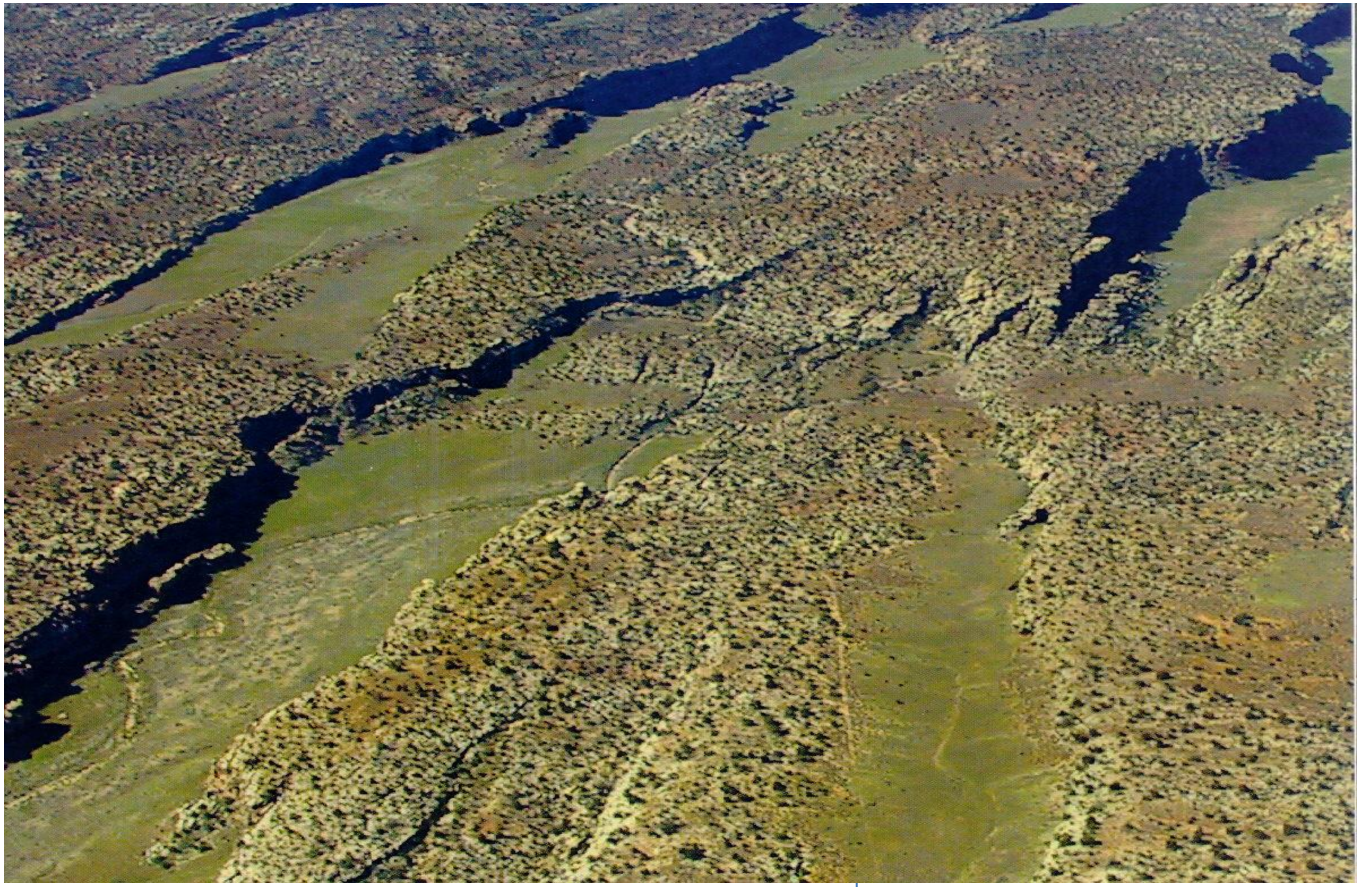


Rift Basin Evolution and Petroleum System Development.

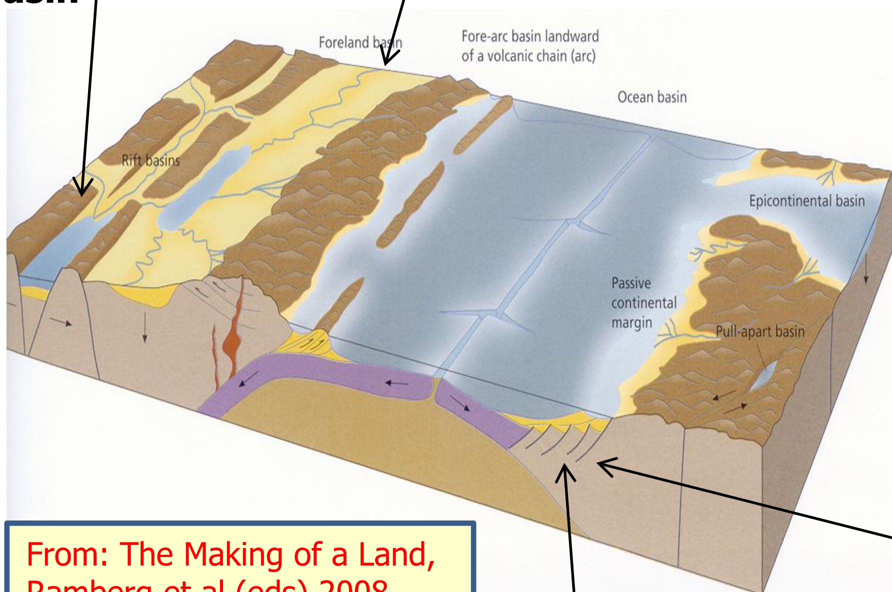
Harry Doust
Utrecht University, The Netherlands

NAPE Abuja May 2019

Basins, rifts and *rift cycles*

Rift cycle / basin

Foreland basins/ cycles are often underlain by both sag & rift cycles



From: The Making of a Land, Ramberg et al (eds) 2008, Geol Soc Norway

Passive margin sag basins/cycles are underlain by rift cycles

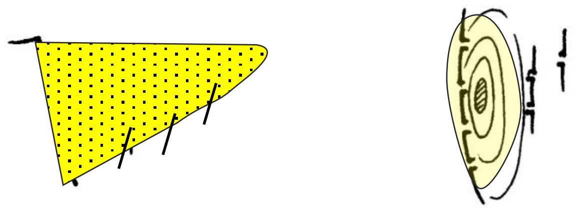
Basins **are composed of one or more tectonostratigraphic *cycles*.**

Rift cycles result from extension of the crust and lithosphere and represent periods of sedimentation during periods of active (mainly normal) faulting…

They are commonly the ***earliest cycle*** in a basin's history , and are usually succeeded by other cycles, such as **sag**, **inversion** or **compressional** cycles.

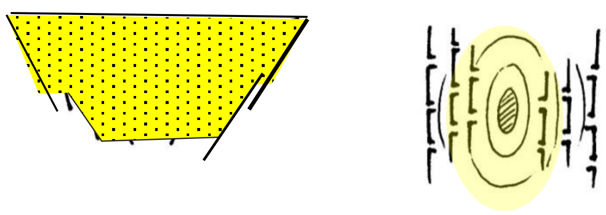
On both sides of the South Atlantic Early Cretaceous rifts underlie Late Cretaceous to Tertiary passive margin sag cycles of varying character

Common rift cycle geometries



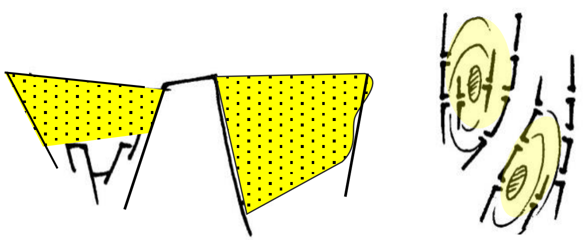
Half grabens – asymmetric, bounded by a master boundary fault, the other flank tilted with minor faults.

Often form the initial stages of rift development and evolve through fault linkage into…

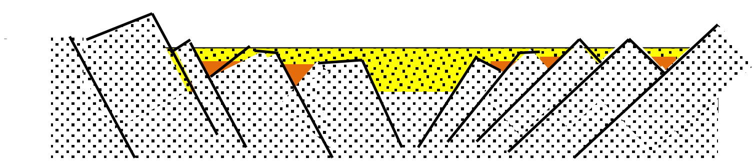


Symmetrical rifts or grabens – result from orthogonal extension and a concordant pre-rift structure. Often comprise a series of tilted fault blocks separated by half graben elements.

Where pre-rift structure is more oblique to the extension the geometry is more complex, leading to the development of…

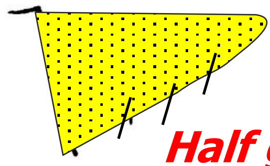


Distributed rifts or grabens – broad, complex graben zones that include one or more horst and graben structures within the rift zone.

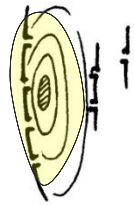


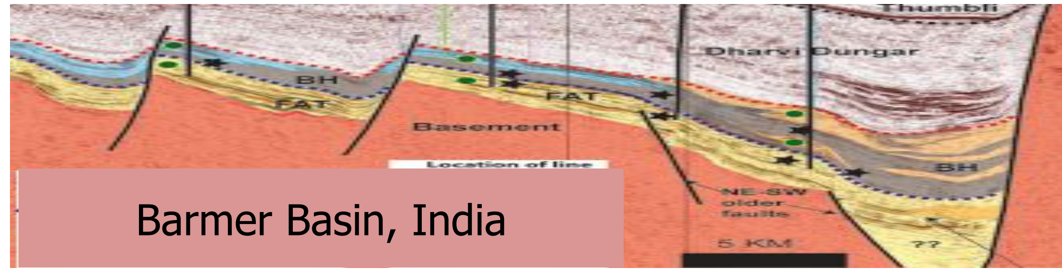
Hyperextended rift zones – form extensive, complex zones of horst and graben structures within a wide rift zone. Development of such zones often precedes continental separation

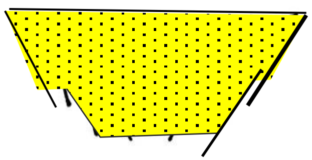
…and examples

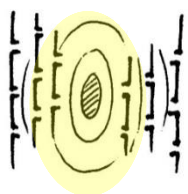


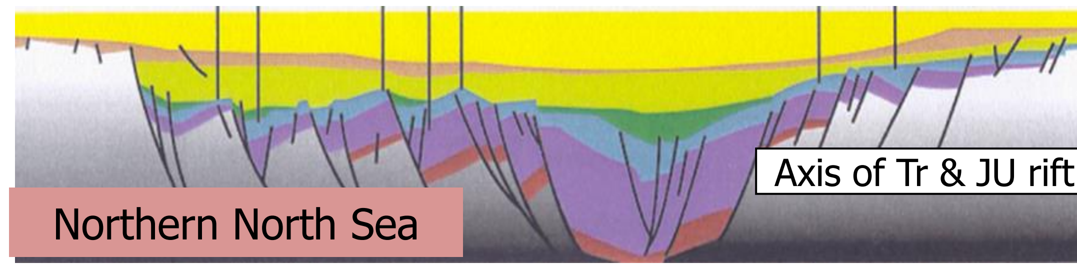
Half graben





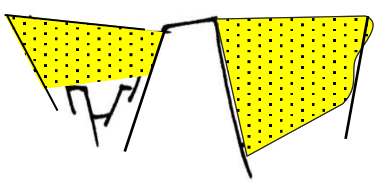


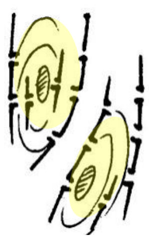


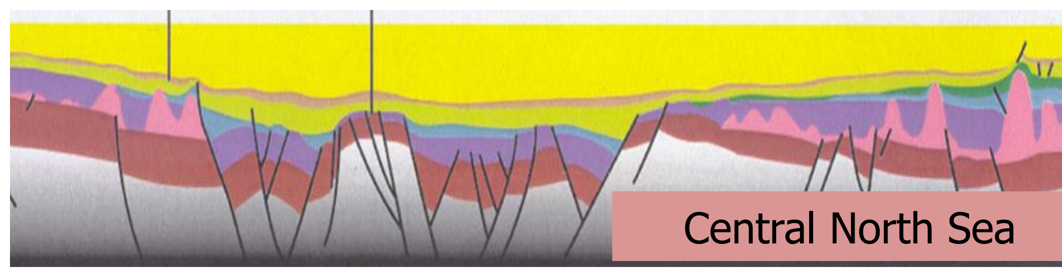


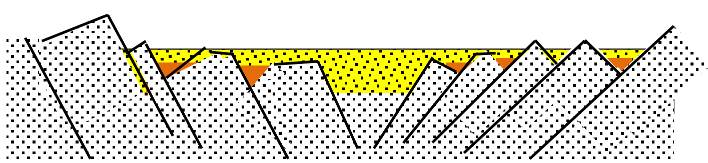
Symmetrical rift

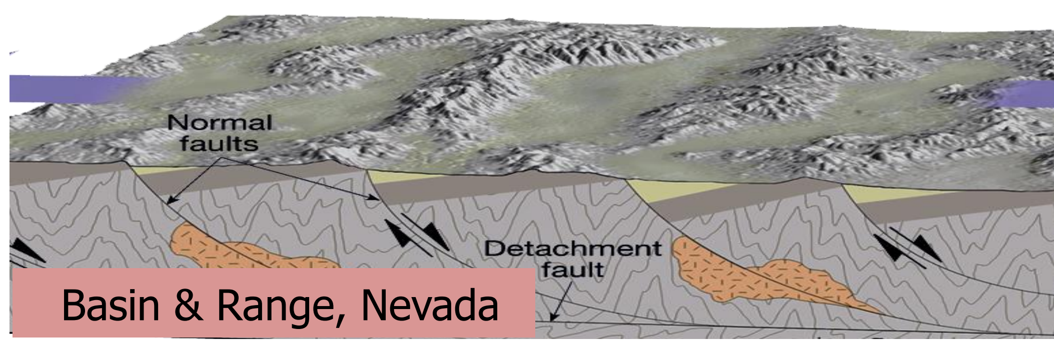
Distributed rift











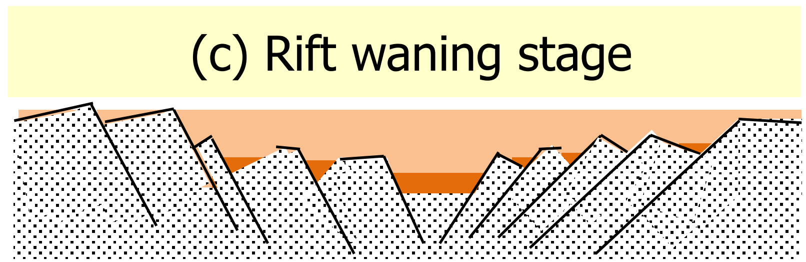
Hyperextended rift

Subsidence & accommodation space creation in rift cycles is fault-driven & controlled.

