# What Drives the Link? Salt, Oil, Gas and Metals*

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## Abstract

The importance of the evaporite-hydrocarbon association is clearly seen in a compilation of giant oil and gas discoveries across the period 2000-2012. Of the 120 giant oil and gas fields discovered in that period some 50% were hosted in marine carbonates and 15% in lacustrine carbonates, meaning about a third of new giant discoveries were in siliciclastic reservoirs. Some 56% of the oil and gas giants had an evaporite seal, with 82% of the marine carbonates having an evaporite seal and 91% of the lacustrine carbonates having an evaporite seal. Clearly, carbonate reservoirs with evaporite seals constitute the majority of the giant oil and gas discoveries in the period 2000-2012, and the proportions of this association are likely to increase in conventional discoveries across the next decades. Predicting the position and quality of potential reservoirs in evaporite terranes is difficult without integrating notions of feedback between deposition, diagenesis, and structural evolution. Therein lies the difficulty in placing evaporite-associated reservoirs and traps in classic terms of structural, stratigraphic, and diagenetic traps. When classifying a field with an evaporite trap, the fact that salt is so mobile, so soluble, and so diagenetically active, separates it from other trap styles in a petroleum system. It means that a salt unit, by its comings and goings, plays ongoing and multiple roles in generating reservoirs and traps from the time of deposition through diagenesis to structuring. Tying oil and gas field occurrences to a static and categoric breakdown is near impossible as salt-induced structuring, diagenesis, and deposition are often penecontemporaneous and in a state of intimate feedback with adjustments continuing throughout the mesogenetic and telogenetic realms.

## Selected References

Downey, M.W., 1984, Evaluating Seals for Hydrocarbon Accumulations: AAPG Bulletin, v. 68, p. 1752-1763.

Jiang, L., C.F. Cai, R.H. Worden, K.K. Li, and L. Xiang, 2013, Reflux Dolomitization of the Upper Permian Changxing Formation and the Lower Triassic Feixianguan Formation, NE Sichuan Basin, China: Geofluid, v. 13, p. 232-245.

Pilcher, R., B. Kilsdonk, and J. Trude, 2011, Primary Basins and their Boundaries in the Deep-Water Northern Gulf of Mexico; Origin, Trap Types, and Petroleum System Implications: AAPG Bulletin, v. 95, p. 219-240.

Warren, J.K., 2016, Evaporites: A Geological Compendium: Springer, Berlin, 1854 p. ISBN 978-3-319-13511-3

# What Drives the Link? Salt, Oil, Gas & Metals

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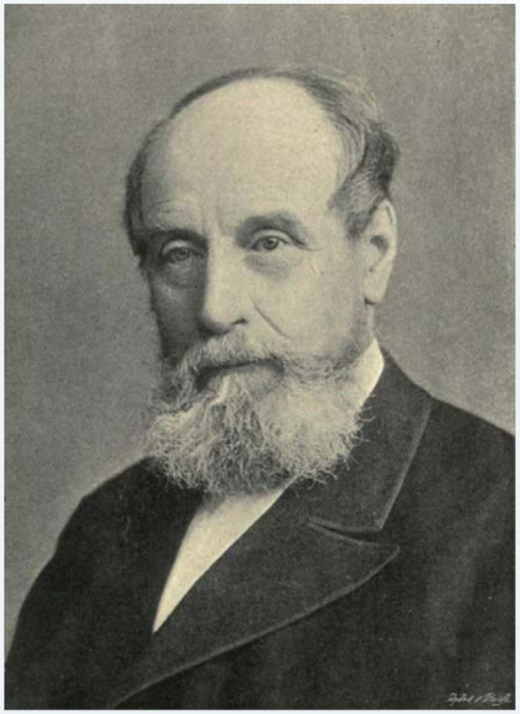
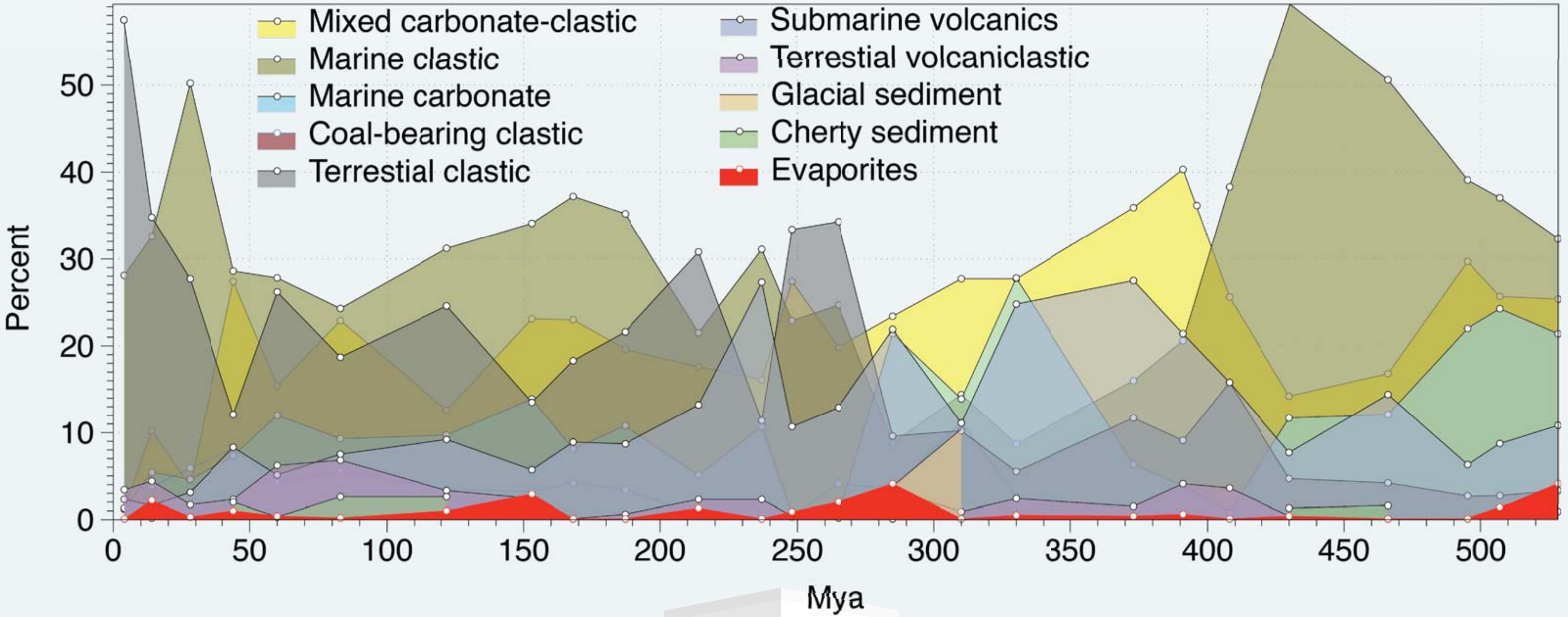


"Geological reading, especially when of a strictly uniformitarian character and in warm weather, sometimes becomes monotonous…"

*Sir John William Dawson (1820–99),Canadian geologist and educator*

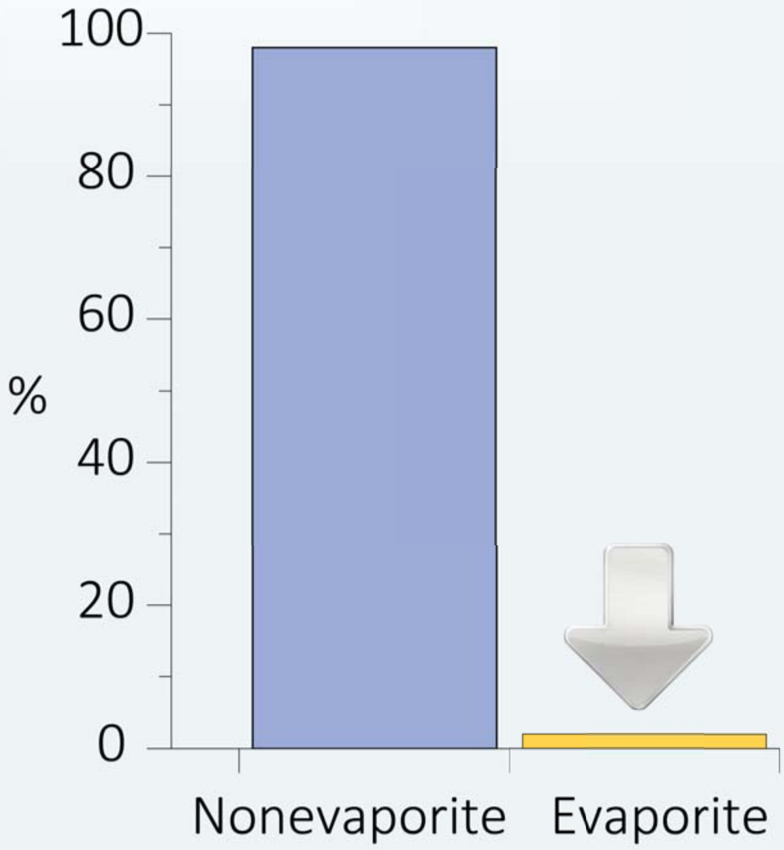
Presenter's notes: The mineral Dawsonite is named in his honor. In his various books on geological subjects he maintained a distinctly theological attitude, refusing to accept the evolution of humans from "brute" ancestors.

