Relating Petroleum System and Play Development to Basin Evolution: West African South Atlantic Basins*

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Abstract

Sedimentary basins can be classified according to their structural genesis and evolutionary history and the latter can be linked to petroleum system and play development. West African South Atlantic basins between Cameroon and Namibia have experienced similar tectonic and sedimentary basin evolution and are genetically related. Four basin cycles have been identified (pre-rift, syn-rift, transitional and post-rift), each associated with at least one type of petroleum system (PST). Two PSTs are regionally extensive and very productive: the lacustrine syn-rift and marine post-rift PSTs, while three minor PSTs, the fluvio-marine transitional, restricted hypersaline transitional and deltaic post-rift PSTs, are locally developed.

Play development is closely related to basin tectonic and sedimentary evolution: syn-rift plays are associated with lacustrine/fluvial facies and trap geometries related to graben development, while post-rift plays include deltaic and shallow to deep marine clastic and carbonate facies in combination with traps which formed due to salt withdrawal. The number and variety of plays increases with basin evolution, as tectonics and sedimentary patterns become more complicated.

Three basin families have been identified. Basin family I includes a lacustrine syn-rift section, followed by a fluvio-marine sand/shale and a restricted hypersaline evaporite unit (the transitional section), and ultimately by a marine post-rift section. It contains the lacustrine syn-rift, fluvio-marine transitional and marine post-rift PSTs. Basin family II is characterized by the same basin evolution, but has a thick deltaic wedge in the latest post-rift phase, which gives rise to an additional PST: the deltaic postrift PST. Basin family III is defined by the same basin evolution as basin family I, except that the transitional section is dominated by shales instead of evaporites, which are the source for the restricted hypersaline transitional PST.

The Douala Basin, the pre-salt section of the Rio Muni and North Gabon Basin and the (ultra)-deep waters of the Ogooue Delta, and Lower Congo, Congo Fan and Kwanza Basin are under-explored areas with high exploration potential. In conclusion, the tectonic and sedimentary evolution of the individual West African South Atlantic basins has led to the development of similar PSTs and plays, which can be used as analogues for evaluating exploration opportunities in basins with similar geodynamic and sedimentary evolution.

Relating Petroleum System & Play Development to Basin Evolution: West African South Atlantic Basins

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Rationale & Methodology

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Sedimentary basins can be classified according to their structural genesis and evolutionary history.

Recognition of :

- Various stages in tectonostratigraphic development or megasequences separated by unconformities.
- Basic sedimentary patterns and structural styles.

Relating development of known hydrocarbon habitats to these basic patterns.

Identification basin families used for broad scale analogue comparison of petroleum system & play development in basins with a similar geological history.

- **Aid in recognizing common petroleum system types with related parameters, as well as plays likely to be associated with them.**
- **Assist in evaluation of exploration opportunities in un- and under-explored rift basins.**

Geological Setting

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Non-volcanic West African South Atlantic Margin (Cameroon -> Angola):

- Douala Basin
- Rio Muni Basin
- Gabon Coastal Basin
- Lower Congo Basin
- Congo Fan Basin
- Kwanza Basin
- Namibe Basin

Modified after IHS-EDIN GIS & Google Earth (2009)

Notes by Presenter:
Our study area encompasses the non-volcanic West African South Atlantic Margin, extending from New Guinea in the north till the Walvis Ridge in the south. The basins along this margin are the Douala, Rio Muni, Gabon Coastal, Lower Congo, Congo Fan, Kwanza and Namibe basins.

Tectonic Basin Evolution

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Basin Cycles	Events	Time
Post-rift (Late Cretaceous - Tertiary) *(Marginal Sag)*	- Halokinesis: * Distorted post-rift strata. * Determined patterns of fan- and turbidite deposition. - Post-rift III: Increase clastic input, due to uplift/tilt African continent. - Post-rift II: Deeper marine clastic deposition. - Post-rift I: Carbonate platform on shelf. - Continuation of opening of the South Atlantic.	~112 Ma
Transitional (Aptian) *(Interior Sag)*	- Northward propagation of oceanic emplacement. - Deposition of fluvio-marine sands/shales followed by evaporites in a region of poorly circulating waters north of the Walvis Ridge.	~126 Ma
Syn-rift (Late Jurassic - Early Cretaceous) *(Interior Fracture)*	- Extensional break up of African and South American continents, initiated by a thermal doming event, followed by at least two active rifting episodes. - Deposition of alluvial, fluvial and lacustrine sediments.	~133 Ma
Pre-rift (Permain, Triassic & Jurassic) *(Interior Sag)*	- Formation of localized sag basins.	