Three stages of development can often be recognized.

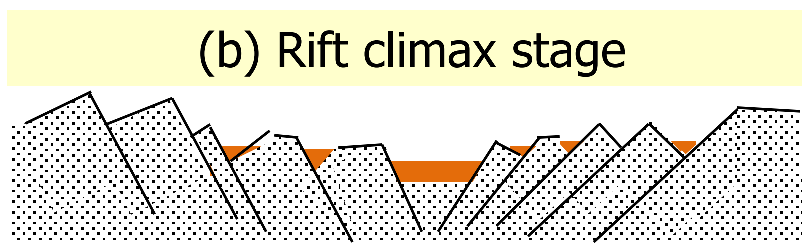
Rift stage | **Typical facies**

Waning stage declining fault activity – rift-flank erosion and infill of rift



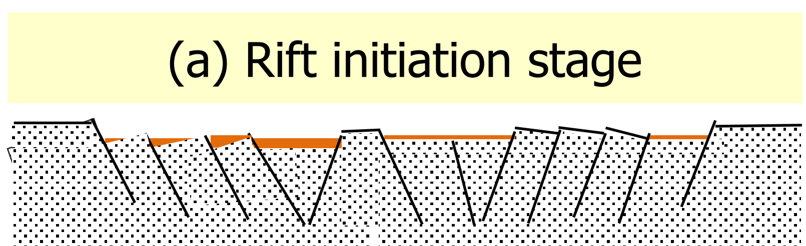
Upward shallowing sequence of often fluvial clastic sediments

Climax (maximum subsidence) stage active faulting and block rotation

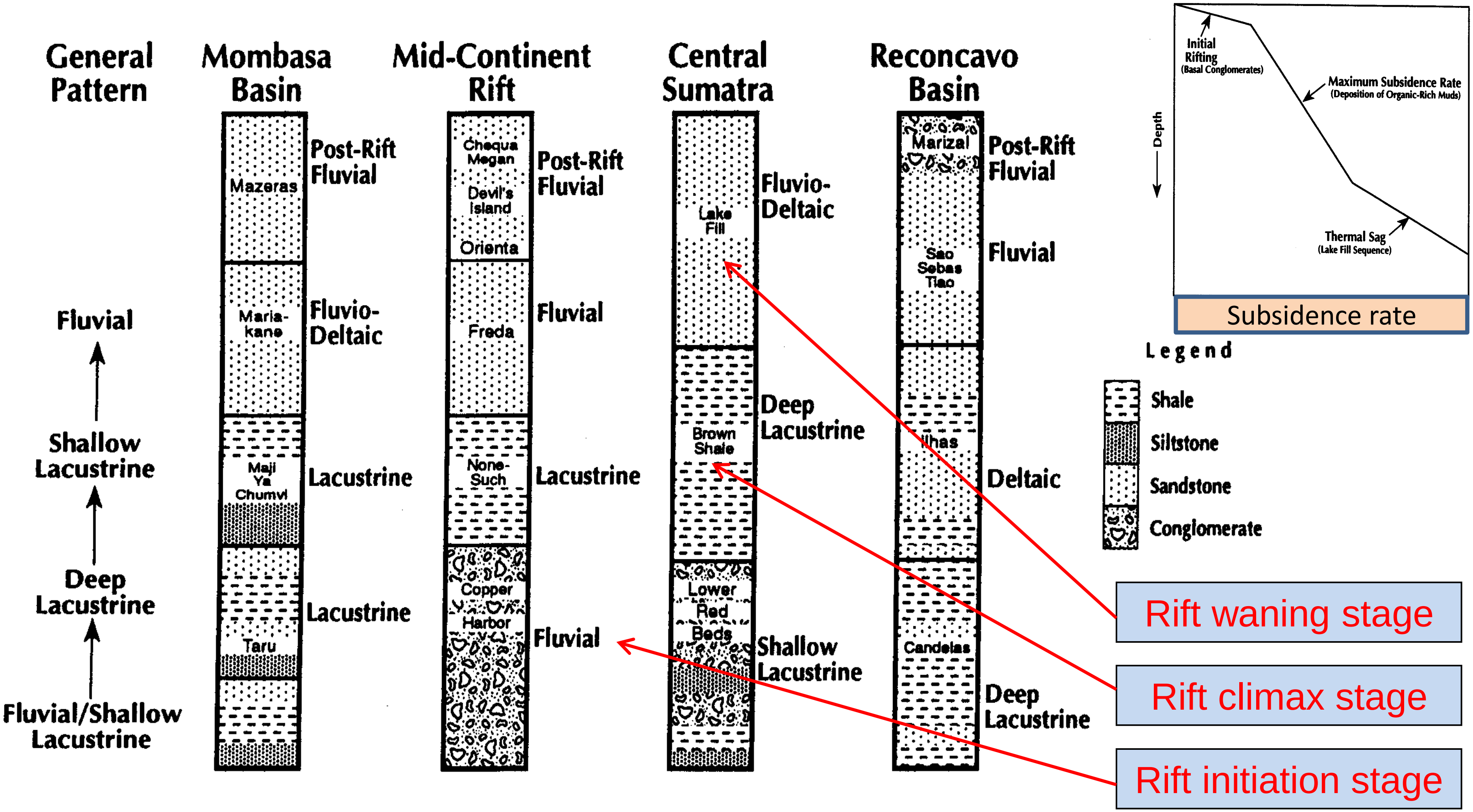


Variety of mainly clastic sediments including deep water clays

Initiation stage formation of fault blocks & minor subsidence / rotation



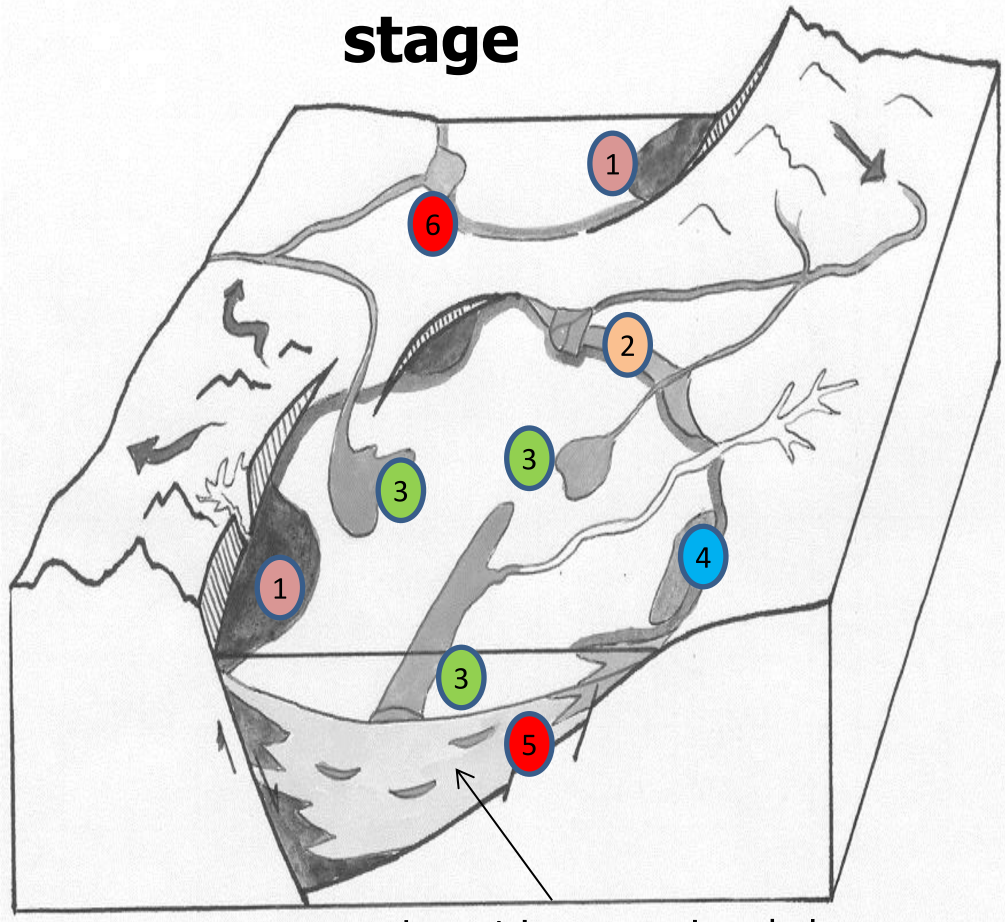
Mainly coarse locally eroded clastic sediments



Sediments accumulating during the rift cycle are *synrift deposits* and reflect typical vertical successions, as seen here in a variety of continental rifts from different continents

From Katz., Geol Soc. Sp. Publ. 80, 1995: 213-242

How is this reflected in petroleum reservoir-seal development? Typical reservoir facies in a synrift climax stage



Facies development is surprisingly consistent, whether the environment is marine or non-marine, mainly comprising:

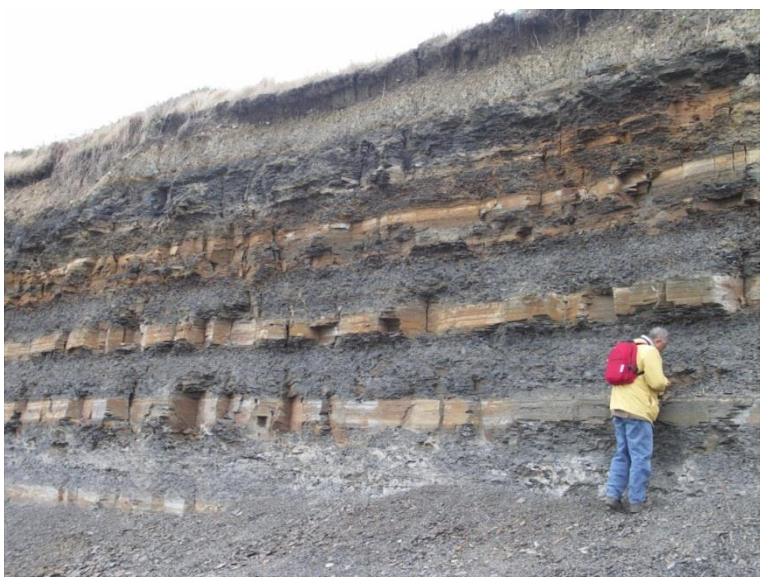
- **1. Talus slope apron fans & fan deltas** adjacent to active boundary faults:
- **2. Deltaic – shoreface sands** on the opposite, less active flanks
- **3. Turbidites –** fans on subsiding slopes and along deep axial portions of rift segments
- **4. Carbonates** in areas isolated from sedimentary input (in suitable conditions)
- **5-6. Fluvio-lacustrine sands** in gently subsiding rifts, thinly interbedded with lacustrine shales and in regressive deltas in the waning stage

Many reservoirs are interbedded with shales and form stratigraphic traps

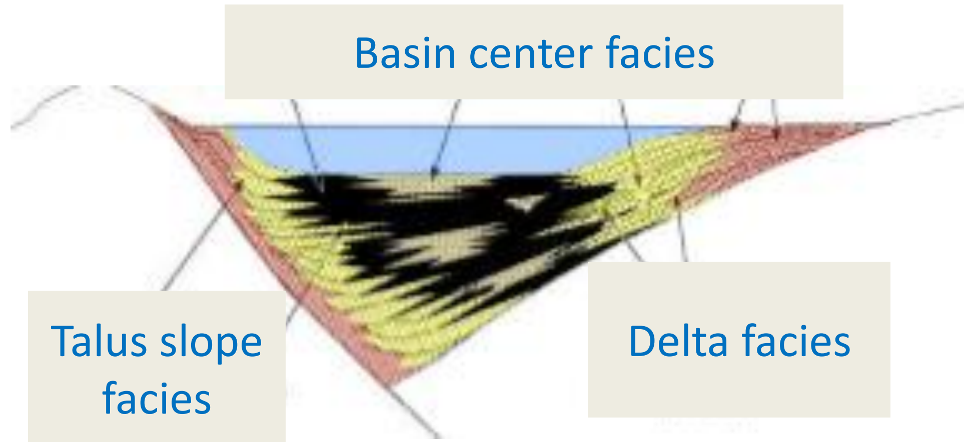
Source rocks in rifts

Rift environments are relatively protected and in appropriate climates host source rocks in both marine and non-marine environments:

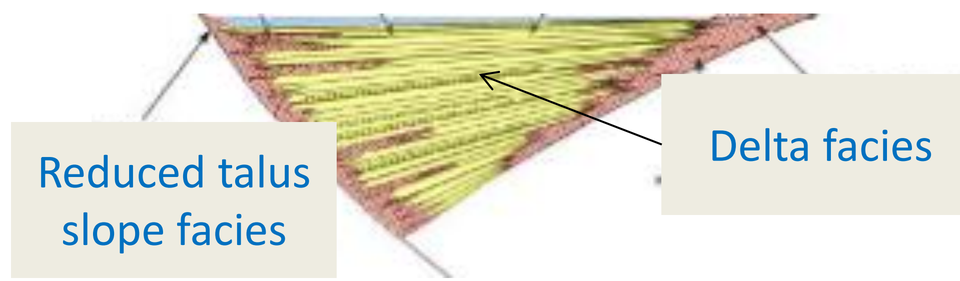
Many of the best synrift ***marine*** source rocks correlate with Ocean Anoxic Events, especially in the Mesozoic.



In ***non-marine*** environments, oil-prone lacustrine source facies characterise the basin center in the rift climax stage:



The *waning stage* is commonly represented by upward shallowing paralic facies with gas and oil-prone coals and coaly shale source rocks.