# EVAPORITES ARE VOLUMETRICALLY TRIFLING (<2% WORLD'S PHANEROZOIC SEDIMENTS)



# LESS THAN 2%

- 50% of world's carbonate reservoirs (this talk)
- All the world's supergiant oil and gas fields in thrusts (this talk)
- All supergiant sedimentary copper deposits (halokinetic brine focus)
- 50% of world's giant SedEx deposits (halokinetic brine focus)
- 80% of giant MVT deposits (sulphate-fixer & brine interface)
- World's largest Phanerozoic Ni deposit (meta-igneous)
- Many larger IOCG deposits (meta-evaporite, brine and hydrothermal)

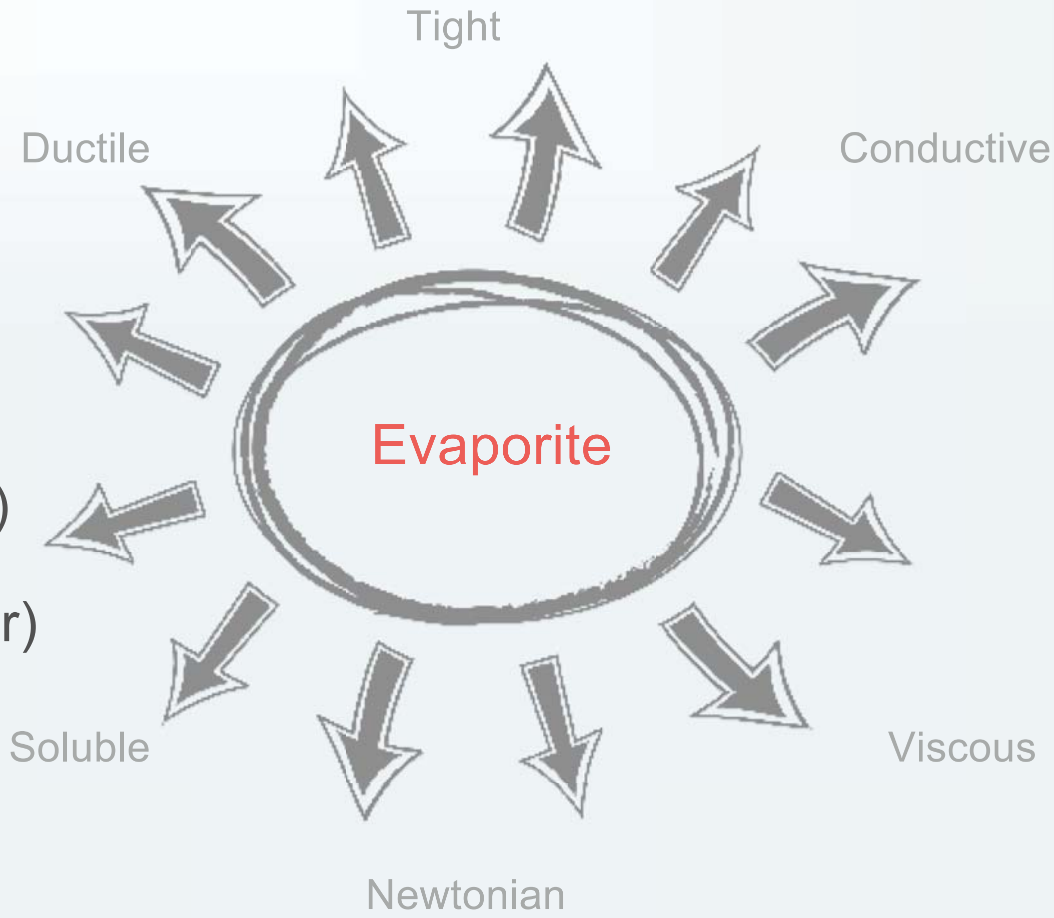



# SALT IS GOOD

Salt in any basin improves, but does not control, commodity enrichment

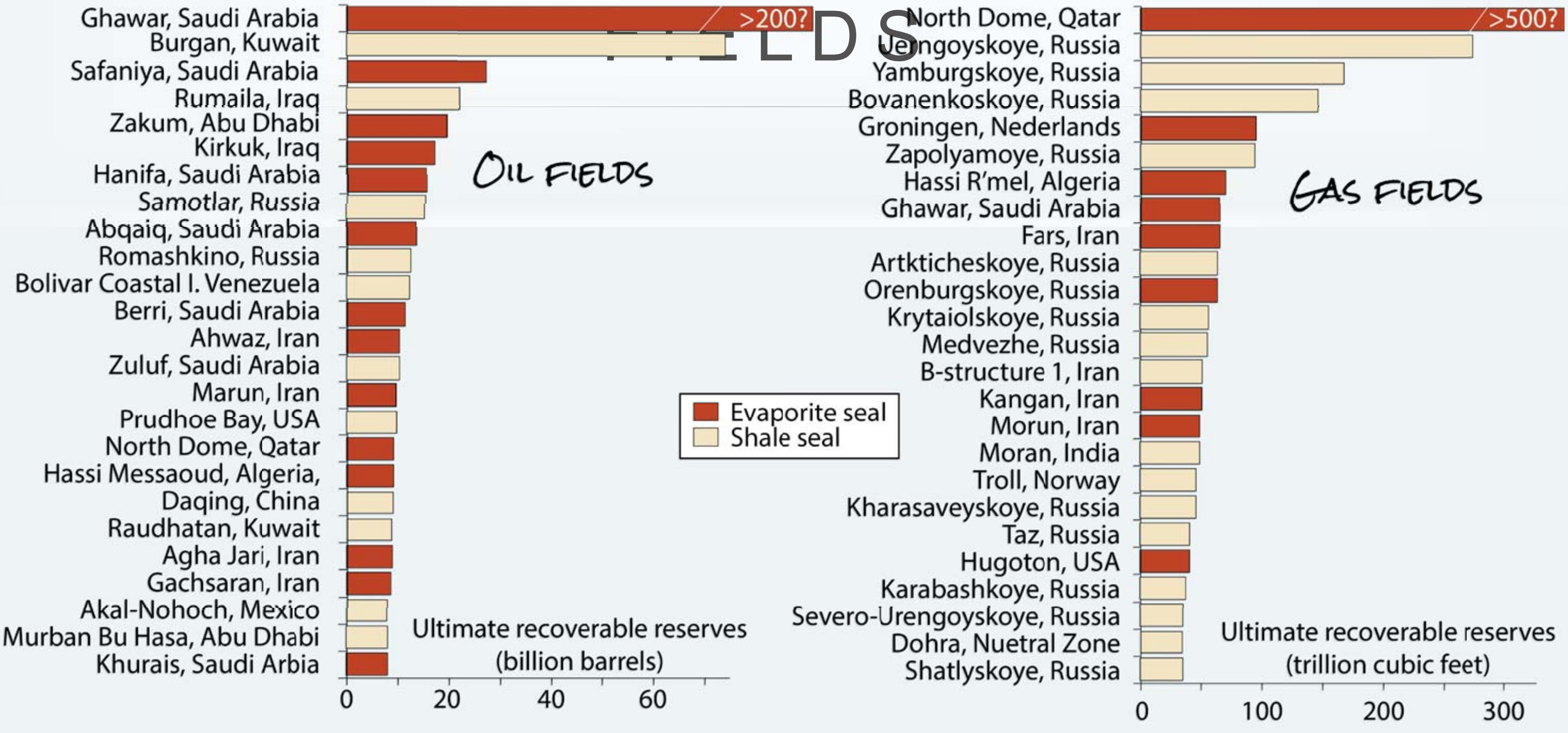
Presenter's notes:For most commodities the presence of salt is beneficial in terms of its volume and richness.

- Seal - bedded and halokinetic
- Fault stopper
- Trap focus
- Source rock (mesohaline carbonates)
- Fluid flow - focus and mixer (stabilizer)
- Metal carrier or fixer (reductant)