Notes by Presenter:
As it turns out, the main geodynamic drivers shaping these basins are the same.

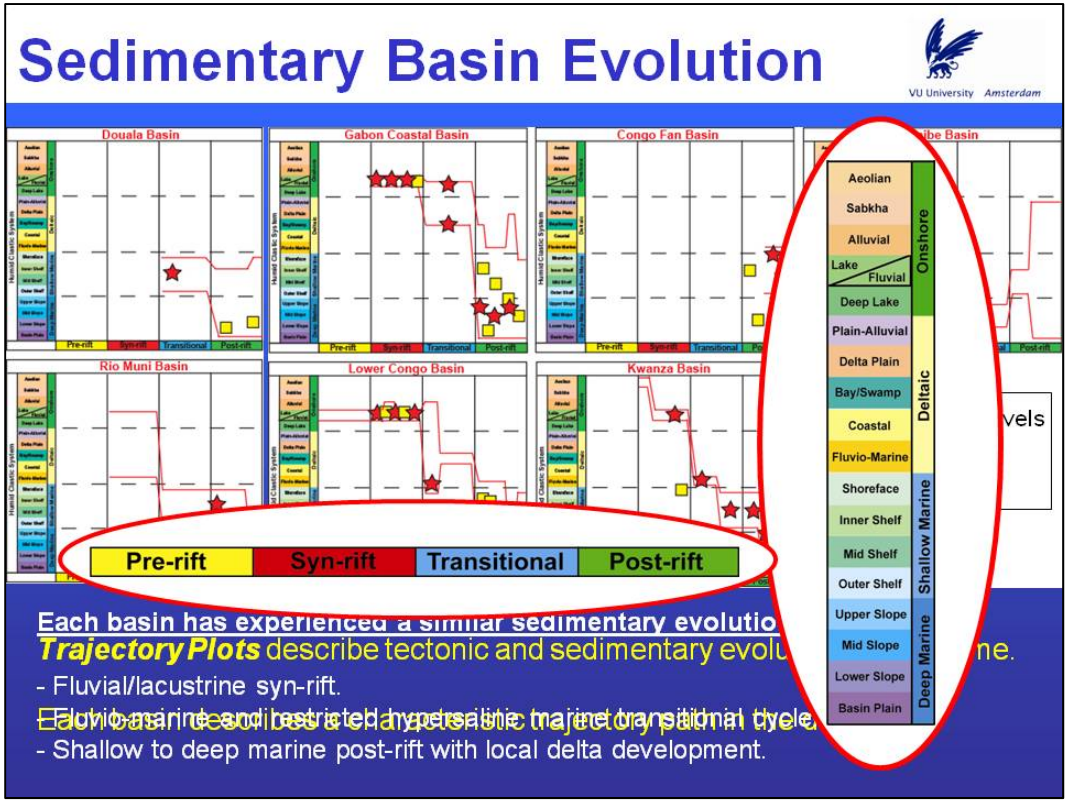
During the pre-rift reactivation of zonal weaknesses in the Precambrian basement of the Super-continent Gondwana took place, which resulted in the formation of localized sag basins and continental deposition.

The syn-rift is characterized by the extensional break up of the African and South American continents, which was initiated by a thermal doming event, and followed by at least two active rifting episodes. The syn-rift stratigraphic section is characterized by alluvial, fluvial and lacustrine sediments. (Notes continued on next slide)

(Notes continued from previous slide)
The transitional period is characterized by northward propagation of oceanic emplacement as continental break up was a fact. An interior sag basin architecture developed. The oldest sediments associated with this cycle involves fluvio-marine sands and shales, followed by a thick evaporite unit. These evaporites were deposited in a region of poorly circulating waters north of the Walvis Ridge.

During the post-rift the opening of the South Atlantic continued. The first stage of the post-rift is characterized by the development of a carbonate platform on the shelf. The second stage is associated with deeper marine clastic deposition. The last stage of the post-rift saw an increased input of clastic sediments due to uplift and tilting of the African continent.

During the post-rift, the evaporites of the transitional cycle started to move under the weight of the deposited post-rift sediments. This process was responsible for the creation of various trap types within the post-rift section, mainly extensional structures in the upper margin and compressional structures in the deeper basinal parts. Further, they also influence the patterns of deposition of fan- and turbidite systems.



Notes by Presenter:
Trajectory plots describe tectonic and sedimentary basin evolution through time. In these diagrams we find the basin tectonic cycle on the horizontal axis, and deepening depositional environment downwards along the vertical axis. The area between the red lines indicates the depositional environments which have been recognized in each basin cycle.