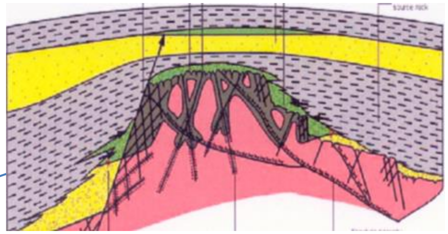


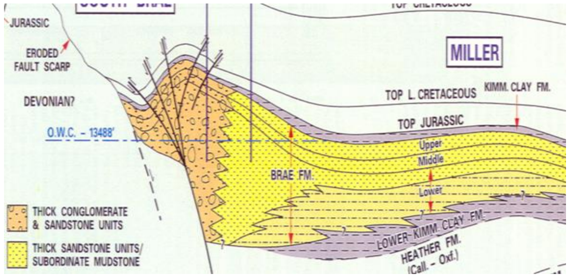
Typical trap geometries in rift sequences may be…

Structural:

- Tilted and rotated fault blocks and horsts –

  affect the pre & early syn-rift sequence



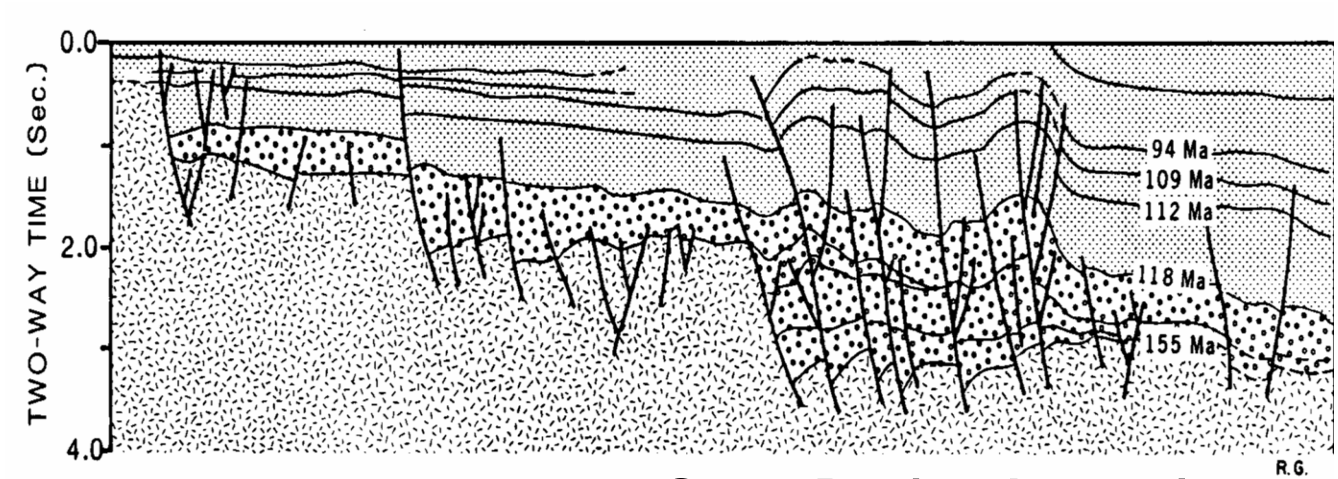


- Buried hills composed of high pre-rift rocks
- Inversion anticlines in syn - postrift sequences

Sealing clays surround sand bodies, but except in deep water rifts

- Seals are mainly local: regional seals are *absent* (often the first regional seal lies at the base of the postrift)
- as faulting continues through the synrift cycle, *leakage* often results in vertical migration into younger cycles

Inversion of rift cycles



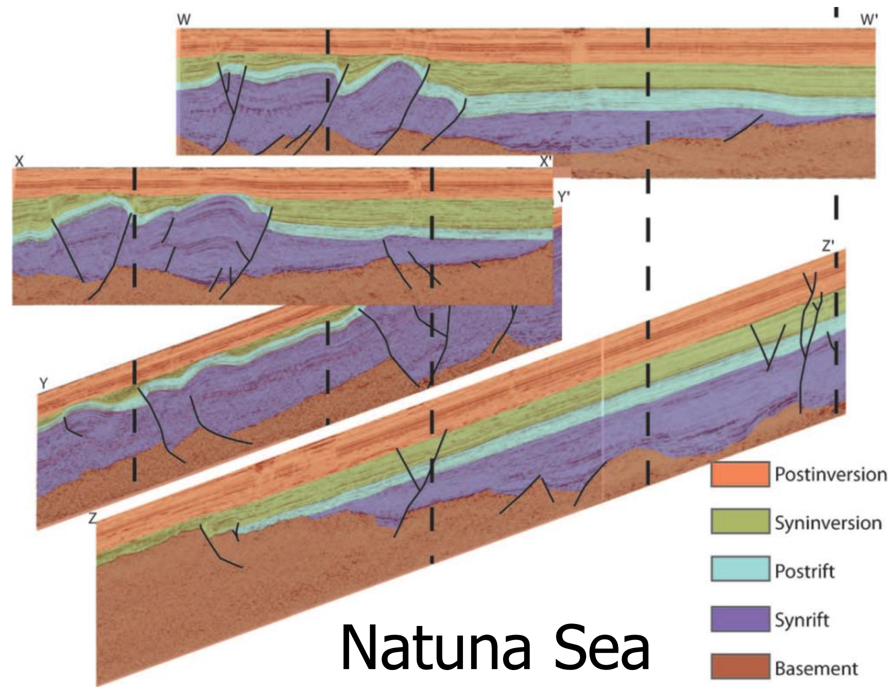
Cuyo Basin, Argentina

Rift sequences are often relatively protected from post-rift tectonic events such as major compression….

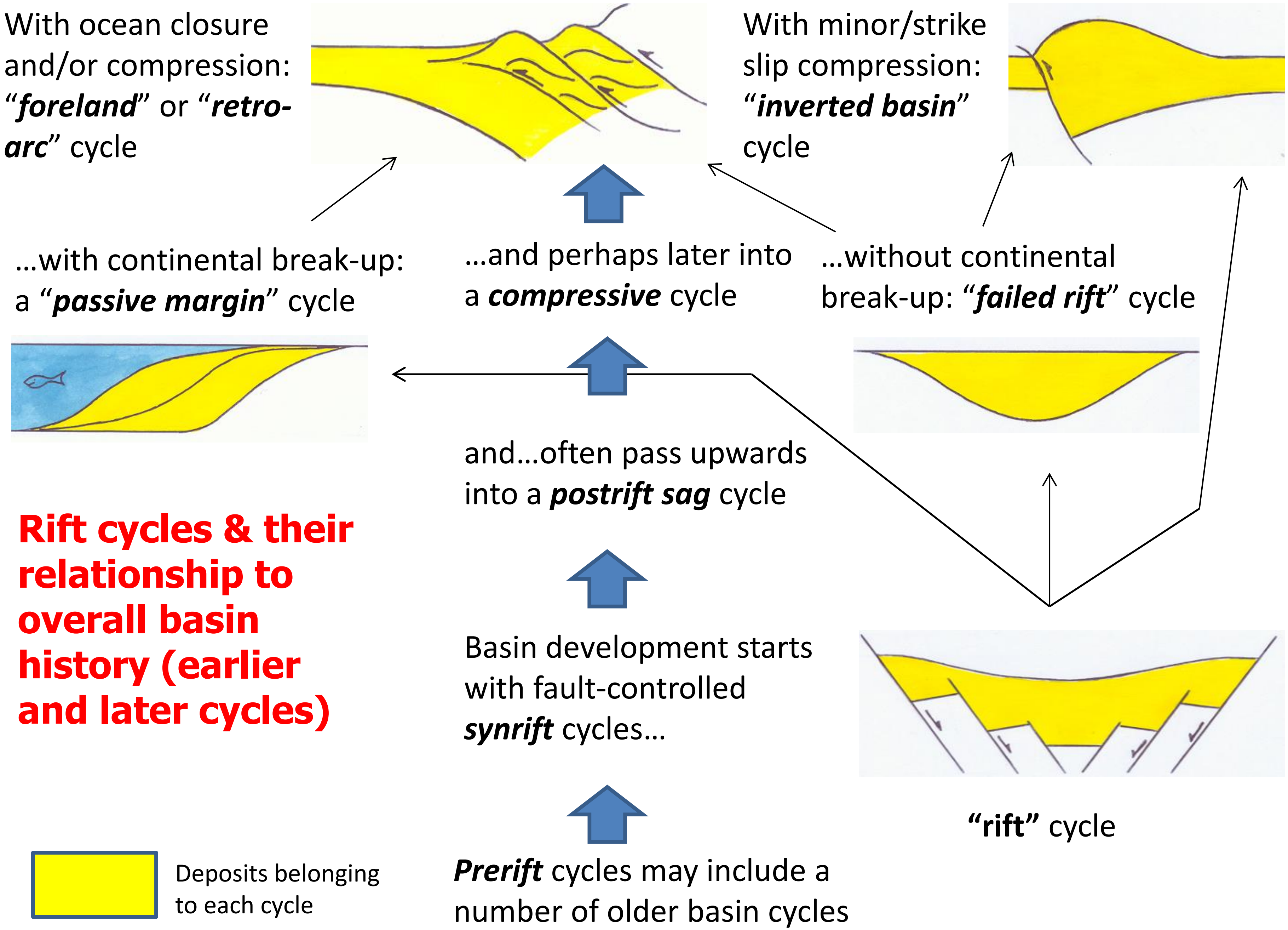
…but are very susceptible to inversion, especially in active tectonic provinces

Inversion can be very local and affect synrift sequences adjacent to faults of particular orientations, resulting in **partially inverted basins**

…and it can lead to deep erosion of the synrift sequence



Natuna Sea
Indonesia

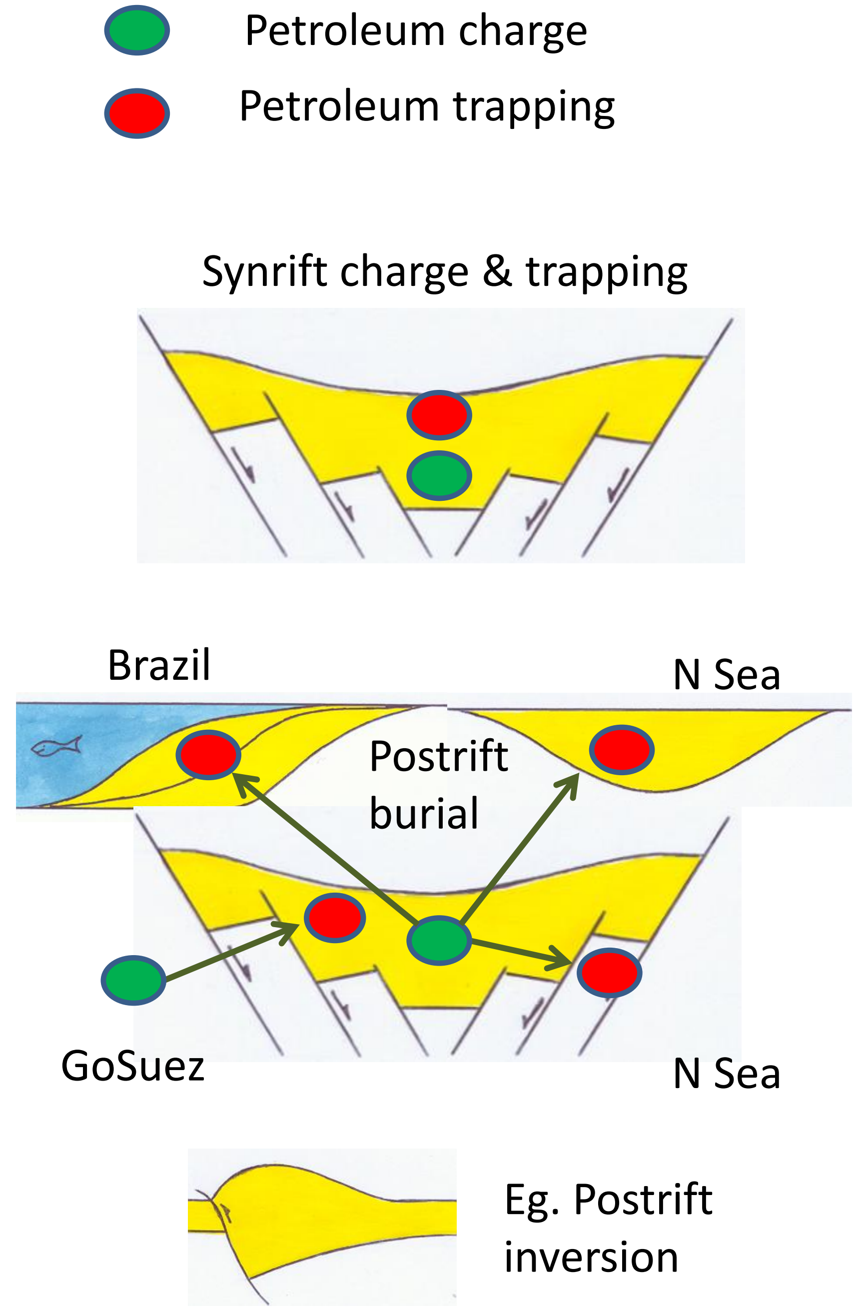


Rift cycles & their relationship to overall basin history (earlier and later cycles)

The pre- and post-rift cycles often play important roles in petroleum occurrence.

Sometimes charge and trapping occur *within* the rift cycle, but the *pre- and post-rift* may contribute essential elements to the petroleum systems. For instance:

- The **pre-rift** may charge into the synrift (eg Gulf of Suez), or contain reservoirs and traps charged from the synrift (North Sea)
- The **postrift** may be charged from the synrift (North Sea, Brazil)
- The **postrift** often provides crucial burial to mature synrift source rocks (as in the South Atlantic African margin)
- Rift trap development and geometry are often dependent on events **pre**- or **post-dating** the rift cycle



We can recognize families of petroliferous rifts, using the following practical criteria

- Is the sedimentary fill marine or non-marine?

  Impacts on the nature and type of the hydrocarbon source/charge system

- Are we near to land or distal?

  Influences the quality of charge, variety of reservoir facies & relative amount of subsidence, which impacts on source rock timing & maturity

- Was the climate tropical or temperate during the rift cycle?