# DRIVERS?

# SEAL TO MANY LARGER FIELDS



# SALT SEAL IS TIGHT & DUCTILE

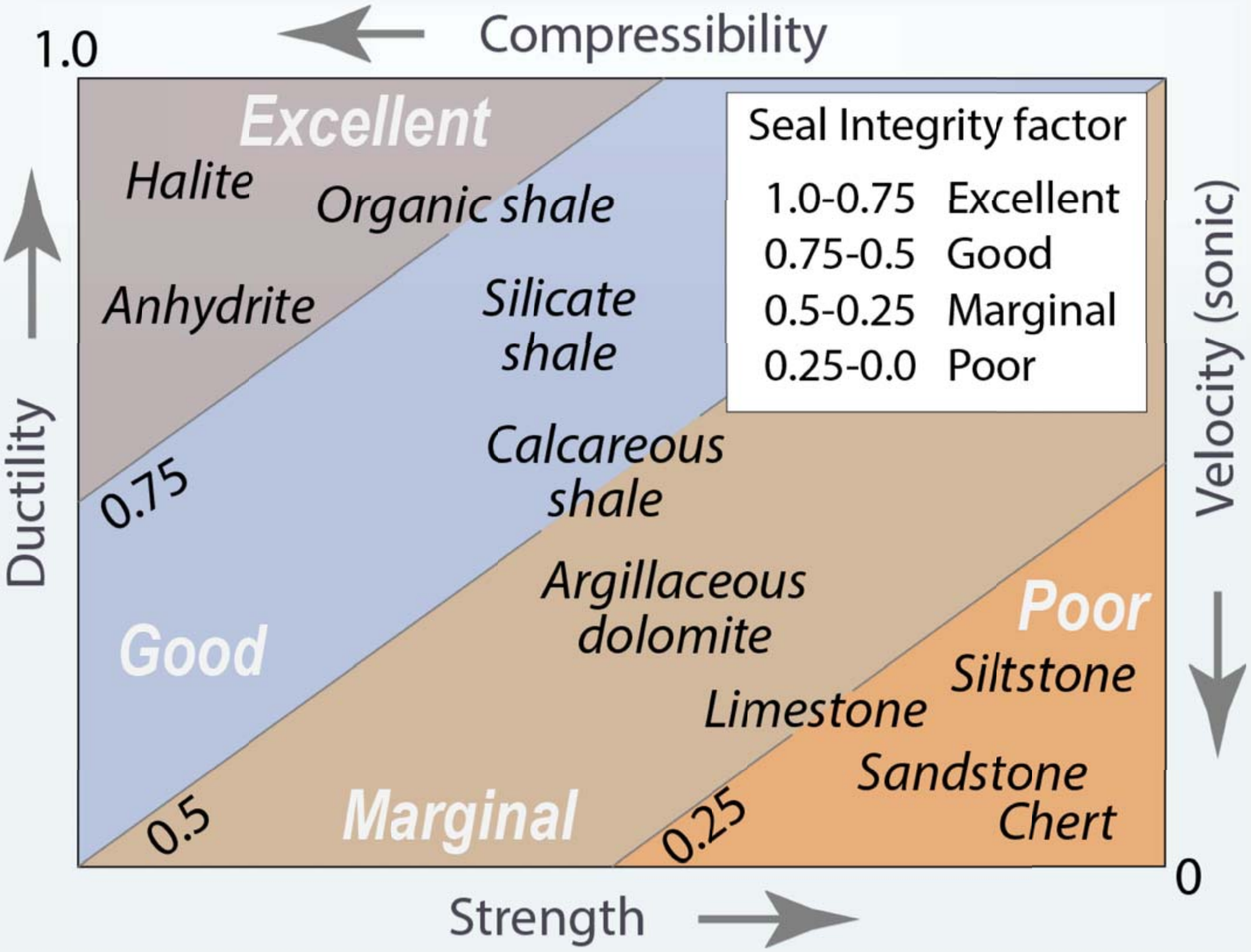
## Rock Strength (Low Temp.)

| | |
|---|---|
| Weakest | Salt |
| | Anhydrite |
| | Shale/mudstone |
| | Marble |
| | Schist |
| | Calcite-cemented Sst. |
| | Limestone |
| | Basalt |
| | Quartz-cemented Sst. |
| | Granite |
| | Quartzite |
| Strongest | |

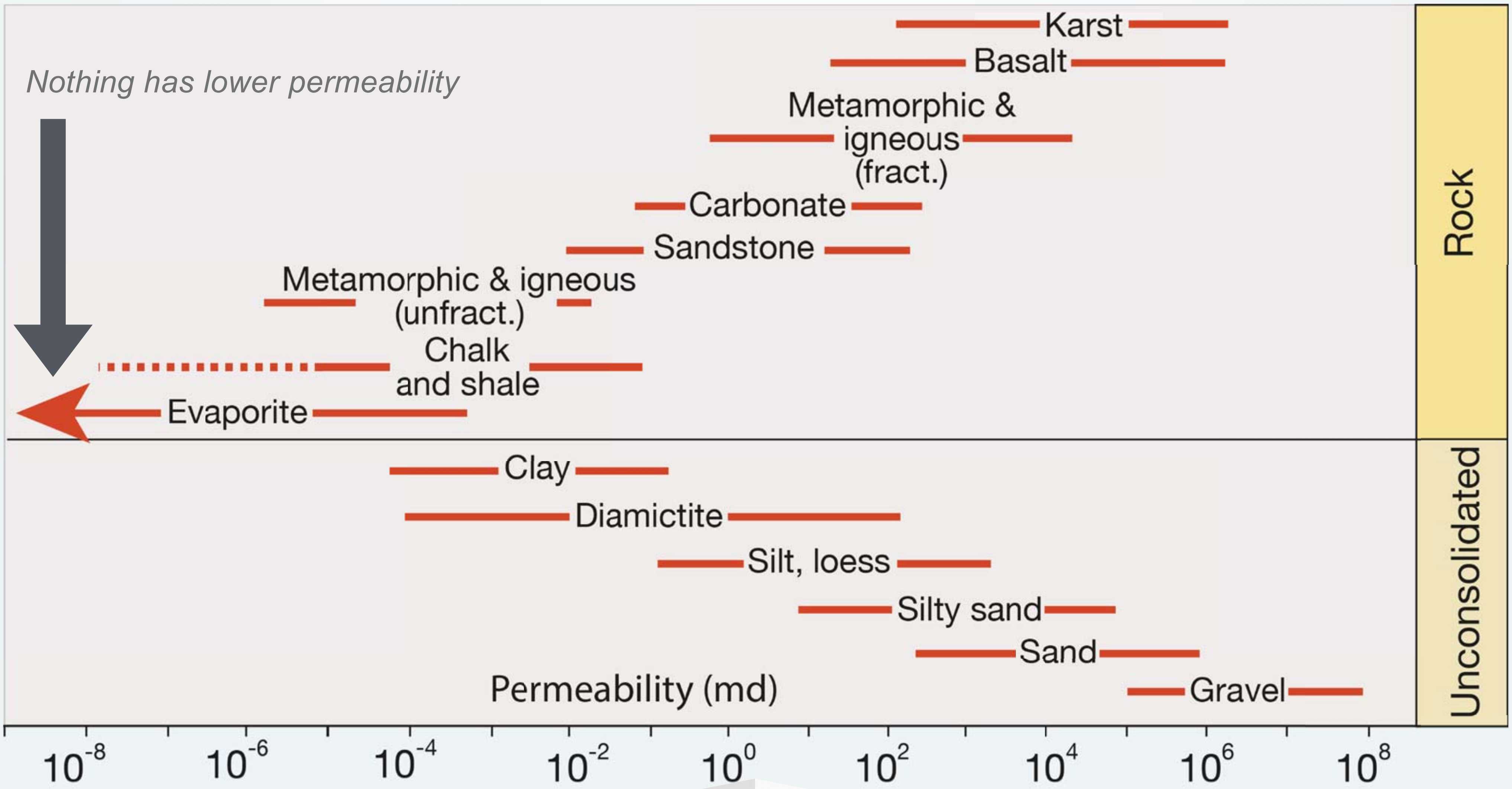
## Seal Capacity

| | |
|---|---|
| Best seals | Clathrates (most ductile and annealable) |
| | Salt |
| | Anhydrite |
| | Kerogen-rich shale |
| | Clay shale |
| | Silty Shale |
| | Carbonate mudstone |
| | Tightly cemented sandstone |
| | Sandy shales |
| | Anhydrite-plugged dolomite |
| | Carbonate/silica cemented sandstones |
| Lesser seals | Chert (least ductile and subject to fracture) |

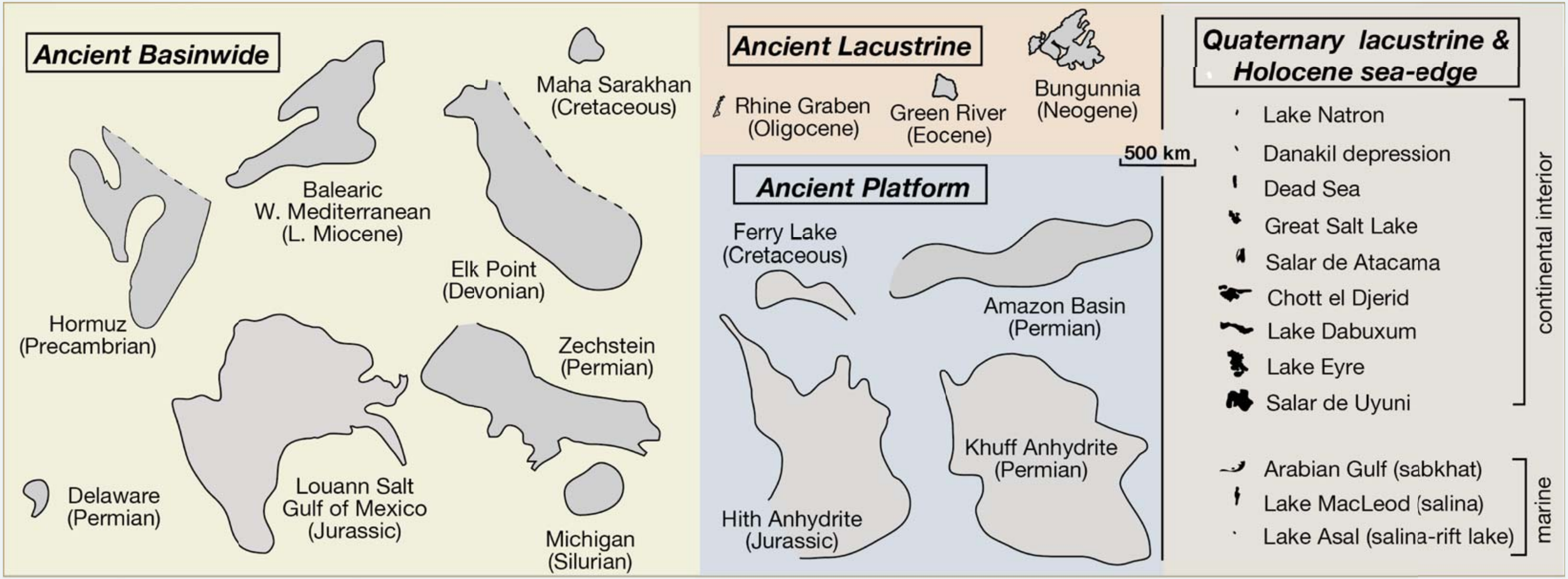
*Downey, 1984*


1.0
Compressibility
Excellent
Halite
Organic shale
Anhydrite
Silicate shale
Seal Integrity factor
1.0-0.75 Excellent
0.75-0.5 Good
0.5-0.25 Marginal
0.25-0.0 Poor
Calcareous shale
0.75
Ductility
Velocity (sonic)
Argillaceous dolomite
Good
Poor
Siltstone
Limestone
Sandstone
Chert
0.5
Marginal
0.25
0
Strength