Each basin is characterized by a characteristic trajectory path in such a diagram. However, it seems that the basins along the West African Margin have all experienced a similar sedimentary evolution. Of course, there are some differences, but the main trend involves a fluvial/lacustrine syn-rift, a fluvio-marine and restricted hypersaline transitional cycle and a shallow to deep marine post-rift with local delta development.

In the diagrams, the most important source and reservoir rock levels are also indicated.

Sedimentary Basin Evolution

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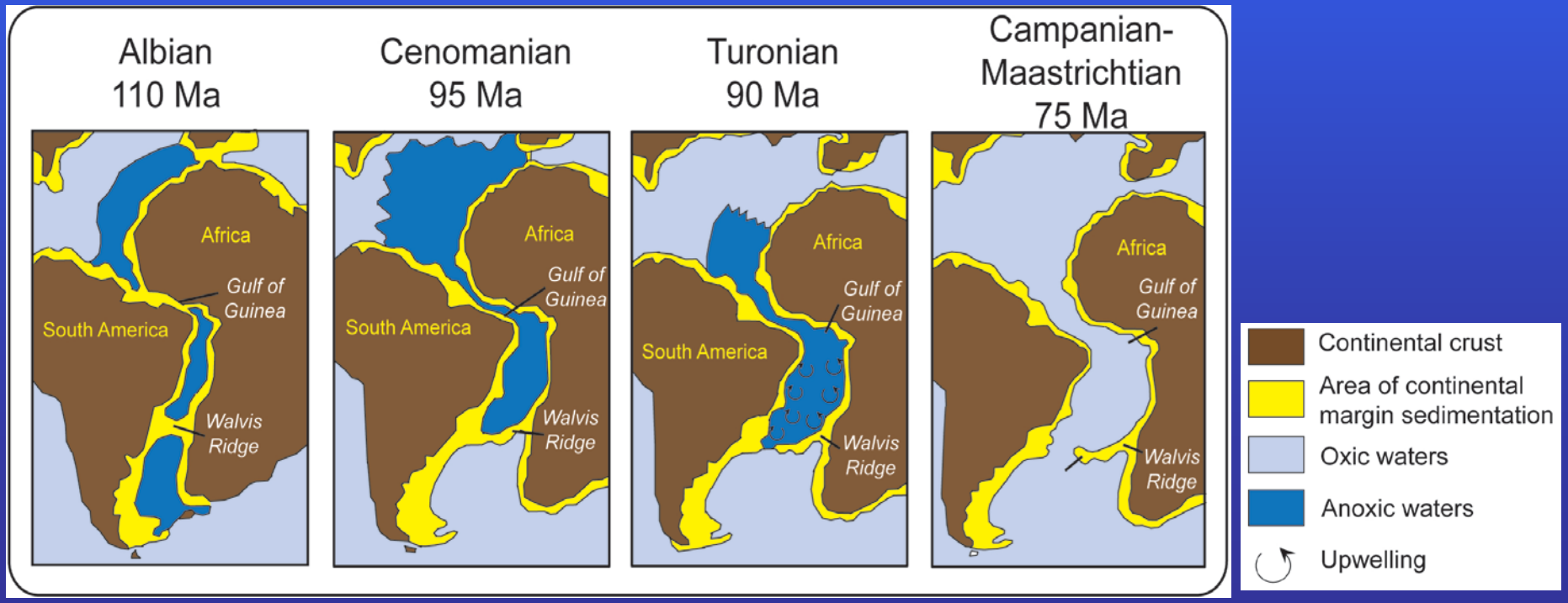
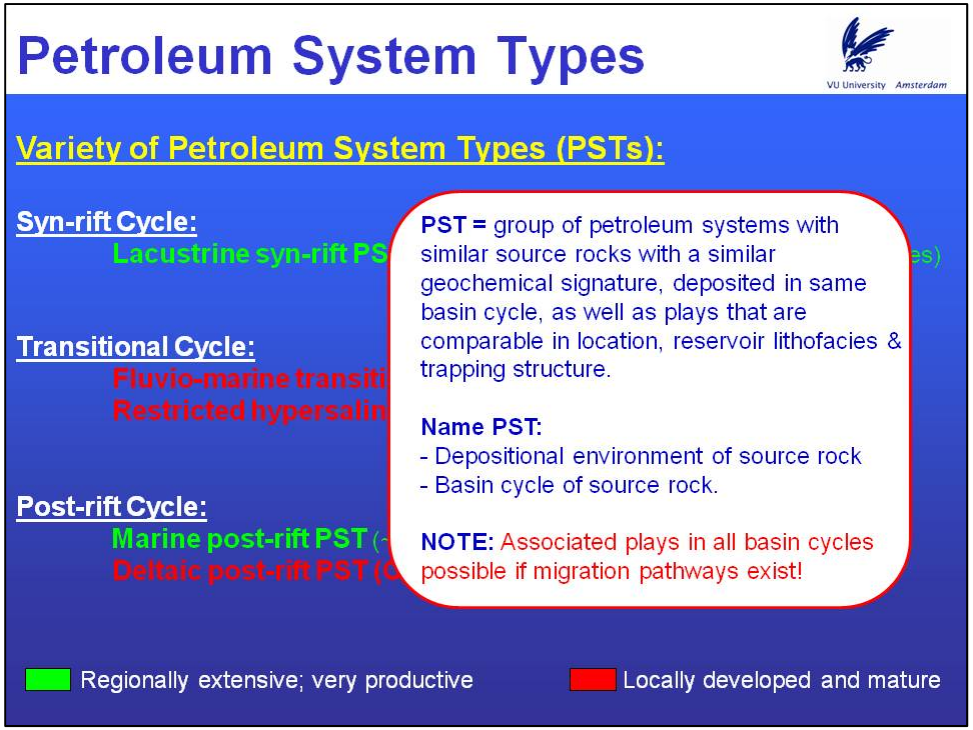
Similar tectonostratigraphic basin evolution led to the development of many equivalent source-, reservoir- & seal rock intervals