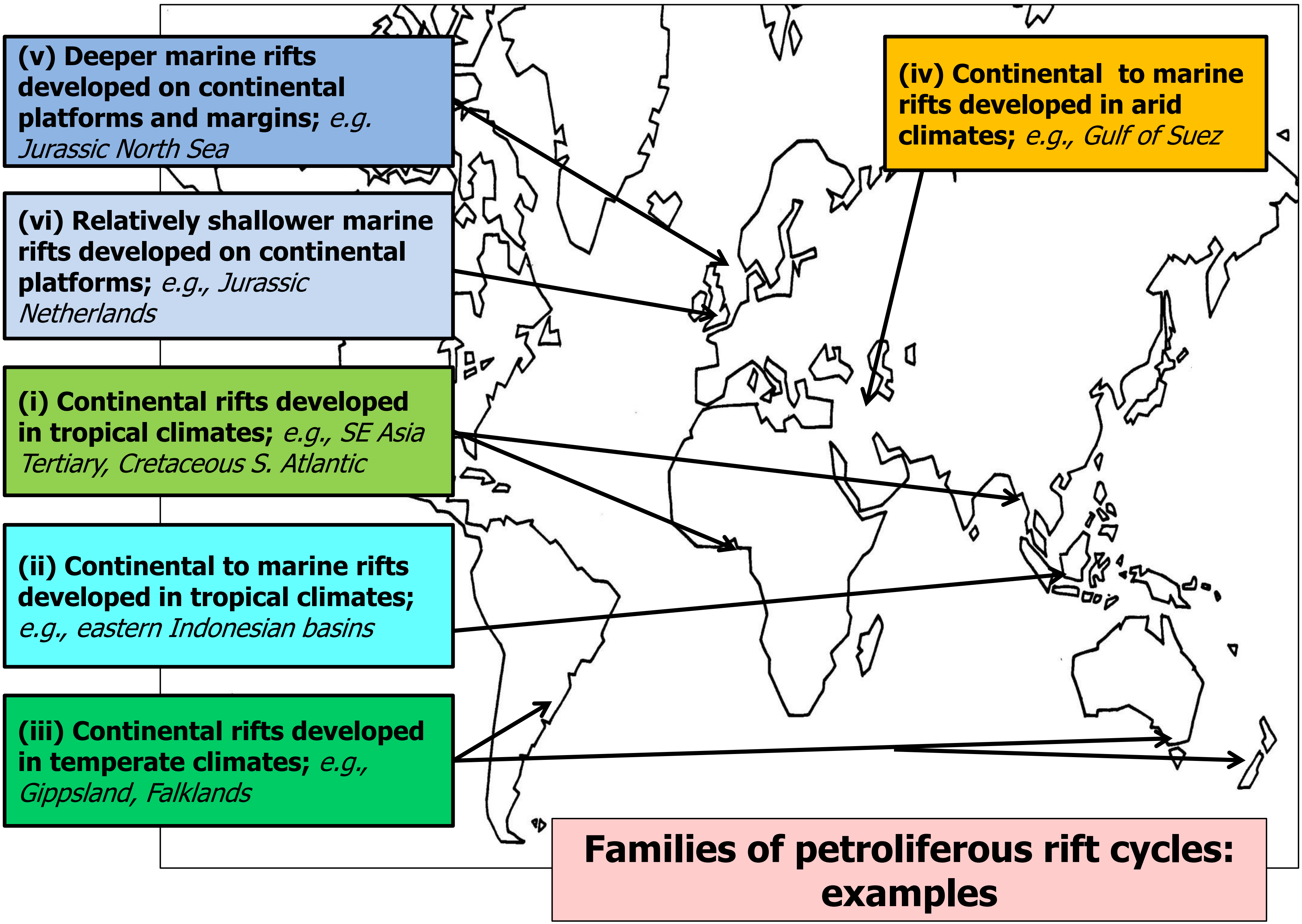
  Controls especially presence & development of lacustrine source facies (typically in basins <30 degrees N & S of the equator)

- Was the climate more humid or more arid during the rift cycle?

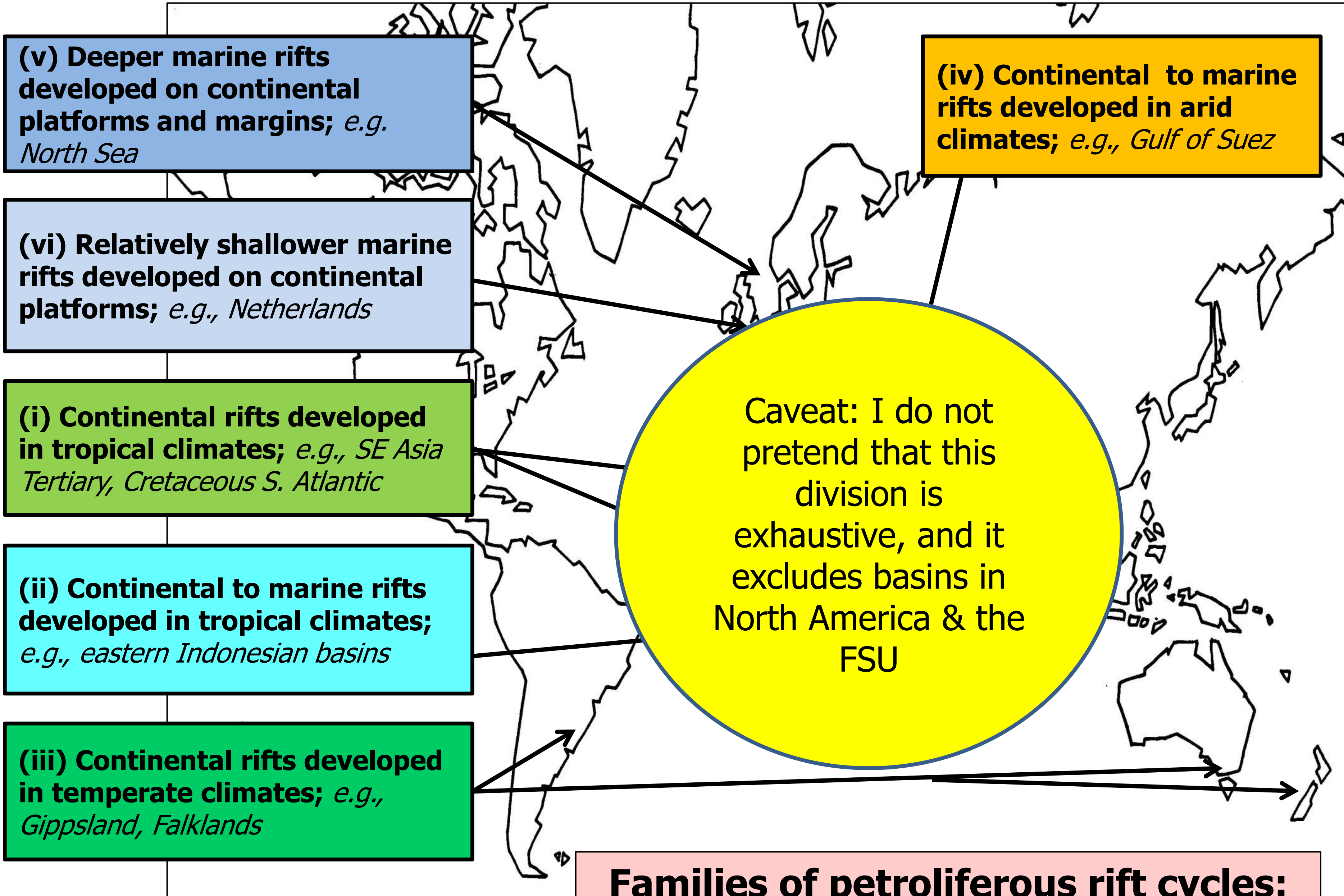
  In arid climates carbonates & evaporite seal facies are widespread while source rock facies are rarer

- Was there a change of environment during the rift cycle - eg from non-marine to marine?

  Impacts primarily on the development of source facies, which may become mixed


(v) Deeper marine rifts developed on continental platforms and margins; *e.g. Jurassic North Sea*
(vi) Relatively shallower marine rifts developed on continental platforms; *e.g., Jurassic Netherlands*
(i) Continental rifts developed in tropical climates; *e.g., SE Asia Tertiary, Cretaceous S. Atlantic*
(ii) Continental to marine rifts developed in tropical climates; *e.g., eastern Indonesian basins*
(iii) Continental rifts developed in temperate climates; *e.g., Gippsland, Falklands*
(iv) Continental to marine rifts developed in arid climates; *e.g., Gulf of Suez*
Families of petroliferous rift cycles: examples

Families of petroliferous rift cycles: examples



Continental rifts developed in tropical climates

- Typically with lacustrine oil-prone source rocks in the rift climax stage and fluvio-deltaic sediments in the waning stage.
- relatively independent of the pre- and post-rift, but may be followed by continent separation (as in South Atlantic).
- Susceptible to inversion.
- Found in many Mesozoic and Tertiary provinces & form bases of rich petroleum provinces in SE Asia and the South Atlantic margins.

Type basins – South Atlantic salt basins and SE Asian rifts

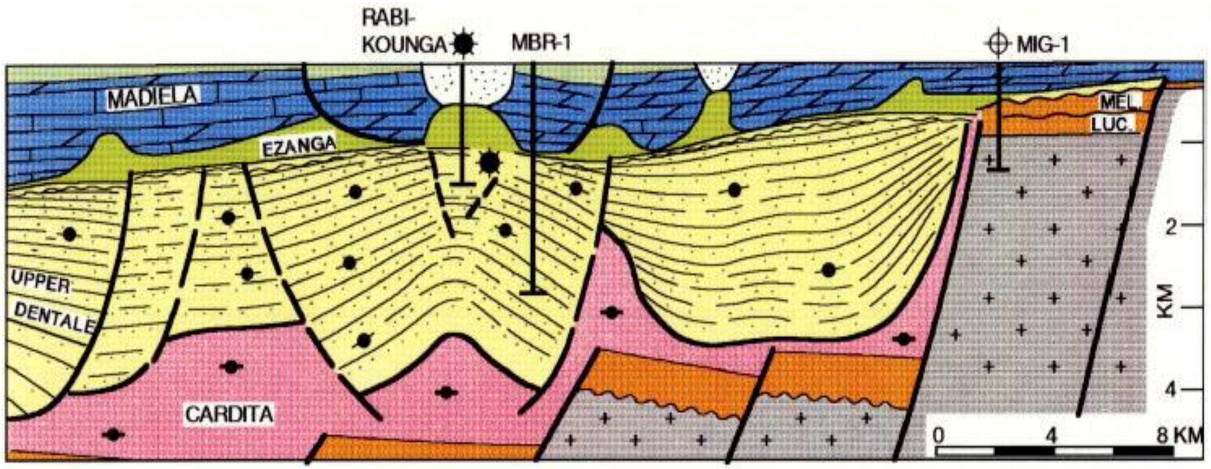
Continental –marine rifts developed in tropical climates

- Palaeogeographically more distal basins are invaded by the sea during the synrift, leading to a second family, with more limited oil-prone source rocks

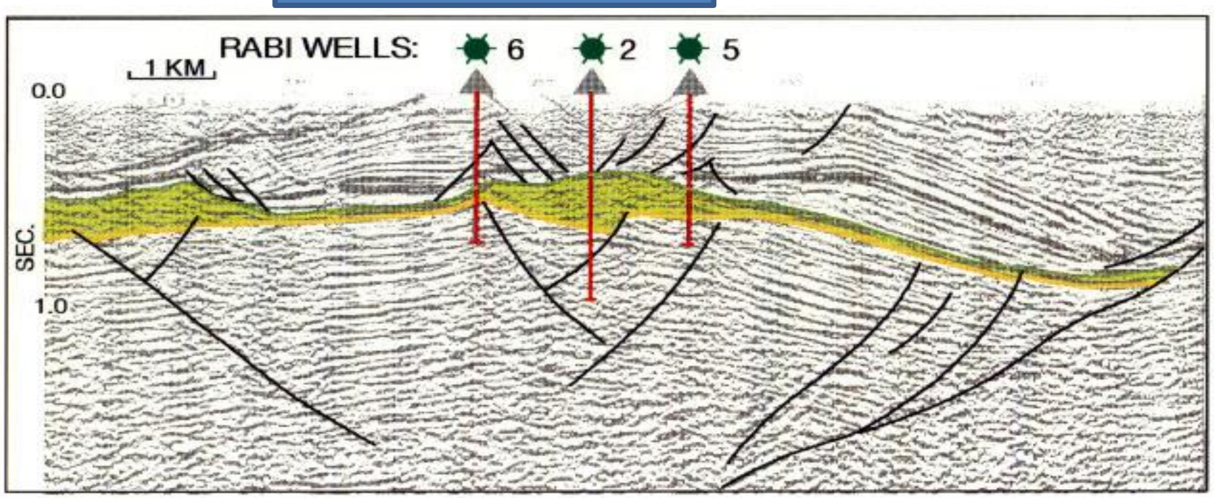
Type basins – Distal Indonesian rifts

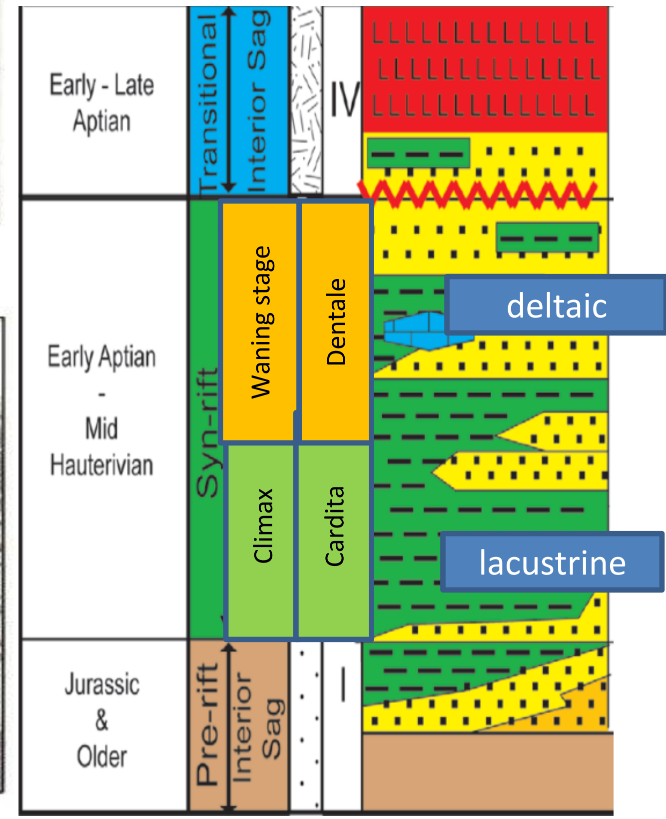
Continental rift developed in tropical climate