Kaldi, 2014


Nothing has lower permeability
Karst
Basalt
Metamorphic & igneous (fract.)
Carbonate
Sandstone
Metamorphic & igneous (unfract.)
Chalk and shale
Evaporite
Clay
Diamictite
Silt, loess
Silty sand
Sand
Gravel
Permeability (md)
Rock
Unconsolidated
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^{0}$
$10^{2}$
$10^{4}$
$10^{6}$
$10^{8}$

# ANCIENT EVAPORITE SEALS ARE DEPOSITIONALLY EXTENSIVE

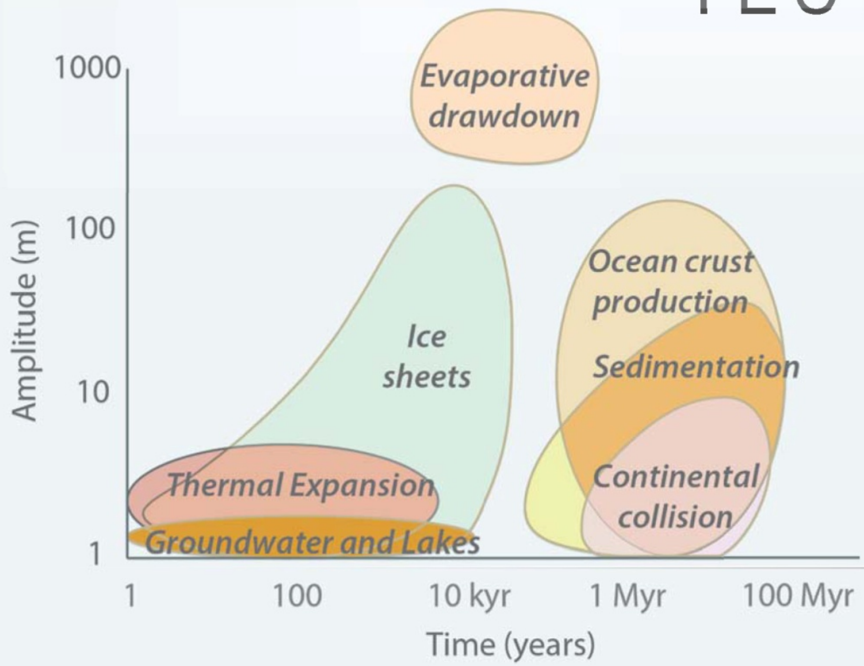



Warren, 2016

- Two styles of ancient evaporites
  - platform evaporites (mostly sulphate-dominant and greenhouse eustatic)
  - basinwide (mostly halite-dominant and tectonic)
- Neither style has a same-scale Quaternary-age counterpart
  - today is ice-house - but platform evaporites (except intracratonic) need greenhouse ecstasy
  - last basinwide evaporites were deposited in the Late Miocene soft suture belt that was the Late Miocene Mediterranean (Messinian salinity crisis)

# MARINE EVAPORITE SEALS

# BASINWIDE EVAPORITES ARE TECTONIC



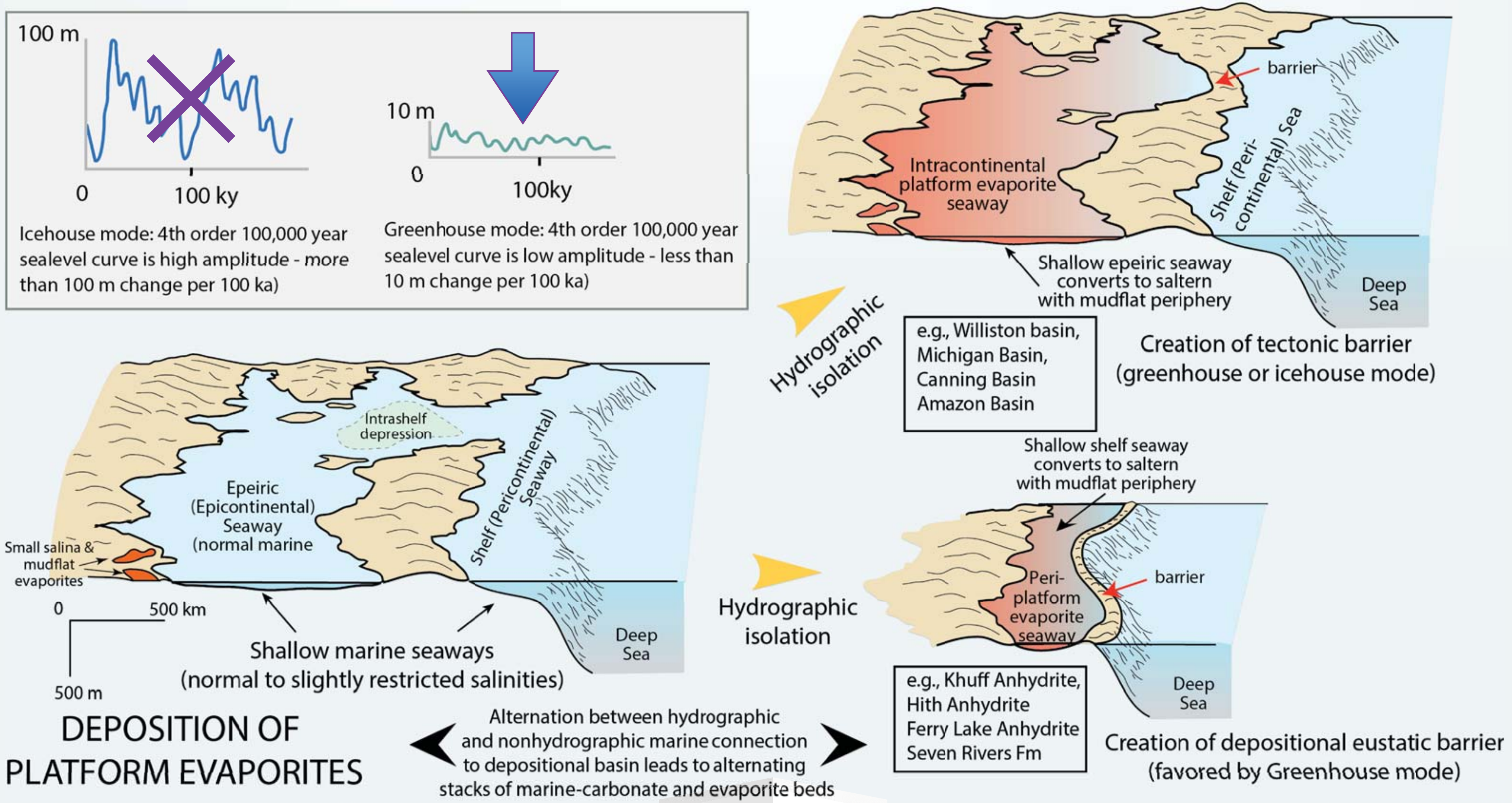

ISOSTATIC & EUSTATIC CHANGE

*Warren, 2016*

# PLATFORM EVAPORITES ARE EUSTATIC

Presenter’s notes: Drawdown needs hydrographic isolation (no surface connection) but ongoing seepage supply.