Source rock development of different origins is remarkably consistent, due to:

- Climatic conditions.
- Restricted water circulation during most of basin evolution.



http://pubs.usgs.gov/publications/txt/historical.html; Brownfield & Charpentier, 2006; modified from Tissot et al., 1980



Notes by Presenter:
What does this mean for the actual petroleum systems which were able to developed in this area?

In the West African South Atlantic basins a variety of petroleum systems has been able to develop. Each petroleum systems is charged by a source rock which is characteristic of the basin cycle it was deposited in.

Two regionally extensive and very productive petroleum system types have been identified in the syn-rift and post-rift cycles: the lacustrine syn-rift PST and marine post-rift PST.

Additionally, three locally developed petroleum system types have been identified, which are the fluvio-marine transitional PST in the Kwanza Basin, the restricted hypersaline transitional PST in the Douala Basin and the deltaic post-rift PST in the Congo Fan Basin.

I will discuss in detail the two most important petroleum system types: the lacustrine syn-rift and marine post-rift PSTs.

Petroleum System Types

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Lacustrine syn-rift PST:

Source:
Syn-rift lacustrine shales.

Generation/Migration:
Albian or short after.

Reservoirs:
- Syn-rift,
- Transitional, and
- Post-rift cycles.

Seal:
- Evaporites of transitional cycle, and
- Intraformational lacustrine, deltaic & marine shales.

Trap Formation:
- Related to graben development (syn-rift) and halokinesis (post-rift).
- Before/during/after source rock deposition.

Marine post-rift PST:

Source:
Early post-rift marine shales/marls.

Generation/Migration:
10-20 Ma.

Reservoirs:
- Post-rift cycle.

Seal:
- Intraformational deltaic & marine shales.

Trap Formation:
- Related to halokinesis (post-rift).
- Just after source rock deposition.

Notes by Presenter:
Let's first consider the lacustrine syn-rift PST. On the right, you find the event charts of some petroleum systems typical of this petroleum system type, summarizing the timing of deposition and formation of the different elements and the timing of different processes involved.

This PST is charged by hydrocarbons generated by lacustrine syn-rift shales. Generation and migration started in the Albian or short after. The reservoirs are located in the syn-rift, transitional cycle, but also in the post-rift cycle. The seal is provided by the regionally extensive evaporites of the transitional cycle, as well as by intra-formational shales occurring throughout the stratigraphy. The formation of traps in the syn-rift is associated with graben development, and in the post-rift with salt-movements, and took place before, during and after source rock deposition. The critical moment of such a petroleum system is at around ~95 Ma.