Example - South Atlantic, Synrift Cardita – Dentale (!) Petroleum System, Gabon: Rabi-Kounga field

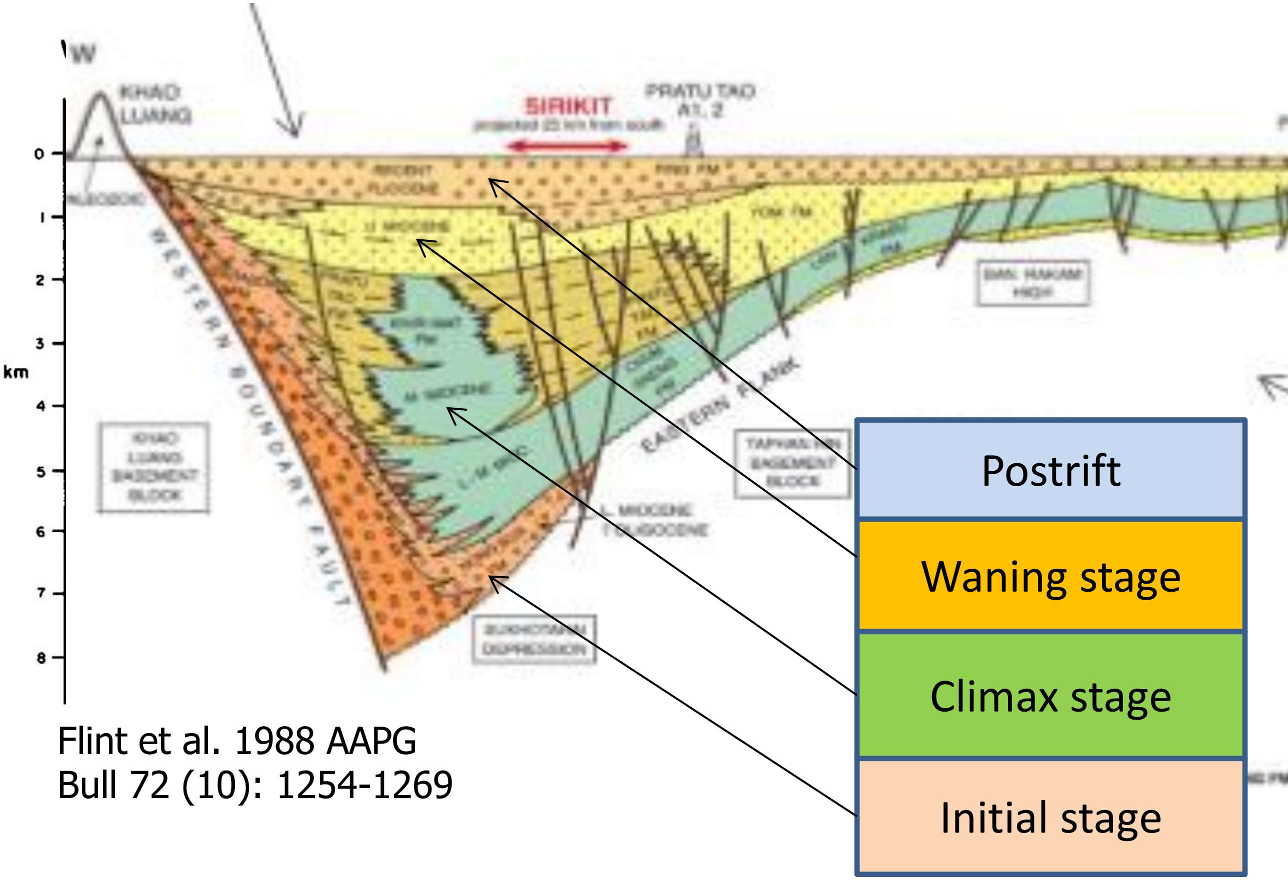


Minor synrift inversion

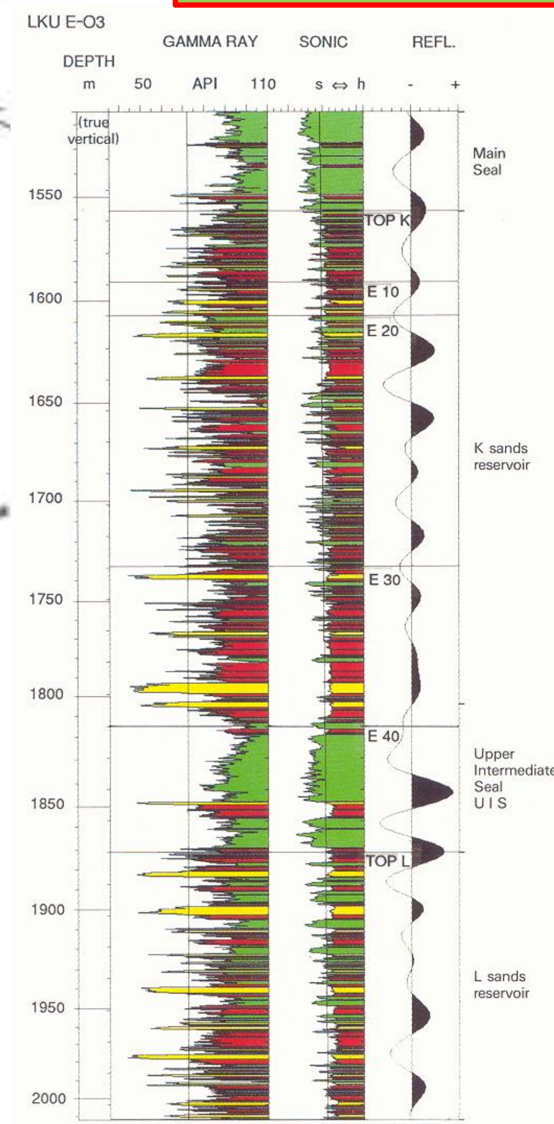




Continental rift developed in tropical climate

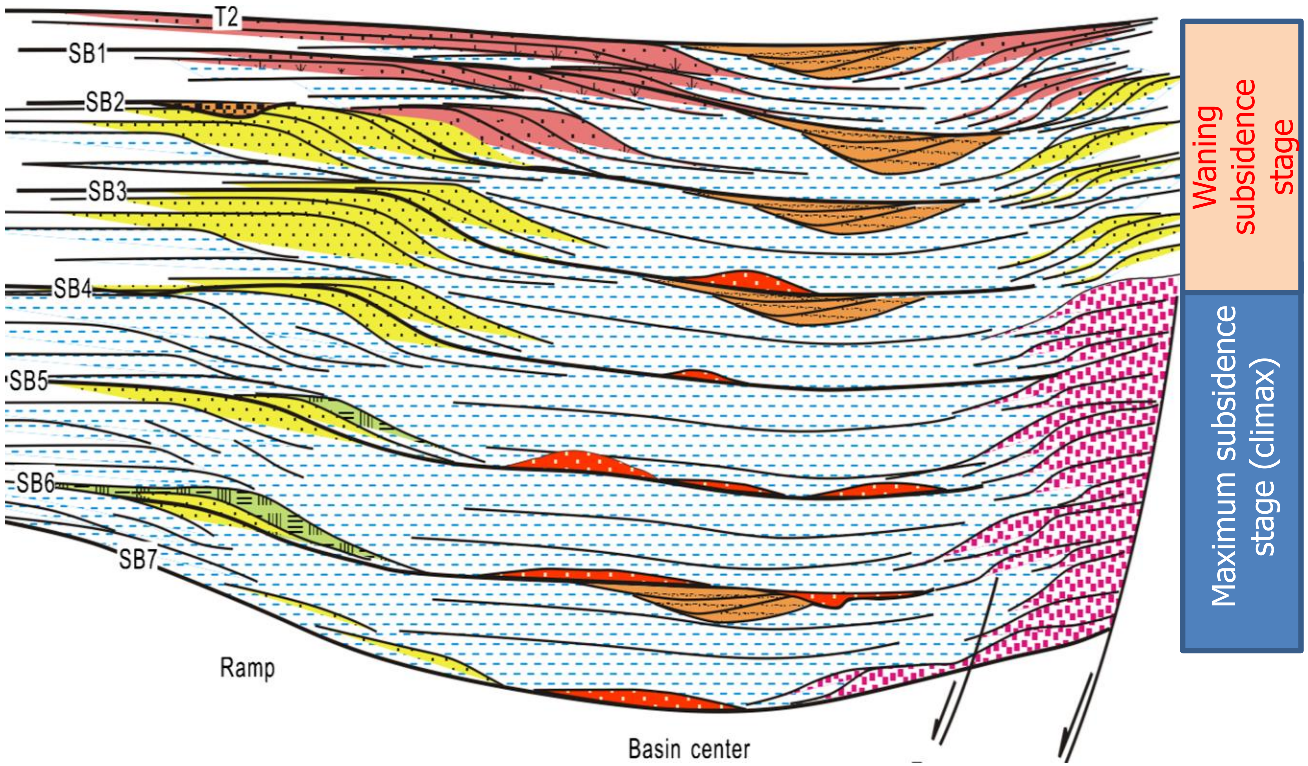


Flint et al. 1988 AAPG
Bull 72 (10): 1254-1269



Example – SE Asia, Synrift Petroleum System, Phitsanulok Basin Thailand: Sirikit Field

Gradual subsidence here led to extensive shallow fluvio-lacustrine sediments, the dominant source & reservoir facies. **Right:** logs from the Sirikit field, showing the thin nature of the fluvio-lacustrine reservoir sands – a great challenge for reservoir modelling!



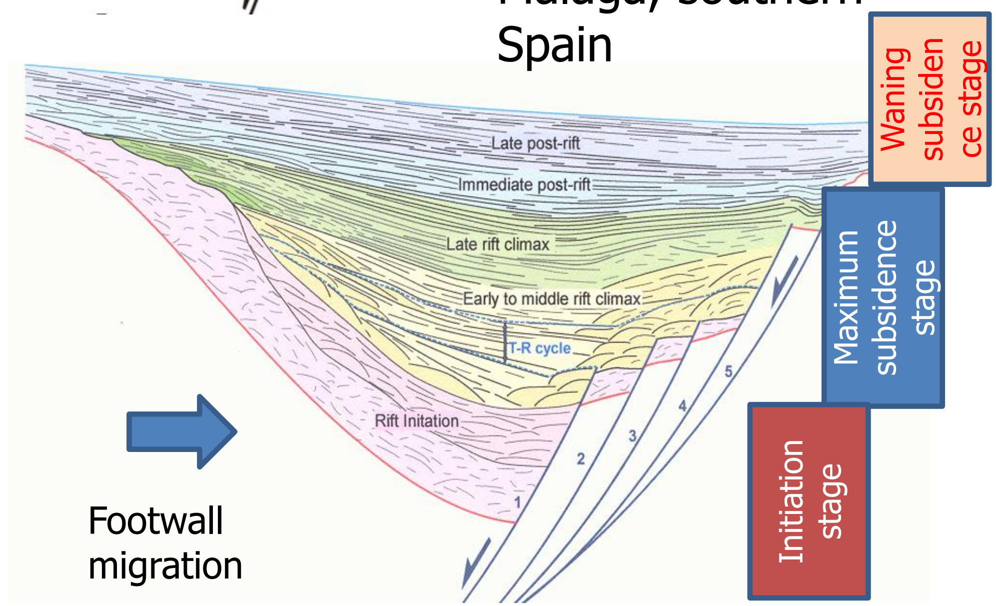
Liaozhong depression, Bohai Bay, East China.

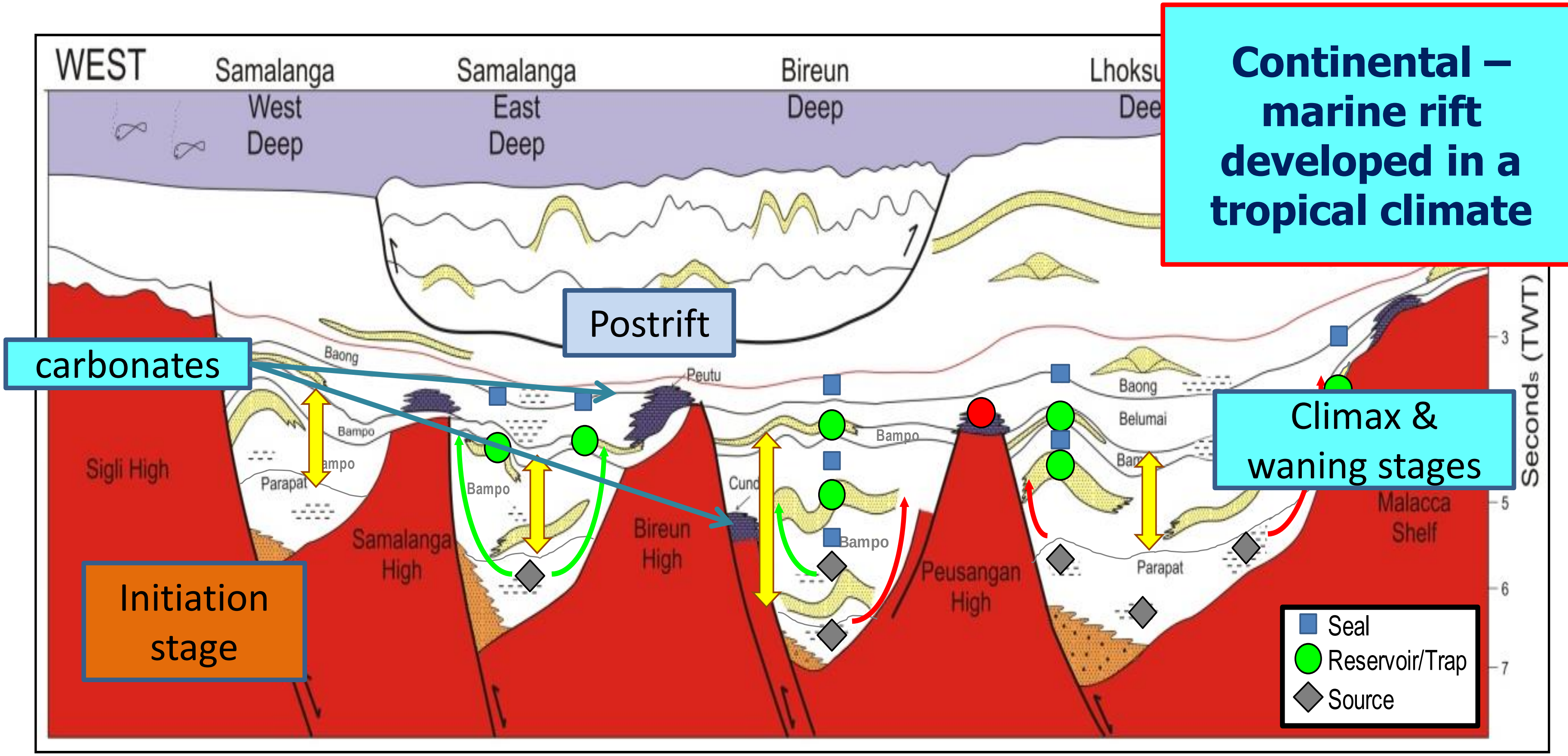
The pattern of reservoir development changes through the synrift cycle

In wide rifts the boundary faults may migrate through time, resulting in shifting (but consistent) sequence stratigraphic relationships.