# DEPOSITION OF PLATFORM EVAPORITES




*Warren, 2016*

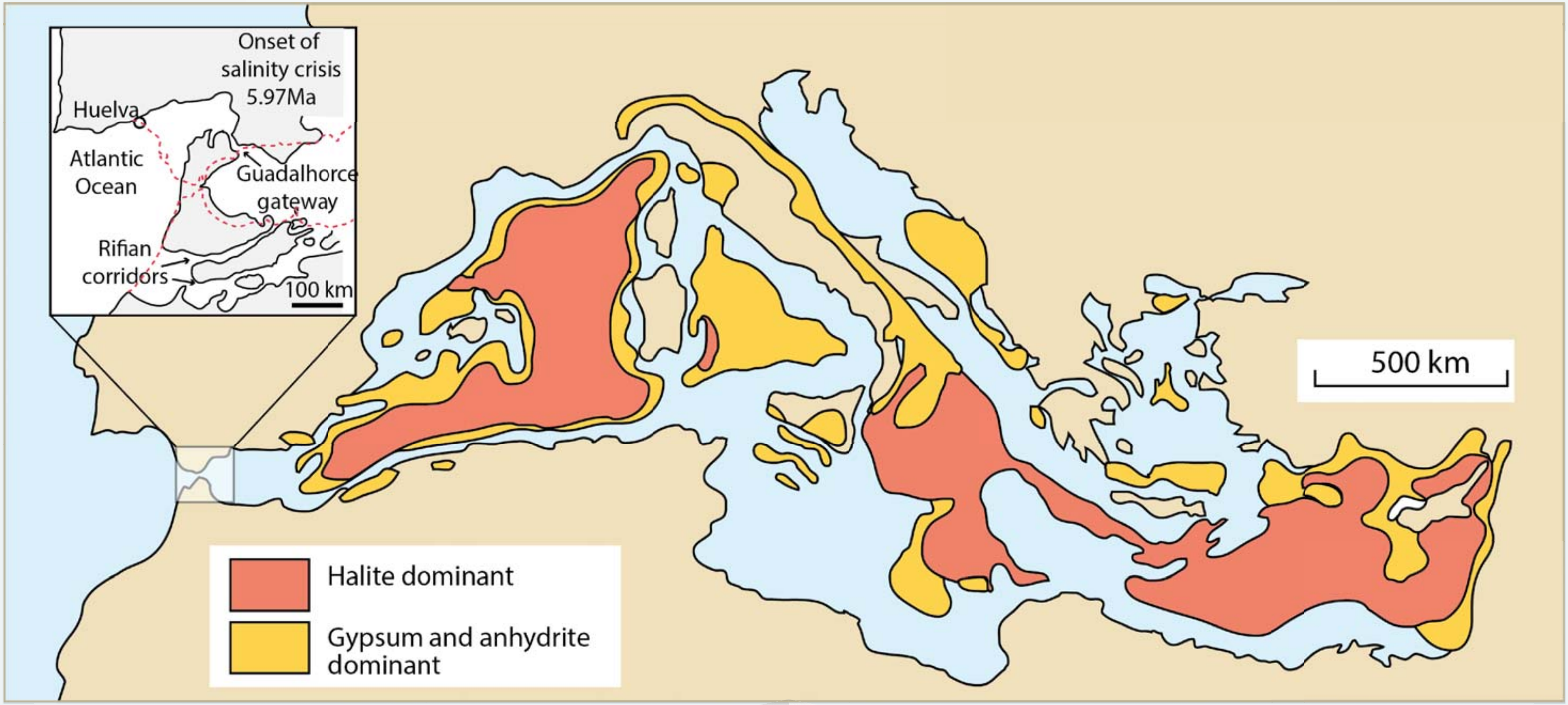
- laterally extensive
- intercalated with carbonates and other porous sediment
- early stages of basin isolation and brine layering favour mesohaline source rocks
- early brine reflux dolomitization
- TSR association (late-stage dolomites)