Petroleum System Types

Petroleum System Type	Basin	Reason for Existence	Potential for other West African South Atlantic Basins	Risk
Fluvio-Marine Transitional PST	Kwanza Basin	Organic-rich fluvio-marine shales between the Aptian Unconformity and the Evaporites.	Identified in most basins	Thickness
				Maturity

Plays

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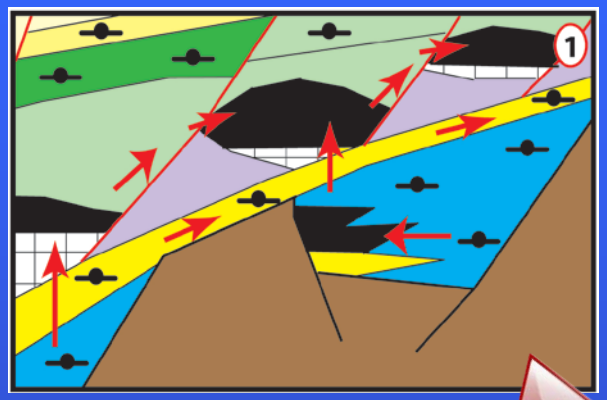
Plays are characteristic of the basin cycle in which they occur!

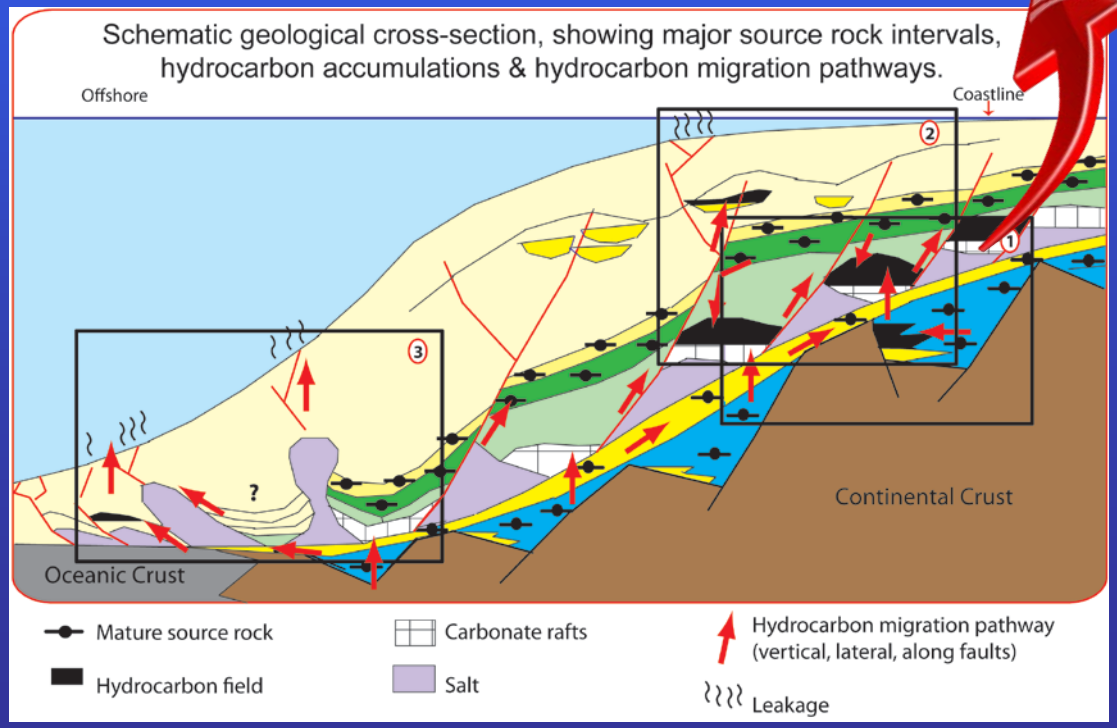


Syn-rift Plays

Reservoir Lithofacies (Play Level):
- Lacustrine sandstone
- Fluvial sandstone

Trap Formation:
- Graben development
- Fast changing facies configurations

Characteristic Trap Types:
- Anticline
- Tilted fault block
- Fault limited closure
- Palaeotopography
- Stratigraphic/diagenetic facies changes



After Tari et al., 2003; Dickson et al., 2003.