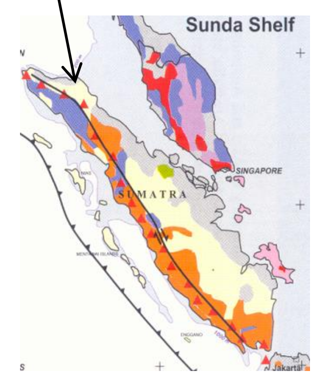
From Suedes et al, Basin Research

Malaga, southern Spain





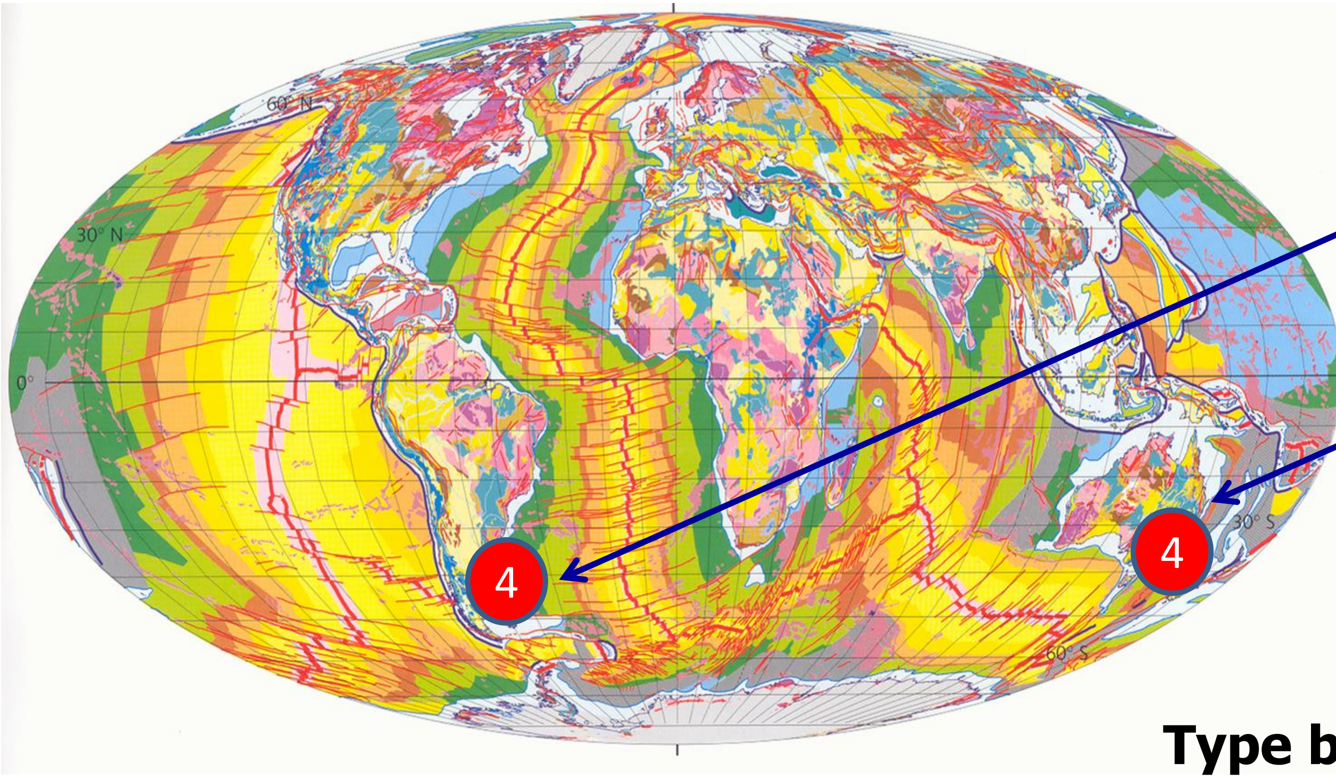
Example – SE Asia, Syn- postrift Petroleum System, North Sumatra Basin, Indonesia: Bampo-Peutu Petroleum system (!)



Non-marine half-grabens were flooded by the sea due to rapid tectonic subsidence & eustatic sea level rise in the climax stage. Slope and basin-floor turbidites filled the accommodation space.

Lacustrine source rocks are absent and this family is much more gas-prone.

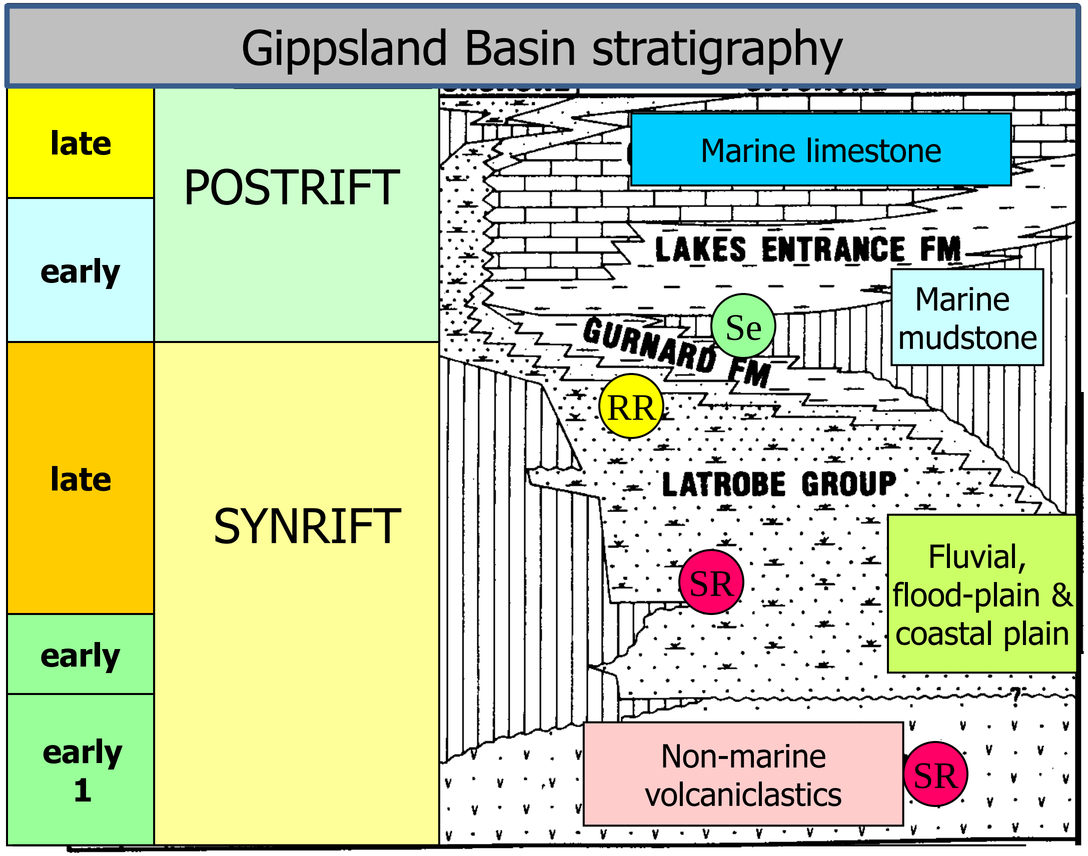
From Meckel, Fosi 2014

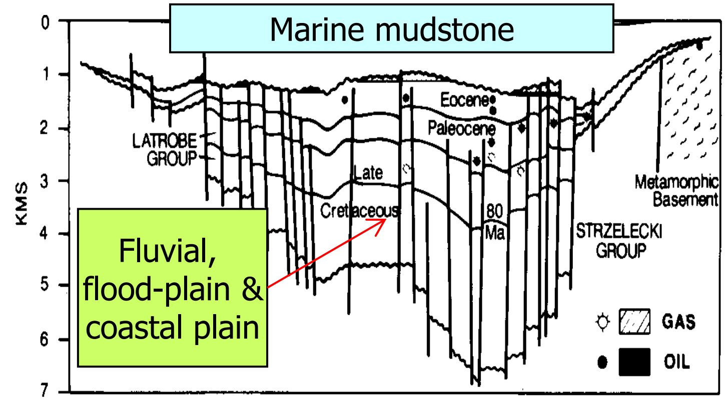


Continental rifts developed in temperate climates

Type basins - Gippsland, Falklands

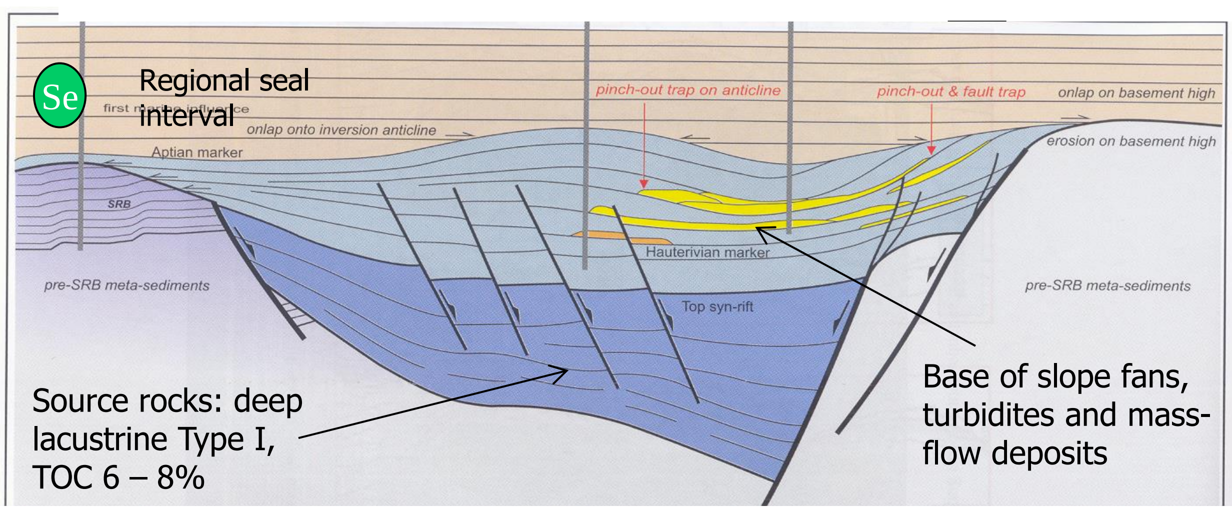
- Similar to the tropical families, but due to the higher latitudes at the time of deposition lacustrine oil-prone source rocks are less well developed or are replaced by alluvial / deltaic sediments.
- Found in many Mesozoic and early Tertiary provinces, forming the bases for oil and gas provinces in SE Australasia (60degrS) and on the southern South Atlantic margin (30-60degrS).





