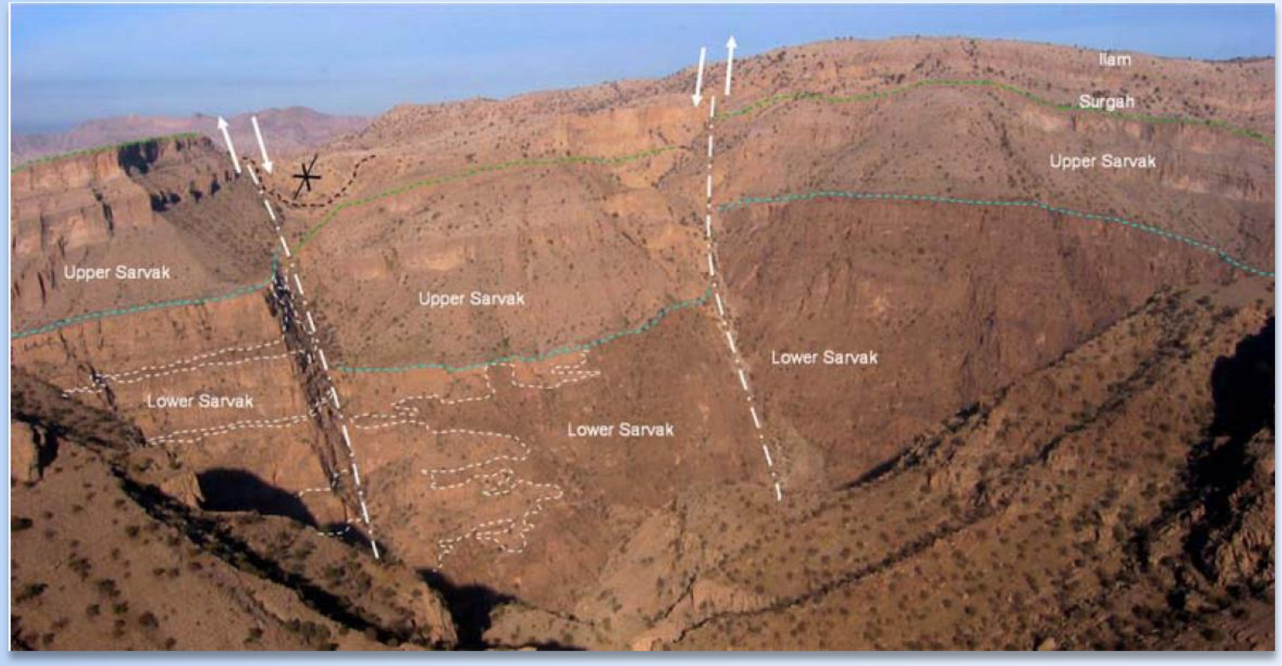


Jurassic dolomite field; production enhanced by hydrothermal event (SE Mexico)

18 wells in total; **5 crestal wells account for 60% of production**
No water break through until 9 years of production

Summary - fracture-related dolomites

- Hydrothermal dolomites can add additional matrix porosity to what would traditionally be considered a fractured reservoir. Type 2 reservoir.
- Reservoir bodies are commonly elongate, associated with the main fault patterns.
- Sheets/fingers of dolomite extend away from dolomite bodies preferentially following specific depositional facies or stratal surfaces
- Need to model both the structural history, and depositional architecture, as often a close link to primary depositional architecture

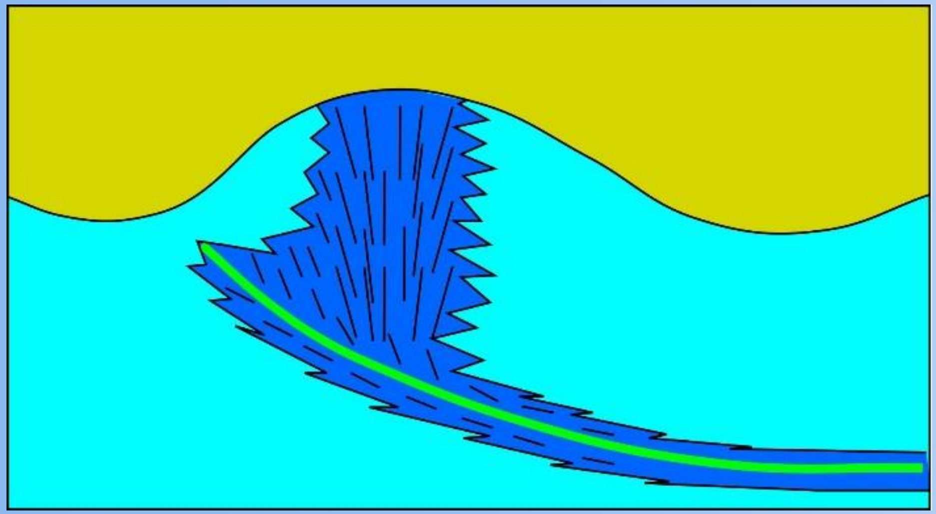


Anaran, Zagros Mountains. Sharp et al. (2010)