Plays

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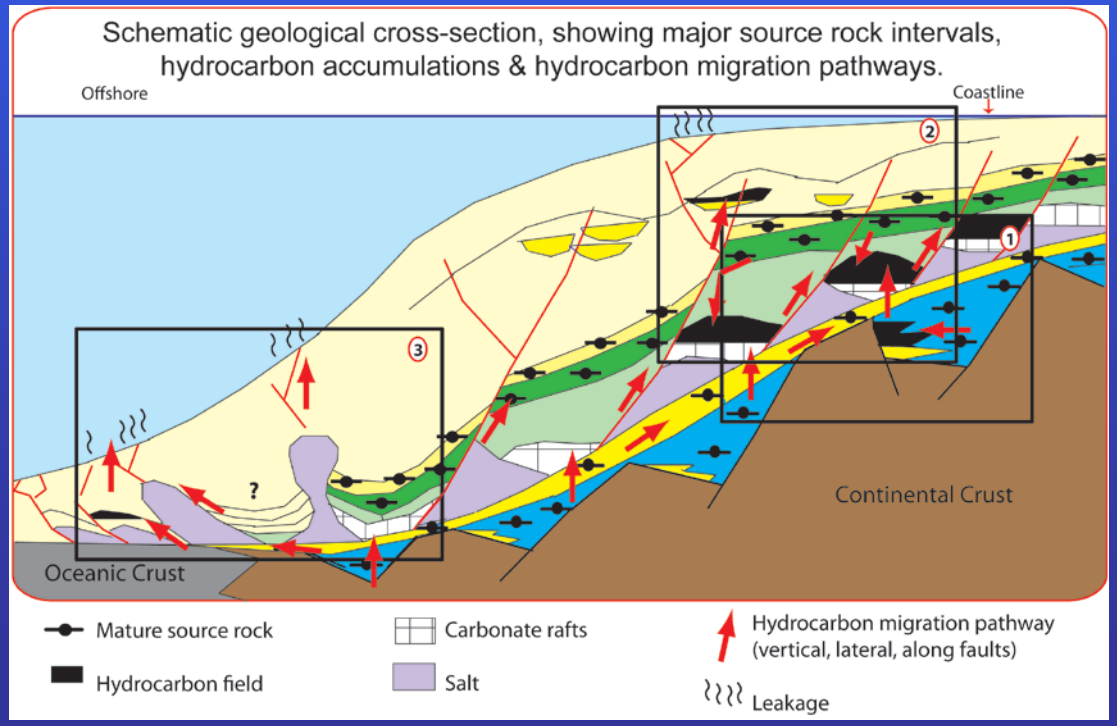
Plays are characteristic of the basin cycle in which they occur!

Transitional Plays

Reservoir Lithofacies (Play Level):
- Fluvio-marine sandstone
- Restricted marine sandstone

Trap Formation:
- Last waning stage of rifting
- Halokinesis

Characteristic Trap Types:
- Tilted fault block
- Fault limited closure
- Paleotopography
- Unconformity bounded structure



After Tari et al., 2003; Dickson et al., 2003.

Plays

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Plays are characteristic of the basin cycle in which they occur!

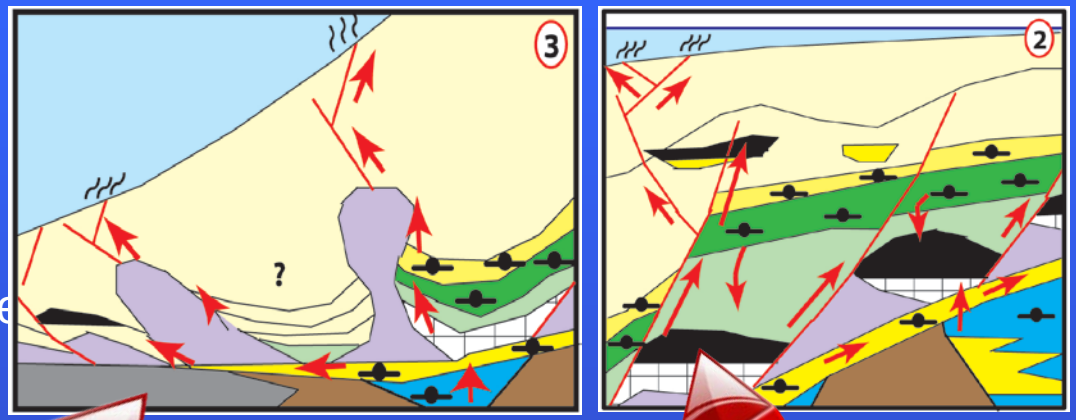
Post-rift Plays (Cretaceous)