Continental rifts developed in temperate climates

Example – SE Australia, Gippsland Basin: Latrobe (!) Petroleum system

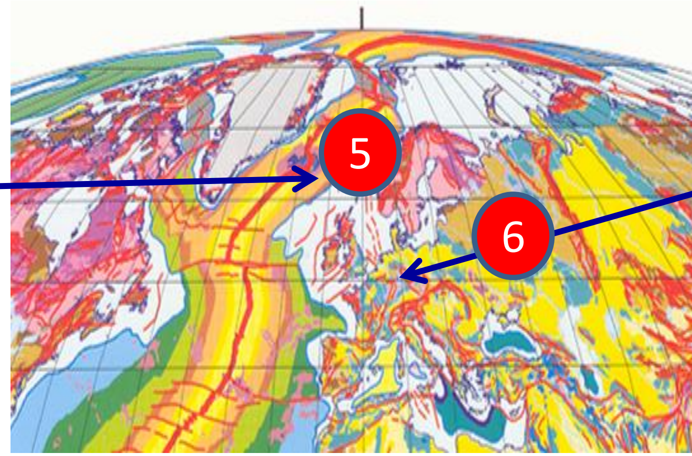


Example – South Atlantic Falklands Basin: Sea Lion Field

From: Petroleum Geoscience 21 (2-3) 2015

Deeper marine rifts developed on continental platforms

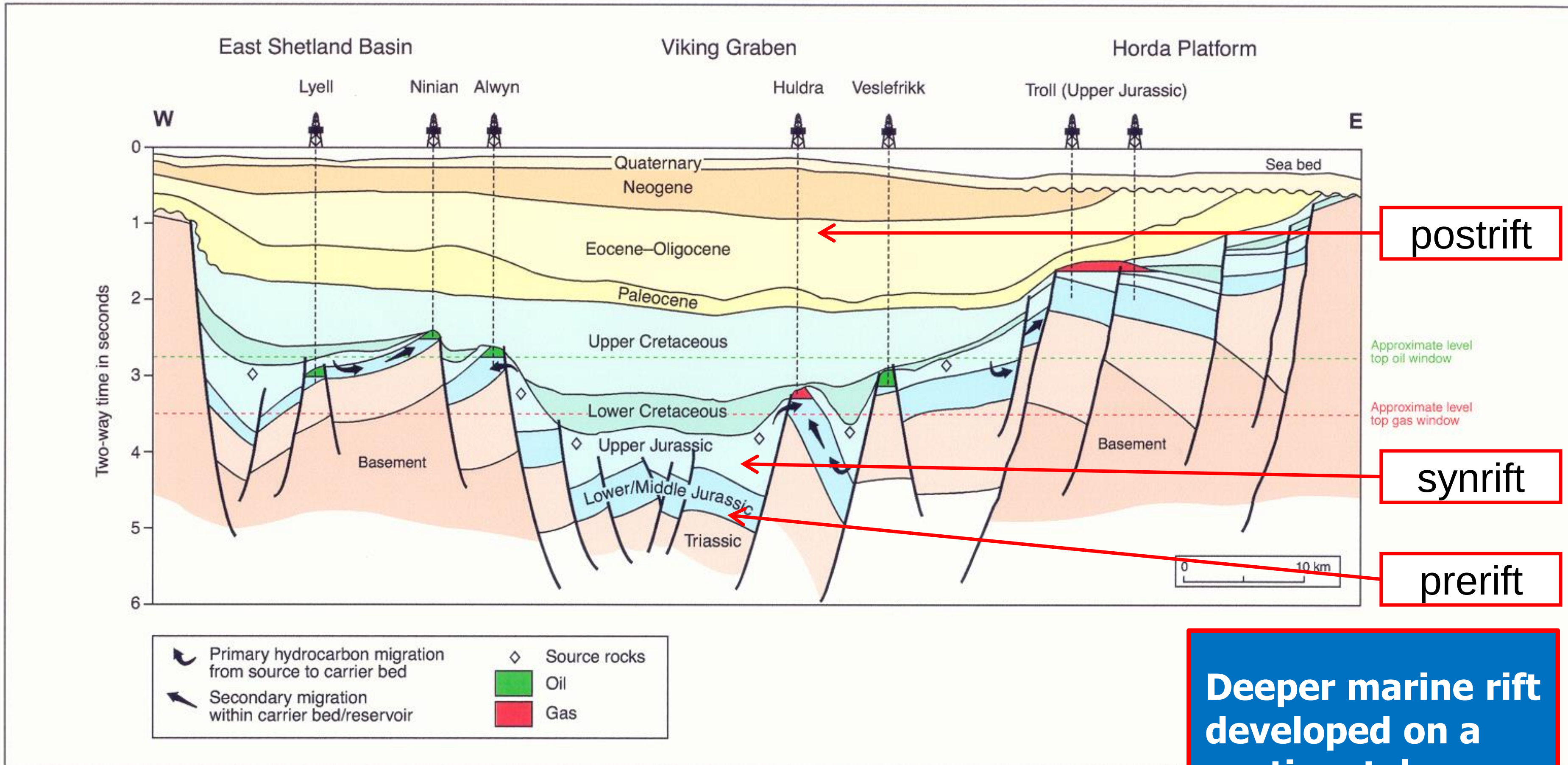
Type Basin – the northern North Sea



Shallower marine rifts developed on continental platforms

Type basins – the southern North Sea & NW Europe

- Exemplified by rifts on broad continental platforms & form failed rifts overlain by postrift sag cycles
- Rich petroleum provinces based on world-class deeper marine synrift source rocks deposited during extensive Mesozoic ocean anoxic events (OAEs)
- Rift stages are not evident; commonly the rift topography is filled in the postrift
- In shallower rifts and/or palaeogeograhically proximal situations source potential declines and rift topography is filled with shallower water or fluvial sediments
- The rift geometry allows for petroleum migration into pre-, syn- and post-rift cycles

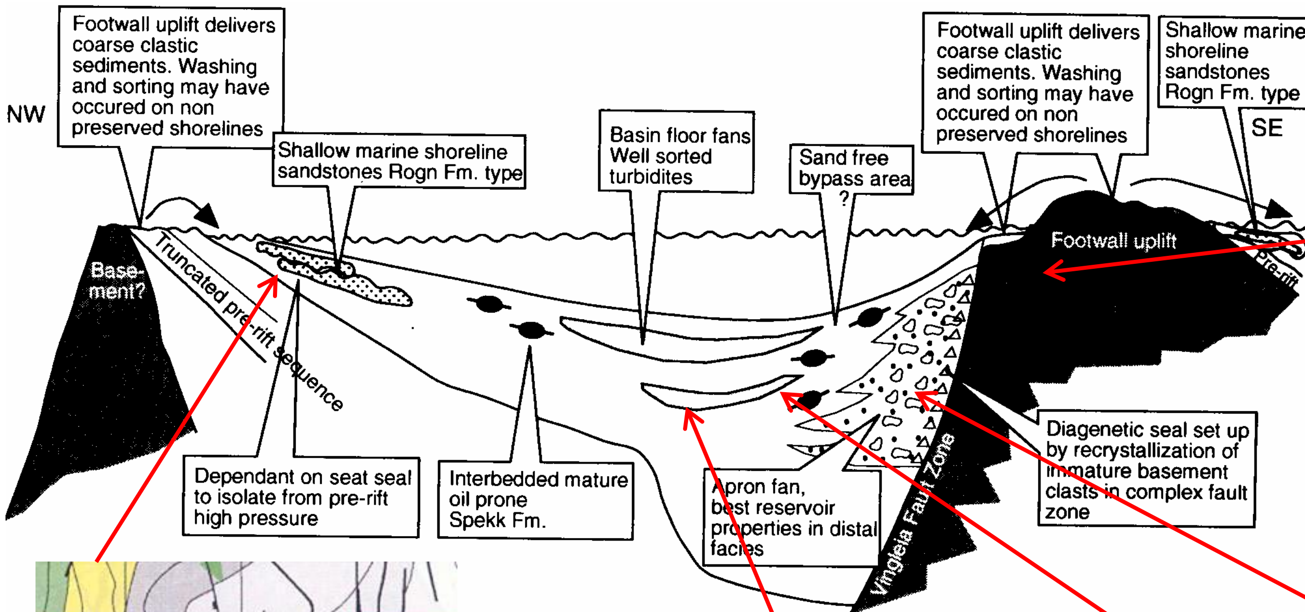


Deeper marine rift developed on a continental platform

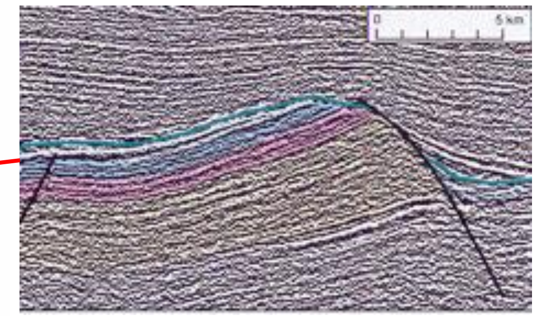
Example – N. North Sea Viking Graben , Synrift Kimmeridge – Brent (!)Petroleum System

Early to middle Jurassic pre-rift sandstones are sealed below Early Cretaceous shales. Charge is from Late Jurassic synrift source rocks into adjacent prerift fault blocks. The excellent combination of essential parameters and their favourable juxtaposition make this a most prolific petroleum province

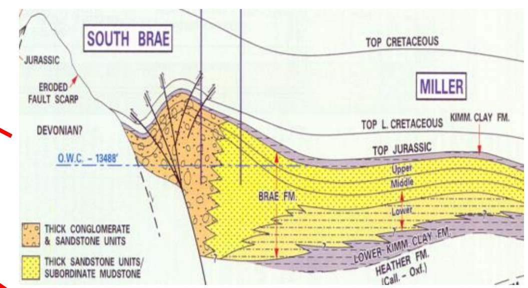
Syn-rift trap types in N. North Sea (offshore UK/Norway)



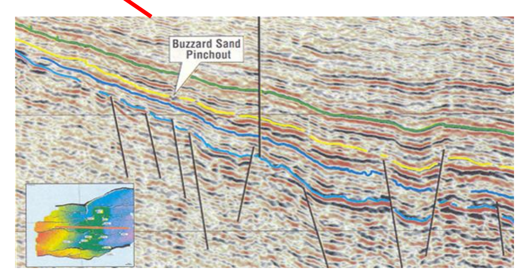
Brent



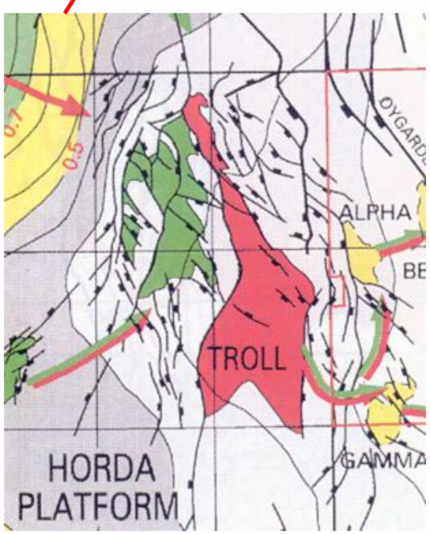
Brae



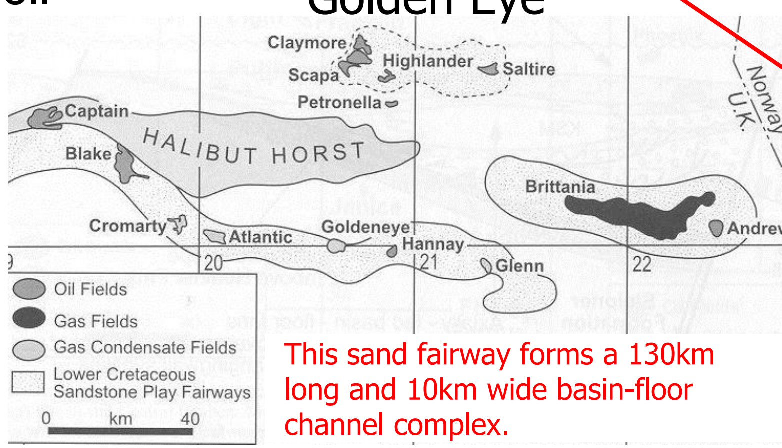
Buzzard



Troll

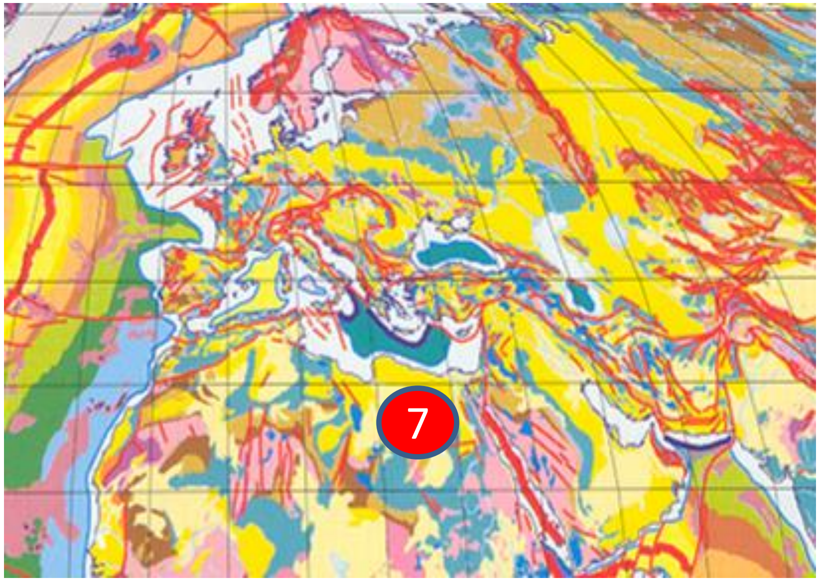


Golden Eye



This sand fairway forms a 130km long and 10km basin-floor channel complex.

From: Spencer et al. First Break 11 (5) 1993: 172



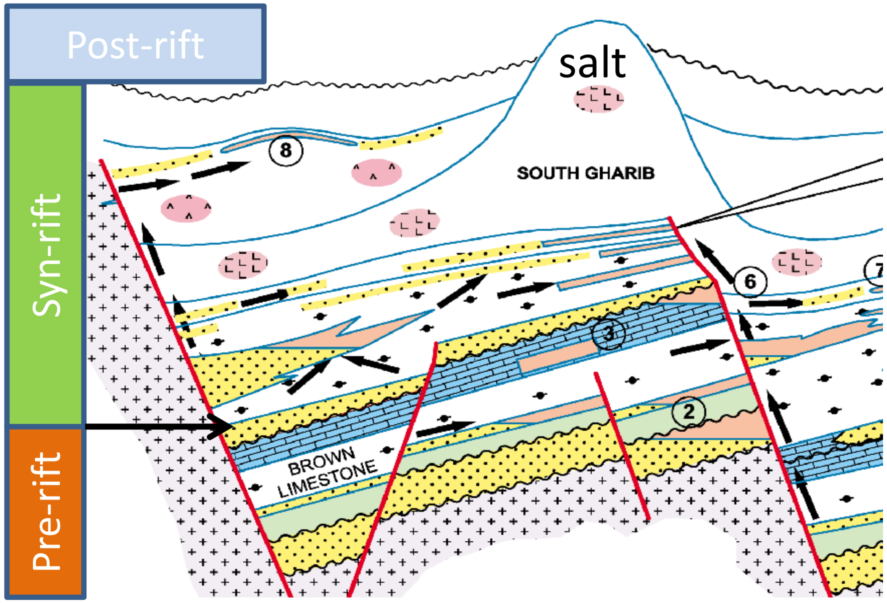
Continental –marine rifts developed in arid climates.