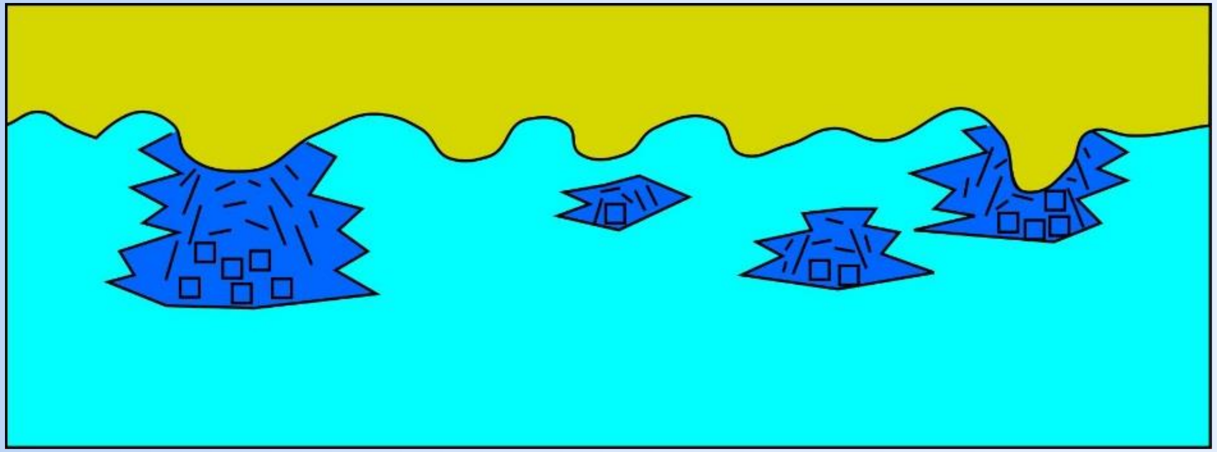
Summary

Fracture styles in carbonates

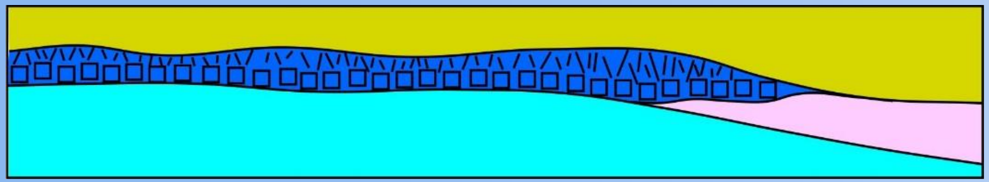
Tectonic fractures predictable and may be modelled



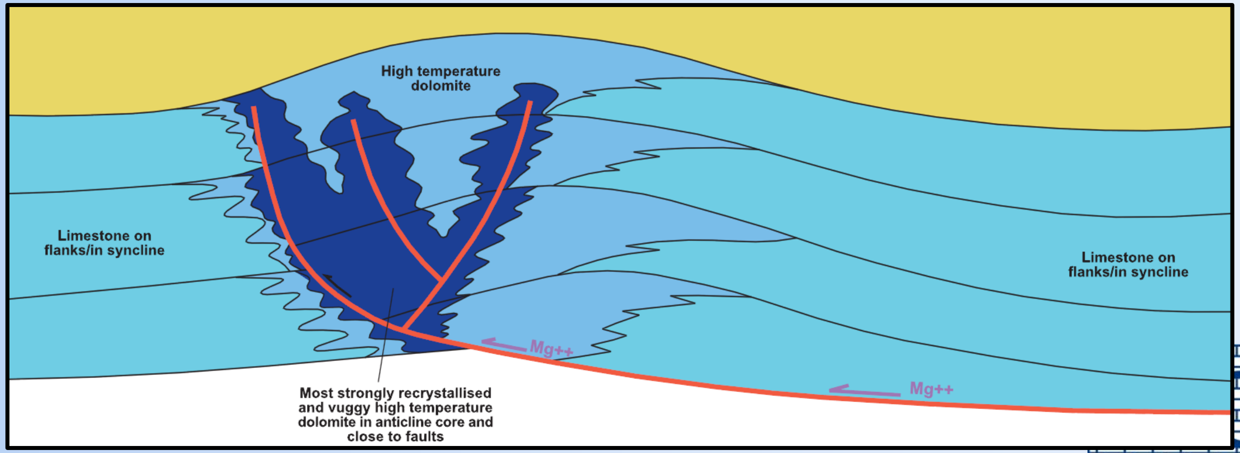
Karst fractures/breccia: stratigraphically related but may be over a thick interval; fracture pattern semi-random within collapsed areas