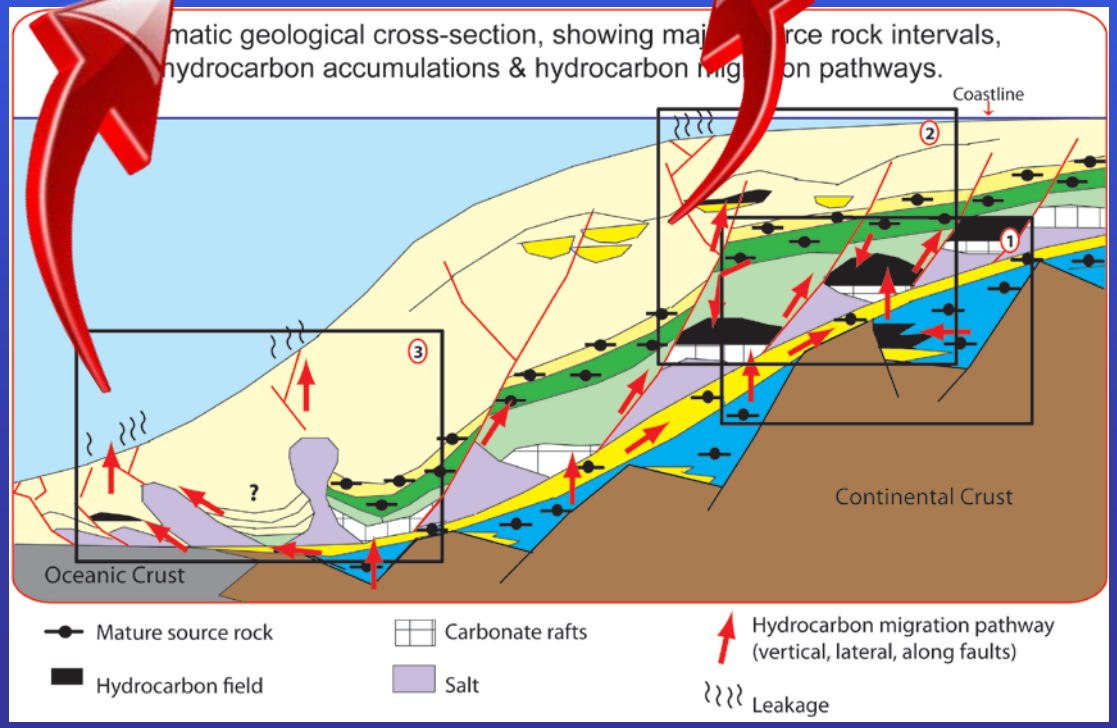
Reservoir Lithofacies (Play Level):
- Carbonate build up
- Shallow to deep marine sandstone

Trap Formation:
- Halokinesis

Salt tectonic domains: extensional structures up margin & linked compressional structures basinward.

Characteristic Trap Types:
- Tilted fault block
- Fault limited closure
- Paleotopography
- Unconformity bounded structure





After Tari et al., 2003; Dickson et al., 2003.

Plays

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Plays are characteristic of the basin cycle in which they occur!

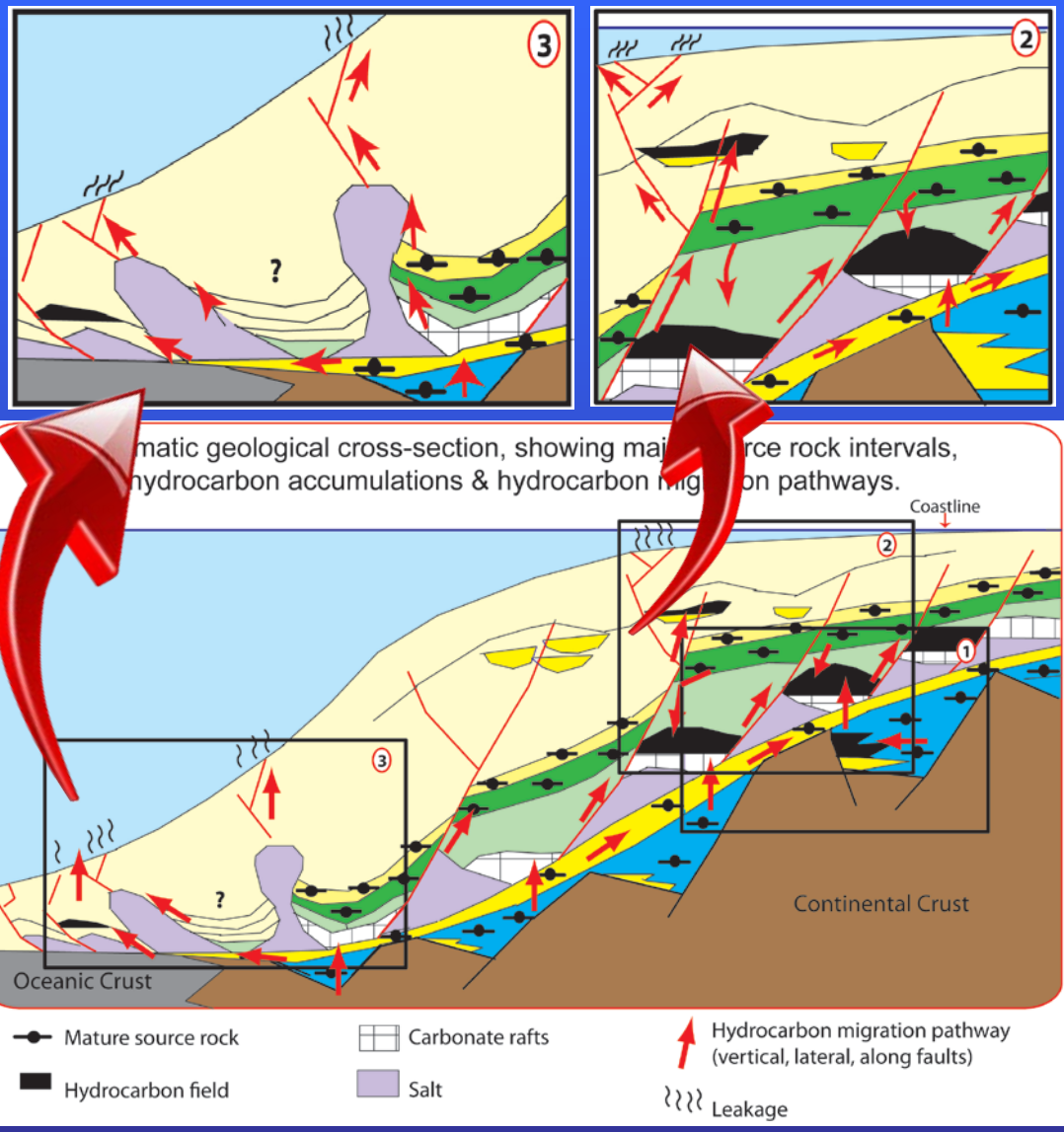
Post-rift Plays (Tertiary)