# PLATFORM & INTRACRATONIC EVAPORITES MAKE EXCELLENT SEALS

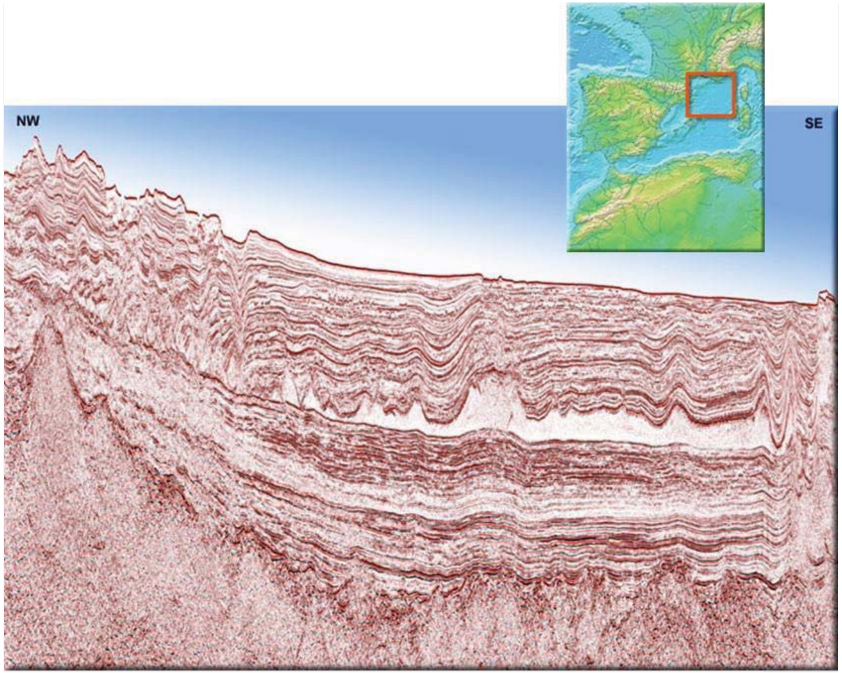
# BASINWIDE EVAPORITE

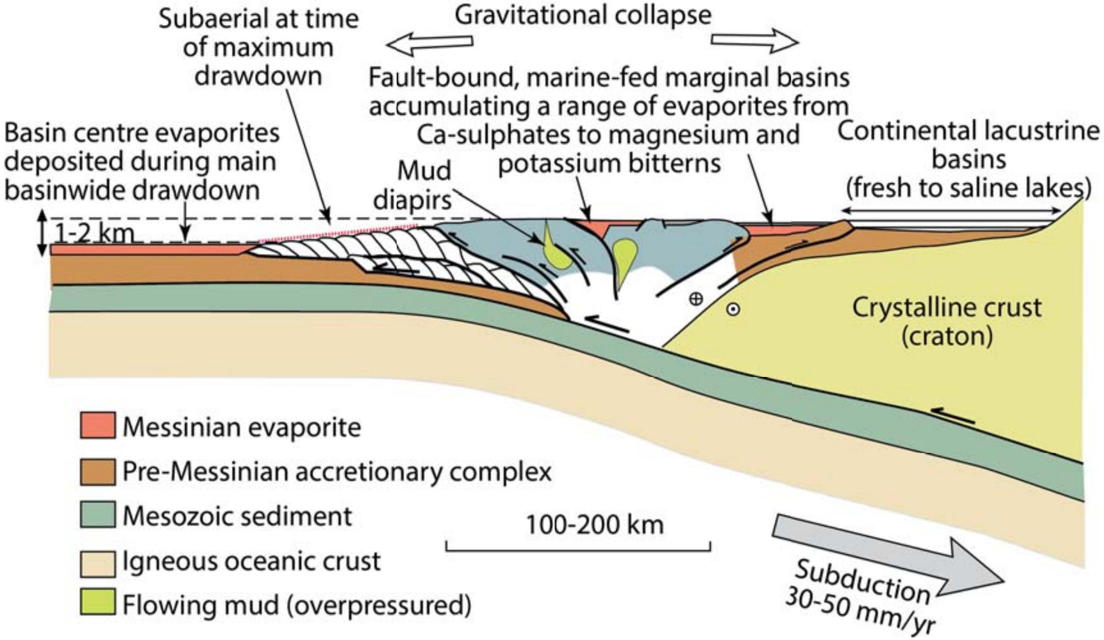
# BASINWIDE EVAPORITE

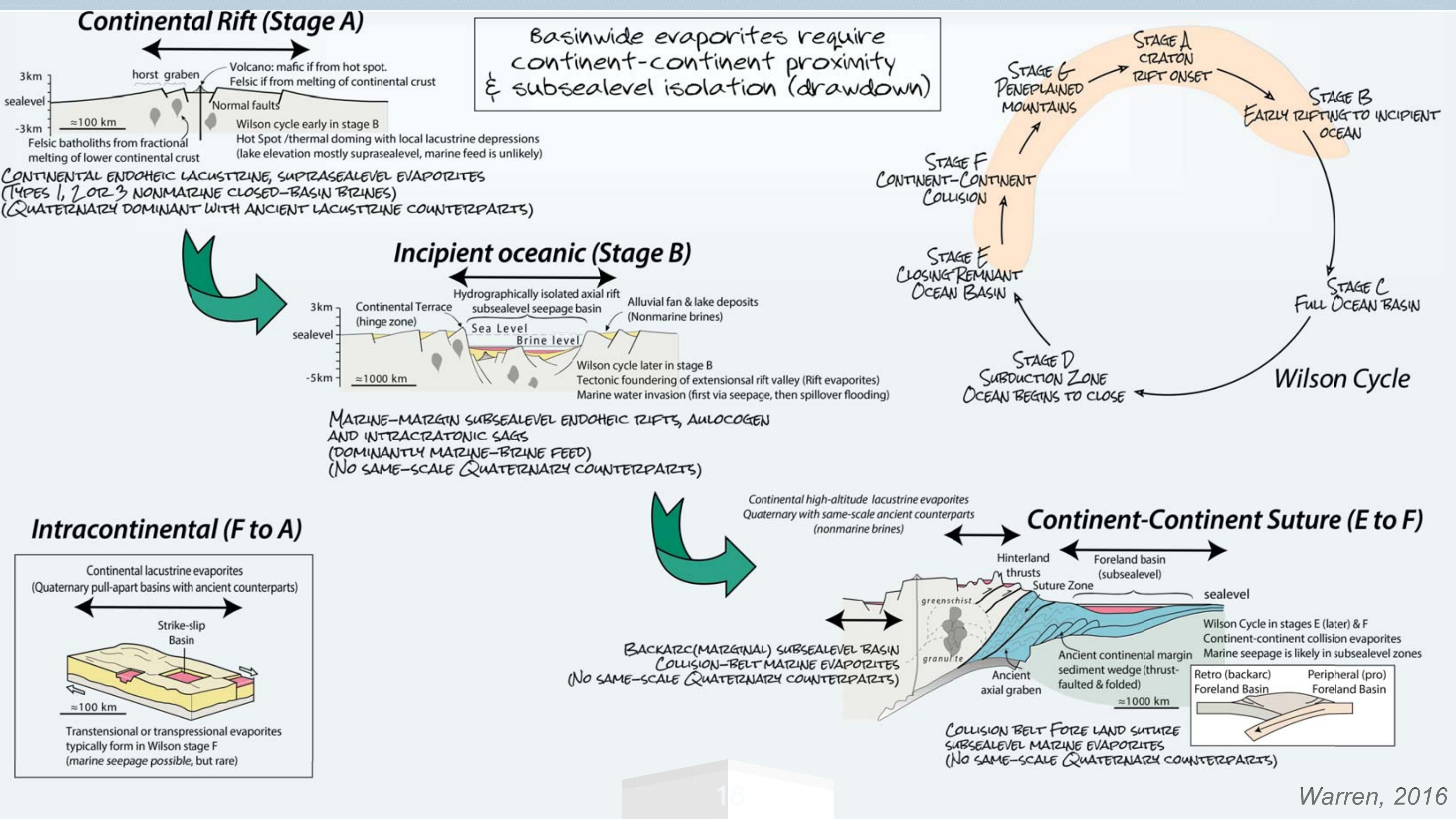
# TYPICAL DRAWDOWN PROFILE

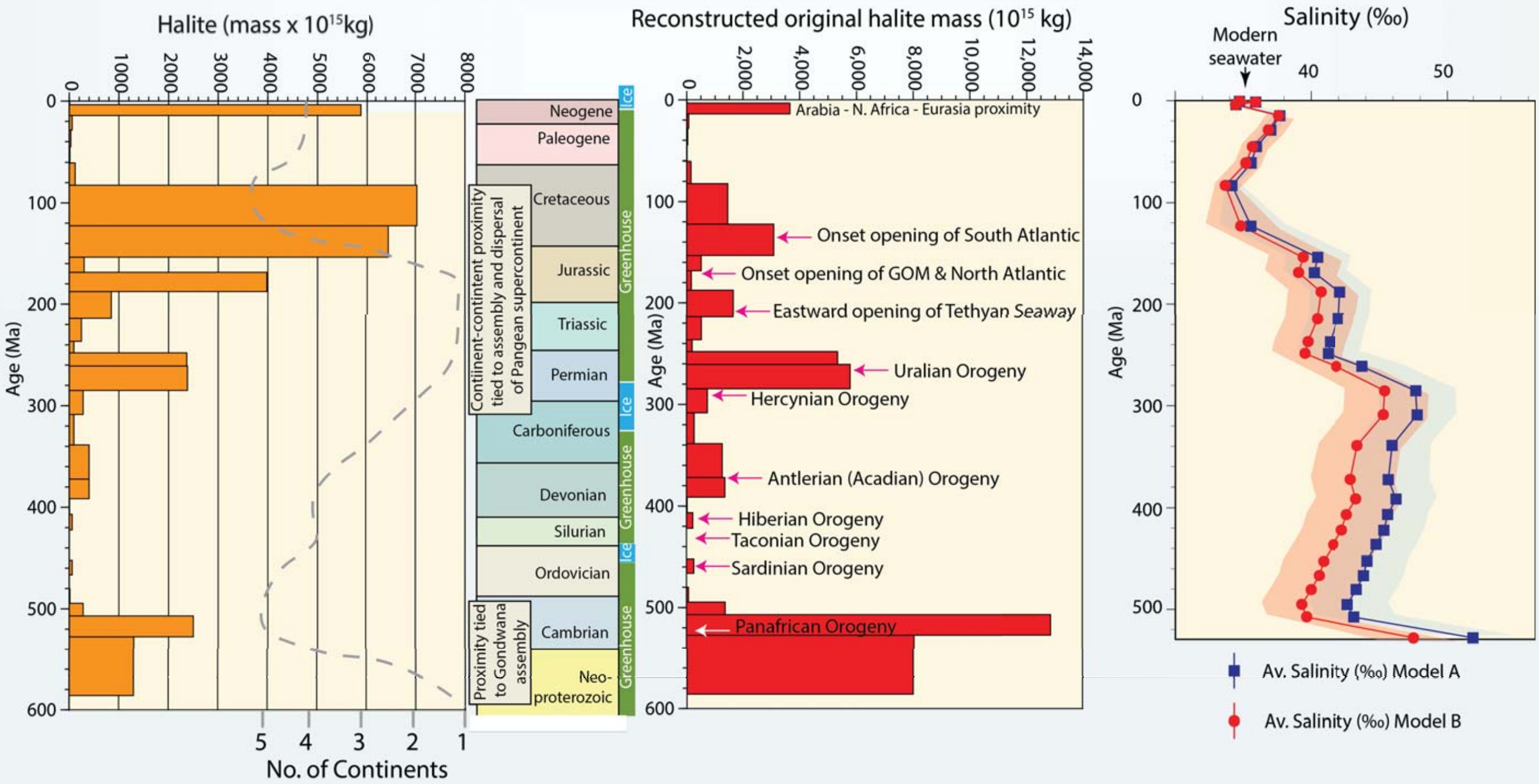


# TYPICAL DRAWDOWN PROFILE



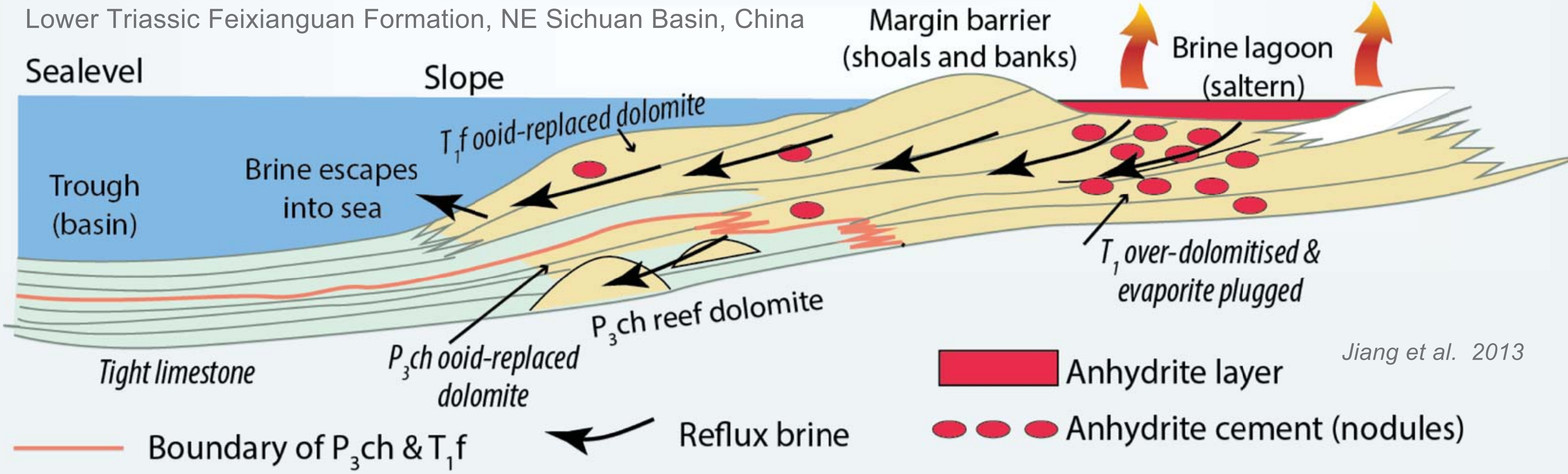

Continental Rift (Stage A)
3km
sealevel
-3km
horst graben
Volcano: mafic if from hot spot.
Felsic if from melting of continental crust
Normal faults
≈100 km
Wilson cycle early in stage B
Hot Spot /thermal doming with local lacustrine depressions
(lake elevation mostly suprasealevel, marine feed is unlikely)
Felsic batholiths from fractional
melting of lower continental crust
CONTINENTAL ENDOHEIC LACUSTRINE, SUPRASEALEVEL EVAPORITES
(TYPES 1, 2 OR 3 NONMARINE CLOSED-BASIN BRINES)
(QUATERNARY DOMINANT WITH ANCIENT LACUSTRINE COUNTERPARTS)
Basinwide evaporites require
continent-continent proximity
& subsealevel isolation (drawdown)
STAGE A
CRATON
RIFT ONSET
STAGE B
EARLY RIFTING TO INCIPIENT
OCEAN
STAGE C
FULL OCEAN BASIN
STAGE D
SUBDUCTION ZONE
OCEAN BEGINS TO CLOSE
STAGE E
CLOSING REMNANT
OCEAN BASIN
STAGE F
CONTINENT-CONTINENT
COLLISION
STAGE G
PENEPLAINED
MOUNTAINS
Wilson Cycle
Incipient oceanic (Stage B)
Hydrographically isolated axial rift
subsealevel seepage basin
3km
sealevel
-5km
Continental Terrace
(hinge zone)
Sea Level
Brine level
Alluvial fan & lake deposits
(Nonmarine brines)
≈1000 km
Wilson cycle later in stage B
Tectonic foundering of extensionsal rift valley (Rift evaporites)