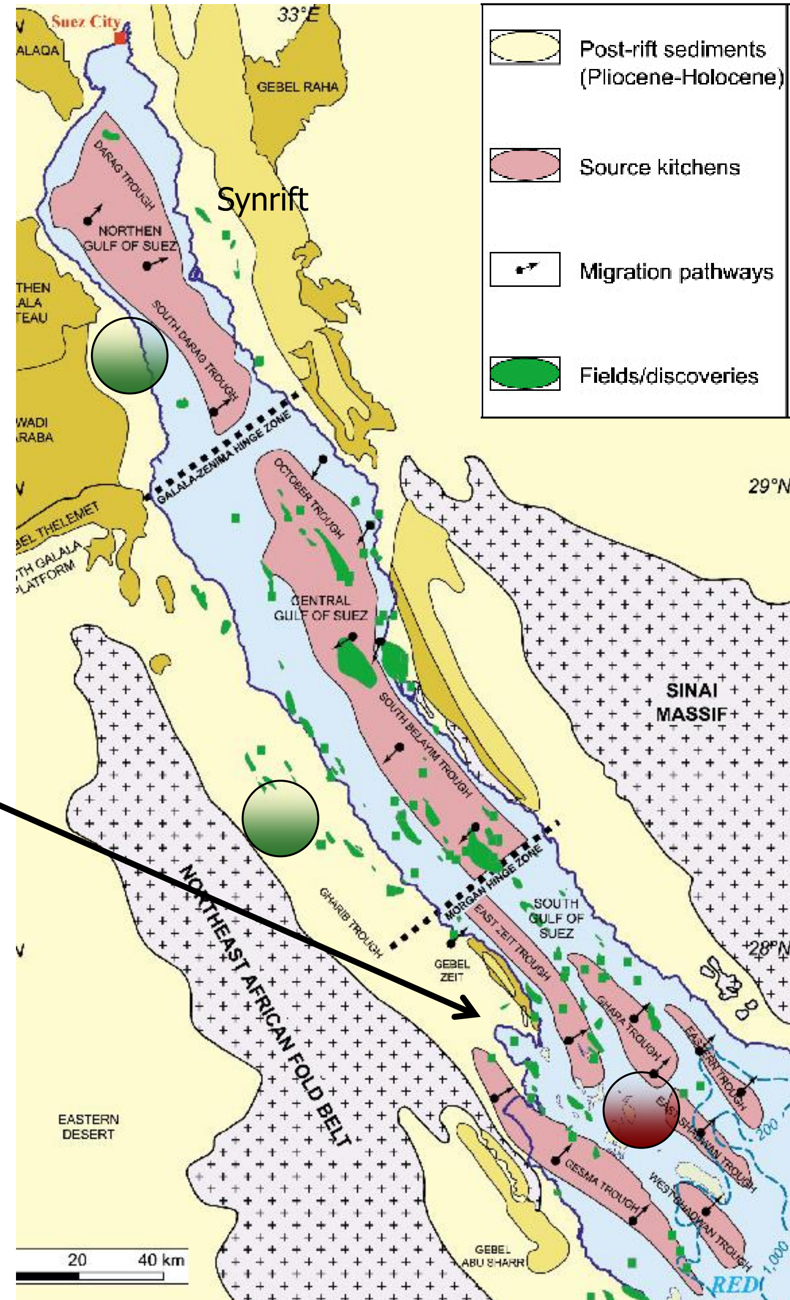
Examples: Gulf of Suez and several basins in Middle East and Europe

- The arid climate provides good to excellent reservoirs in wadi, fluvial and dune clastics. In appropriate palaeoclimates reef and platform carbonate reservoirs are developed.
- Source rocks are interbedded or are locally developed in deeper marine situations, but are often poorly developed; the main charge may be derived from pre-rift source rocks
- Salt and other evaporites provide excellent seals, but are sometimes inter-bedded and may inhibit vertical migration
- Are rarely inverted - most traps are related to pre-rift structural highs, drapes and stratigraphic pinch-outs
- The prerift can be charged laterally from synrift sources

Continental –marine rifts developed in arid climates.

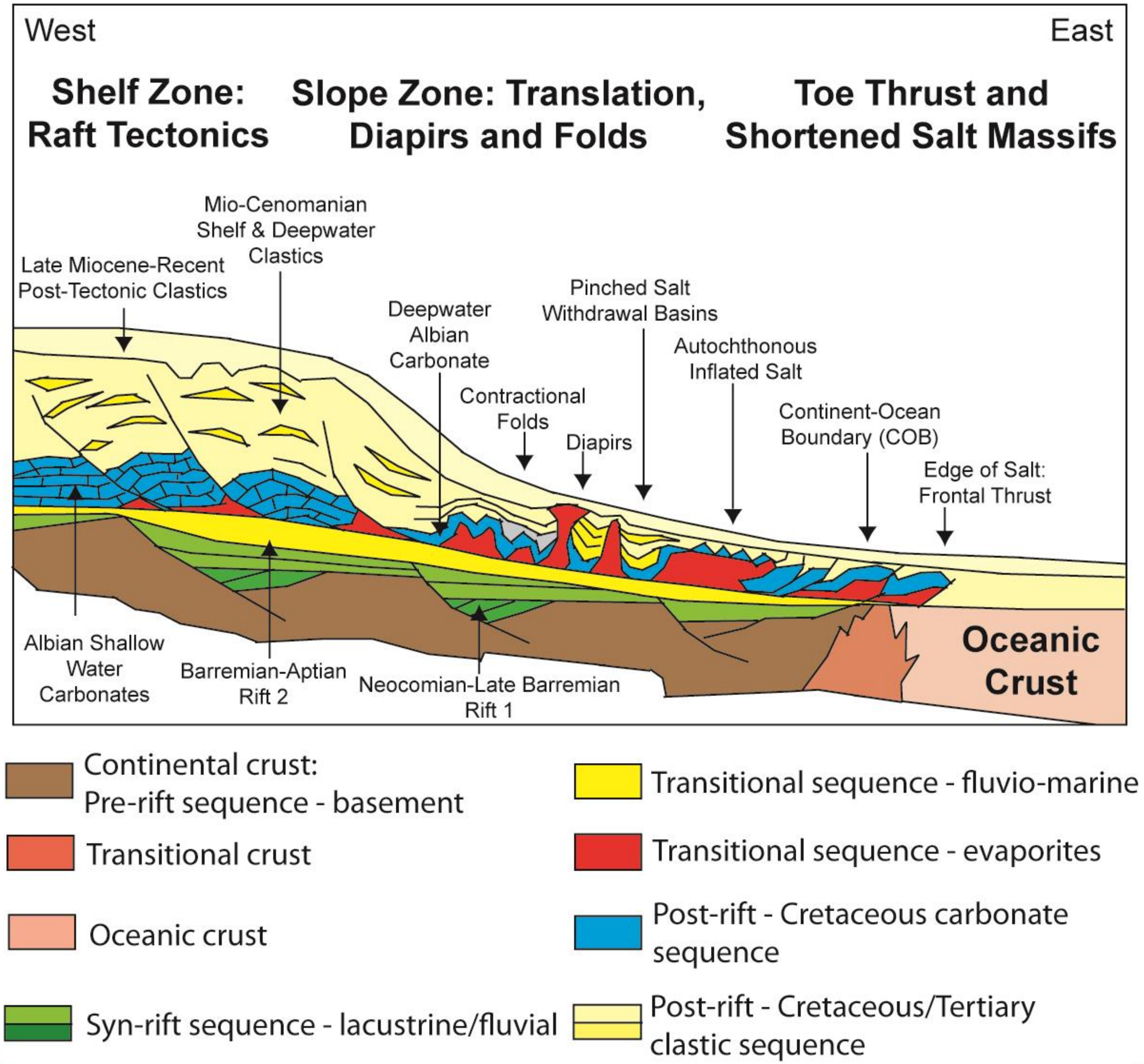
Example: Gulf of Suez, a complex of three separate rift basins





Synrift Petroleum system (Rudeis source rock)

Prerift petroleum system (Thebes source rock)



Summing up: Brazil: synrift and postrift passive margin cycles

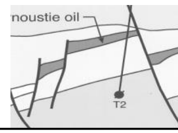
Synrift source rock charges both syn- and postrift reservoirs through gaps (windows) in transition sequence salt

From Beglinger thesis VU Amsterdam

..and what plays do they contain?

Basin Cycle / Characteristic trap types

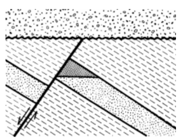
Pre-Rift



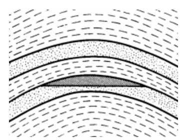
Horst Block

Synrift

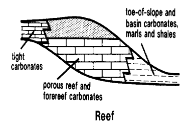
Rift Fault Block



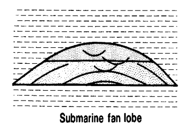
Anticline



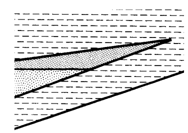
Carbonate Build-Up



Turbidite

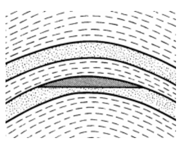


Stratigraphic Pinch-Out

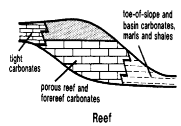


Transitional

Anticline

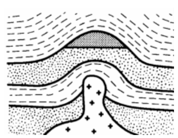


Carbonate Build-Up

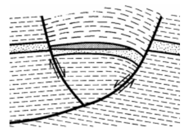


Postrift (marginal sag)

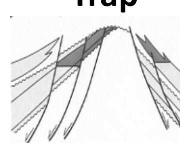
Salt-Rooted Anticline



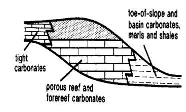
Growth Fault Rollover



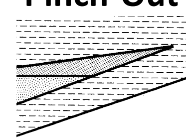
Combination Trap

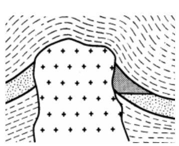


Carbonate Build-Up



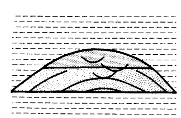
Stratigraphic Pinch-Out

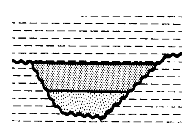




Salt Diapir Flank

Turbidite





Shale Channel Truncation

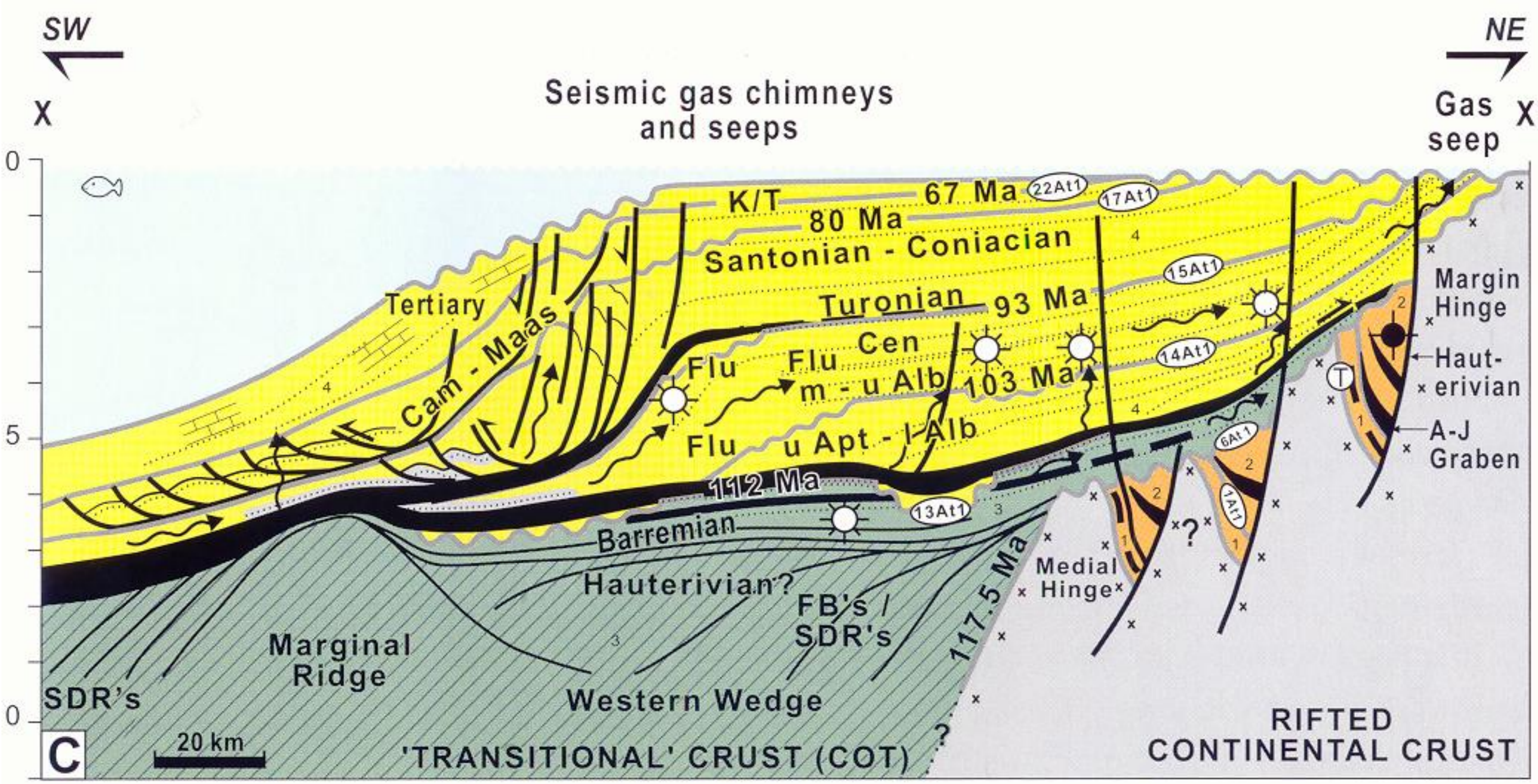
LACUSTRINE PETROLEUM SYSTEM

In the synrift here we see the same *basin cycle type* and same *petroleum system type* as in the SE Asian Tertiary basins

MARINE PETROLEUM SYSTEM

In the postrift here we have a good analogue *petroleum system type* for other passive margin cycles

Finally, its good to remember that not all postrift sediments overlie synrift grabens! The rift grabens may be isolated and eroded. Also that some related rifts may *not* be petroliferous, eg if volcanics are widespread, if alluvial facies are too dominant or if inversion has been too severe



Schematic profile across the central Orange Basin, showing the isolated nature of the synrift grabens (ochre colour)

Thank you for your attention during this brief review!

Current areas of investigation…

- Investigating the links between detailed rift sequence stratigraphy (thickness and facies) and periodicit of movements on individual faults and
- The nature and significance of flooding surface clays
- Linkage of subsidence rates to orientation and movement of main rift-defining faults
- Lags in reaction time between tectonic events and sedimentary responses
- Seismic facies characteristics of the synrift
- Thermal evolution models for different categories of rift basin