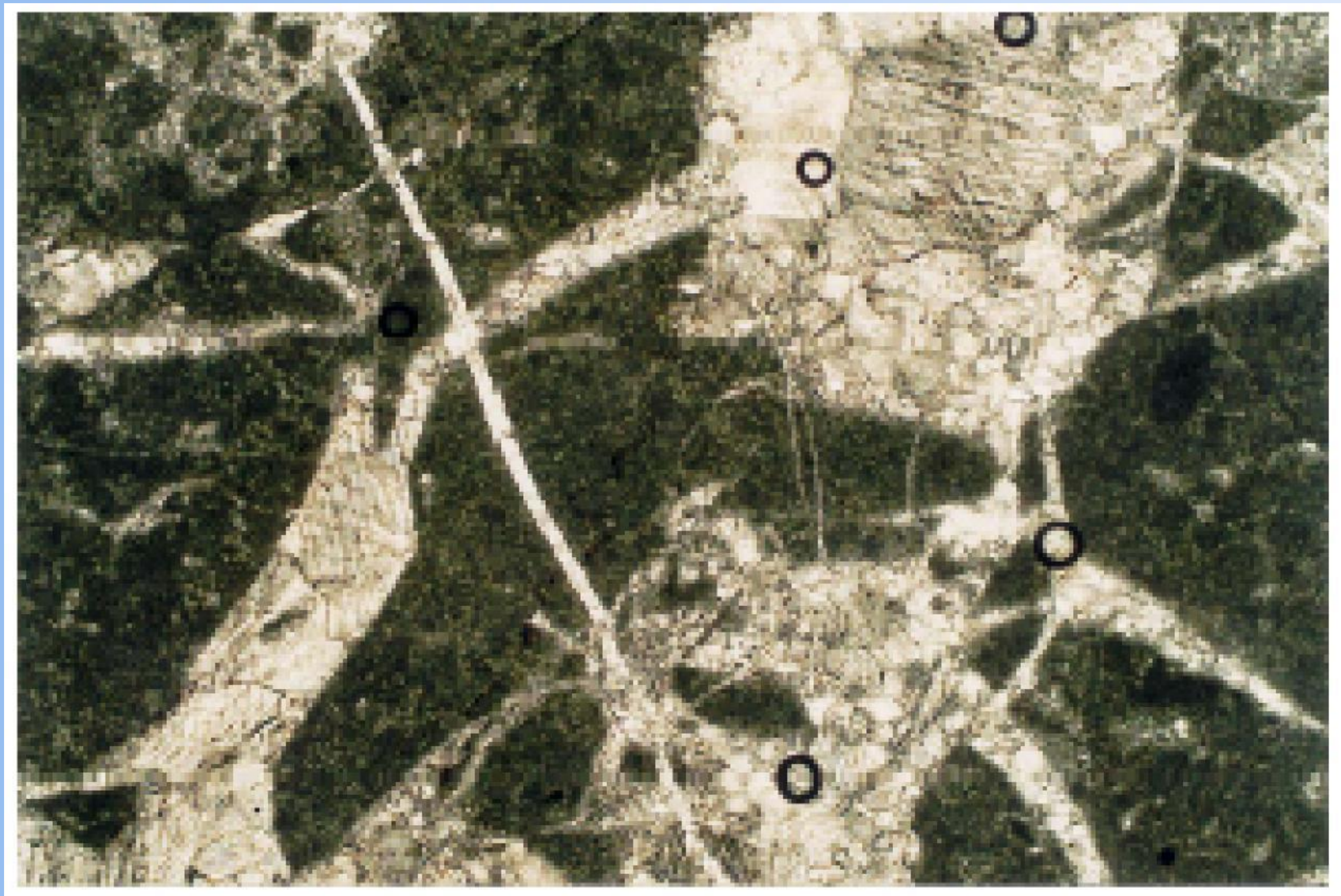
Evaporite collapse breccia in thin, strongly stratigraphically controlled intervals; fracture pattern essentially random



Hydrothermal dolomitisation: fracturing related to structural setting, dolomitisation partially stratigraphically controlled



Problem



Therefore…

- Need to accommodate multiple fracture-generating events of different types
- Need diagenetic studies and careful recording from core, log and image log data of different fracture types; seismic attributes will also help
- Should not assume simple structural models
- Prediction of fracture density and heterogeneity away from wellbore requires clear insight into which mechanism forms fractures