Marine water invasion (first via seepage, then spillover flooding)
MARINE-MARGIN SUBSEALEVEL ENDOHEIC RIFTS, AULOCOGEN
AND INTRACRATONIC SAGS
(DOMINANTLY MARINE-BRINE FEED)
(NO SAME-SCALE QUATERNARY COUNTERPARTS)
Intracontinental (F to A)
Continental lacustrine evaporites
(Quaternary pull-apart basins with ancient counterparts)
Strike-slip
Basin
≈100 km
Transtensional or transpressional evaporites
typically form in Wilson stage F
(marine seepage possible, but rare)
Continental high-altitude lacustrine evaporites
Quaternary with same-scale ancient counterparts
(nonmarine brines)
Continent-Continent Suture (E to F)
Hinterland
thrusts
Suture Zone
Foreland basin
(subsealevel)
sealevel
greenschist
granulite
Wilson Cycle in stages E (later) & F
Continent-continent collision evaporites
Marine seepage is likely in subsealevel zones
BACKARC(MARGINAL) SUBSEALEVEL BASIN
COLLISION-BELT MARINE EVAPORITES
(NO SAME-SCALE QUATERNARY COUNTERPARTS)
Ancient
axial graben
Ancient continental margin
sediment wedge (thrust-
faulted & folded)
≈1000 km
Retro (backarc)
Foreland Basin
Peripheral (pro)
Foreland Basin
COLLISION BELT FORE LAND SUTURE
SUBSEALEVEL MARINE EVAPORITES
(NO SAME-SCALE QUATERNARY COUNTERPARTS)
Warren, 2016




# PRESENT IS NOT THE PAST

# MARINE EVAPORITE DIAGENESIS

Lower Triassic Feixianguan Formation, NE Sichuan Basin, China




Jiang et al. 2013

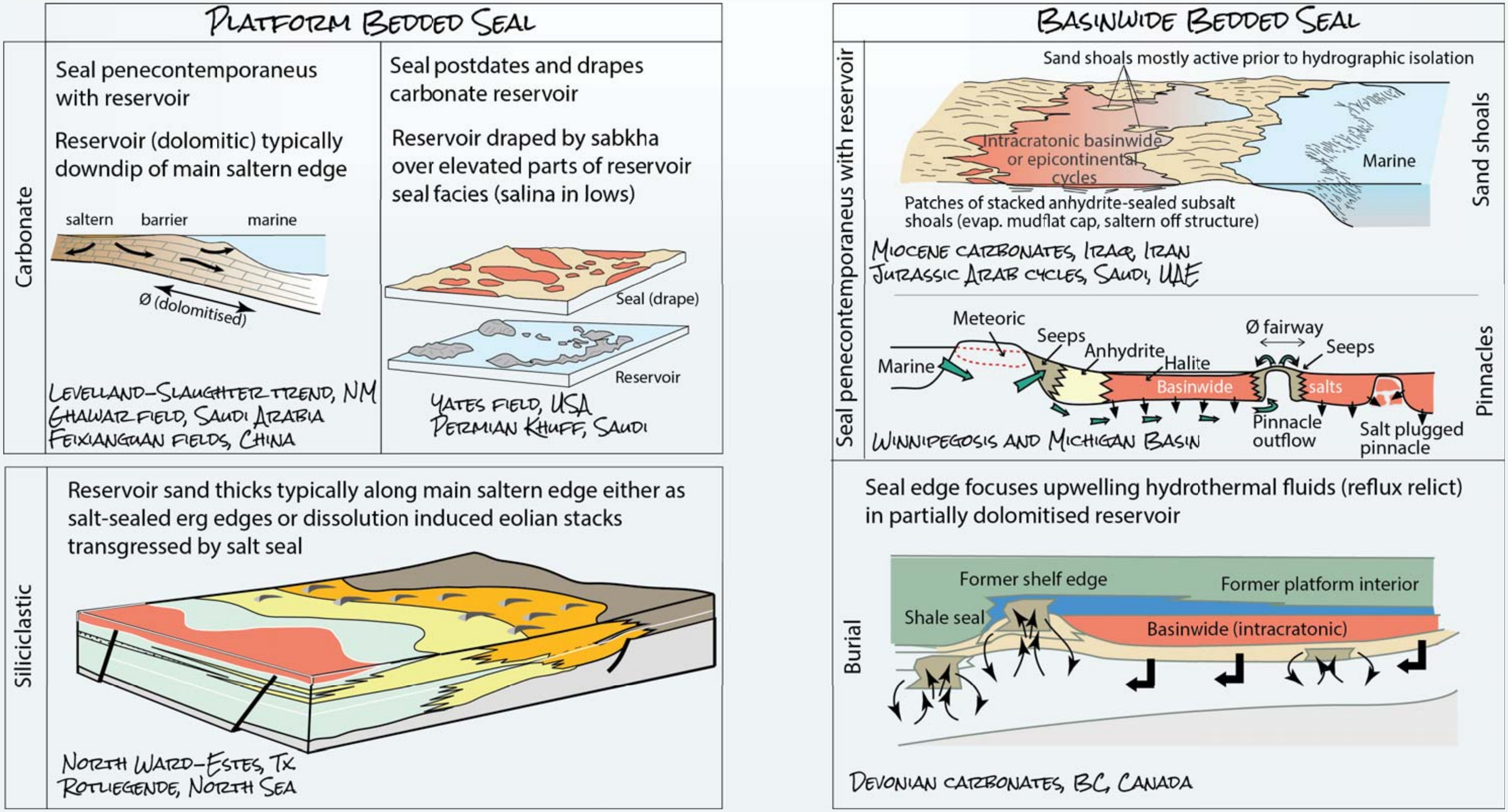
- Evaporites drive reflux or dissolve at various times in the subsurface so act as both a brine source and a focus to brine flow

# BRINE DENSITY DIAGENESIS

*Sichuan Basin* *Western Canada*

*Delaware Basin* *Zechstein Basin*

*Arabian Basin* *Aptian salt basins*

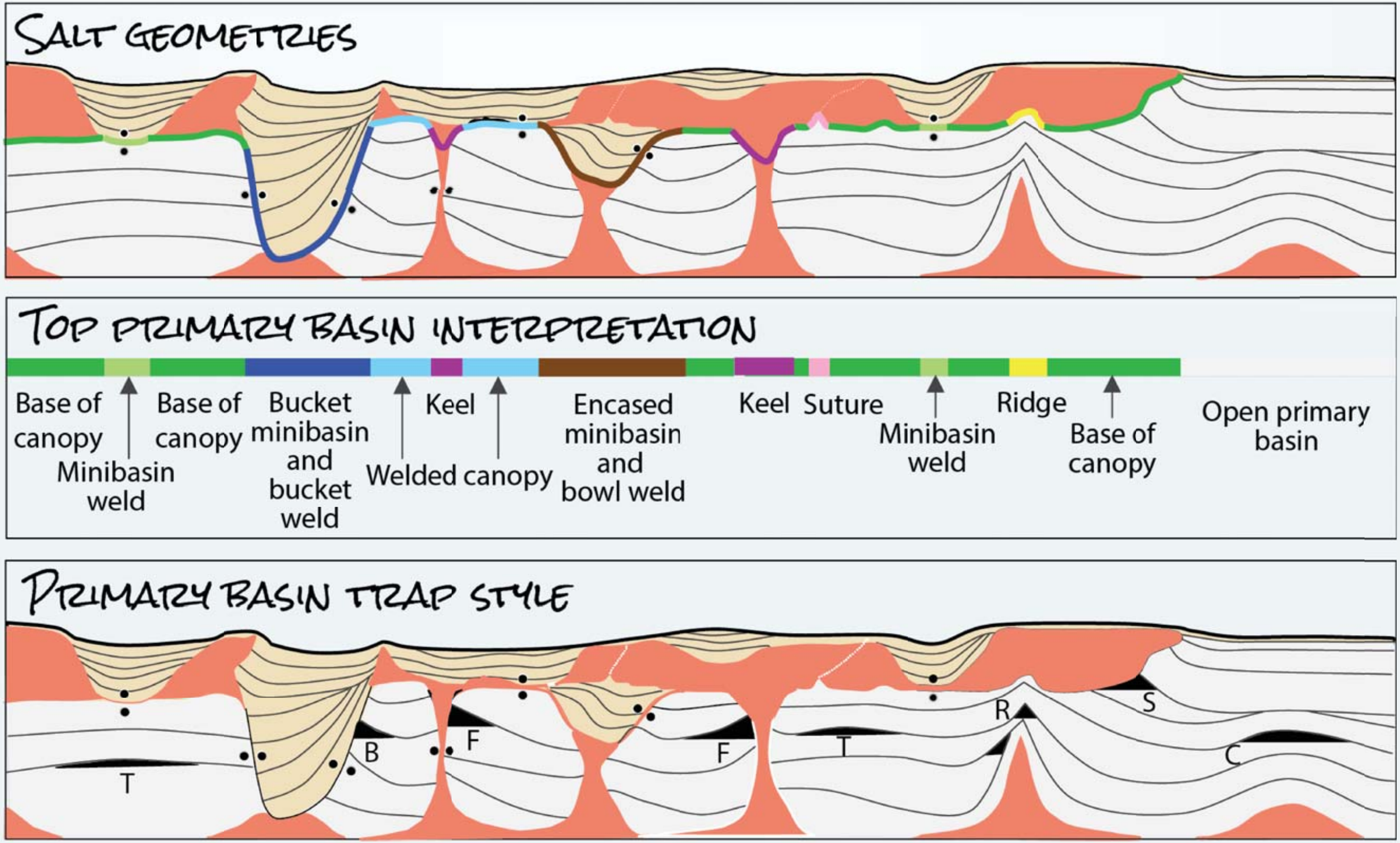


Platform Bedded Seal
Basinwide Bedded Seal
Carbonate
Seal penecontemporaneus with reservoir
Reservoir (dolomitic) typically downdip of main saltern edge
saltern
barrier
marine
Ø (dolomitised)
Levelland-Slaughter trend, NM
Ghawar field, Saudi Arabia
Feixianguan fields, China
Seal postdates and drapes carbonate reservoir
Reservoir draped by sabkha over elevated parts of reservoir seal facies (salina in lows)
Seal (drape)
Reservoir
Yates field, USA
Permian Khuff, Saudi
Seal penecontemporaneus with reservoir
Sand shoals mostly active prior to hydrographic isolation
Intracratonic basinwide or epicontinental cycles
Marine
Sand shoals
Patches of stacked anhydrite-sealed subsalt shoals (evap. mudflat cap, saltern off structure)
Miocene carbonates, Iraq, Iran
Jurassic Arab cycles, Saudi, UAE
Meteoric
Seeps
Anhydrite
Halite
Ø fairway
Seeps
Marine
Basinwide
salts
Pinnacles
Pinnacle outflow
Salt plugged pinnacle
Winnipegosis and Michigan Basin
Siliciclastic
Reservoir sand thicks typically along main saltern edge either as salt-sealed erg edges or dissolution induced eolian stacks transgressed by salt seal
North Ward-Estes, Tx
Rotliegende, North Sea
Burial
Seal edge focuses upwelling hydrothermal fluids (reflux relict) in partially dolomitised reservoir
Former shelf edge
Former platform interior
Shale seal
Basinwide (intracratonic)
Devonian carbonates, BC, Canada


*Warren, 2016*

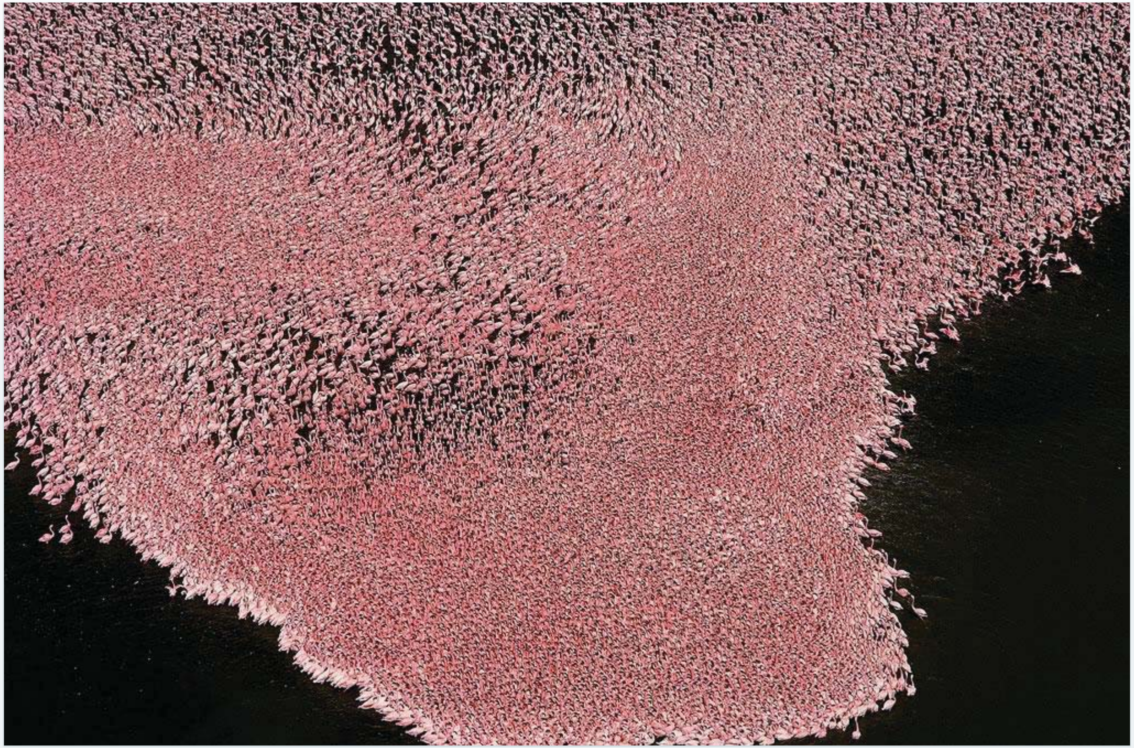
- widespread and thick halites
- form in tectonically active regions (incipient oceans and continent-continent collisions)
- favour minibasin(depopod) loading in marine and continental settings
- association with structural traps
- subsalt, intrasalt and suprasalt giant fields

# CONTINENTAL PLATE-MARGIN BASINWIDES BECOME HALOKINETIC




T = Turtle Structure B = Bucket weld F = Salt feeder R = Salt ridge S = Base-of-salt truncation C = Salt-cored fold

*Pilcher et al., 2011*

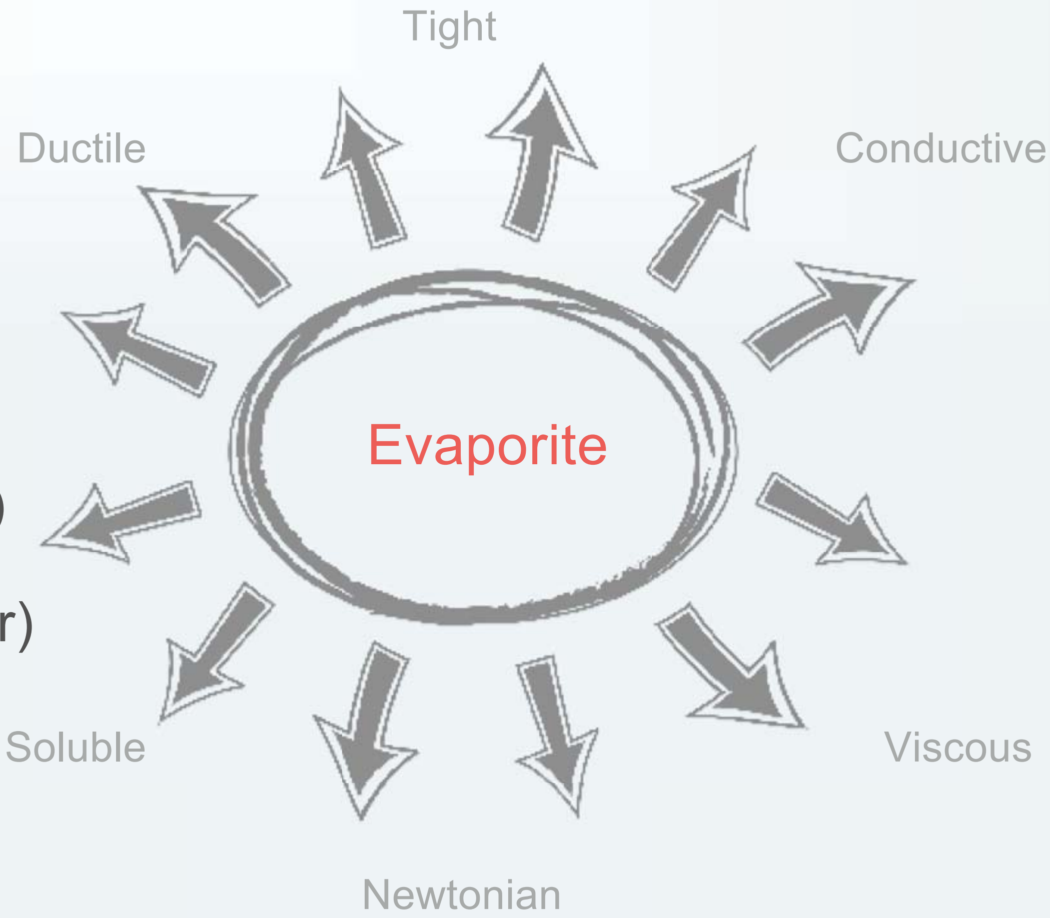


# EVAPORITIC CARBONATES CAN BE ORGANIC RICH


*SaltWork database version 1.6*

# MESOHALINE SOURCE ROCKS

- Seal - bedded and halokinetic
- Fault stopper
- Trap focus
- Source rock (mesohaline carbonates)
- Fluid flow - focus and mixer (stabilizer)
- Metal carrier or fixer (reductant)




# DRIVERS?

# SALT IS MORE THAN A SEAL, THEN.....

- Reservoir Quality Control (Depositional & diagenetic)
- Reservoir Paleotopography (Saltern versus Mudflat)
- Trap Position (Bedded & Halokinetic/Structural)
- Source Rock Quality in Evaporitic Settings