Reservoir Lithofacies (Play Level):
- Deltaic & Deep water sandstone

Trap Formation:
- Halokinesis
- Delta development

Characteristic Trap Types:
- Anticline
- Tilted fault block
- Depositional pinch outs
- Turbidite/channel geometries

Note: migration pathways from syn-rift to post-rift due to salt windows.



After Tari et al., 2003; Dickson et al., 2003.

Plays

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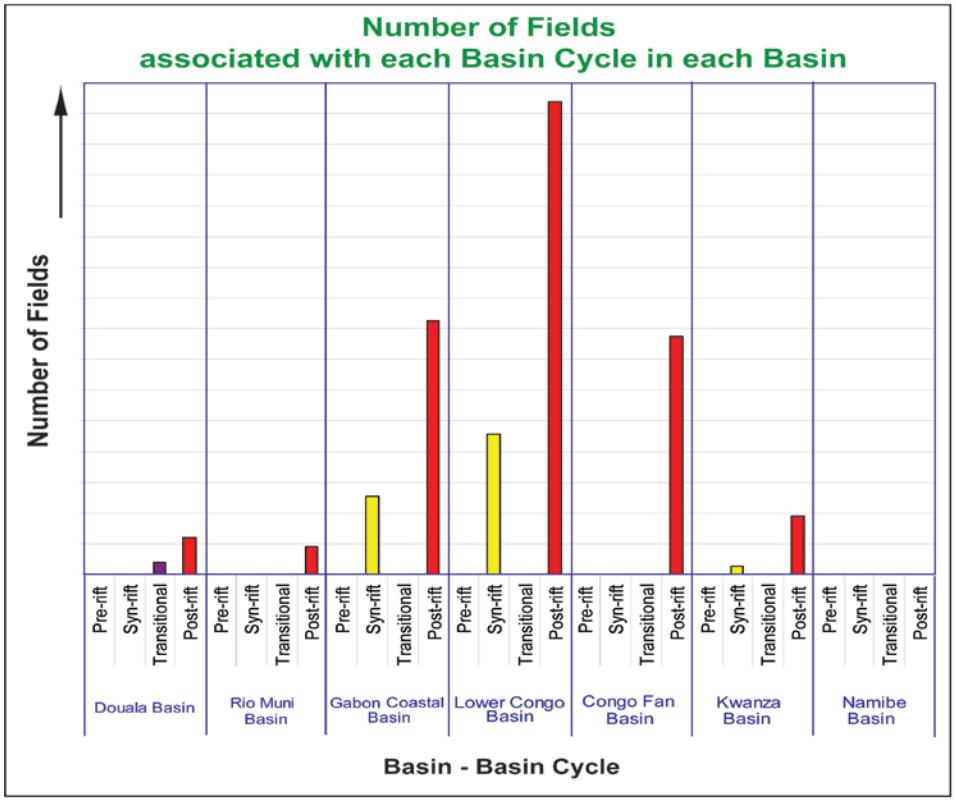
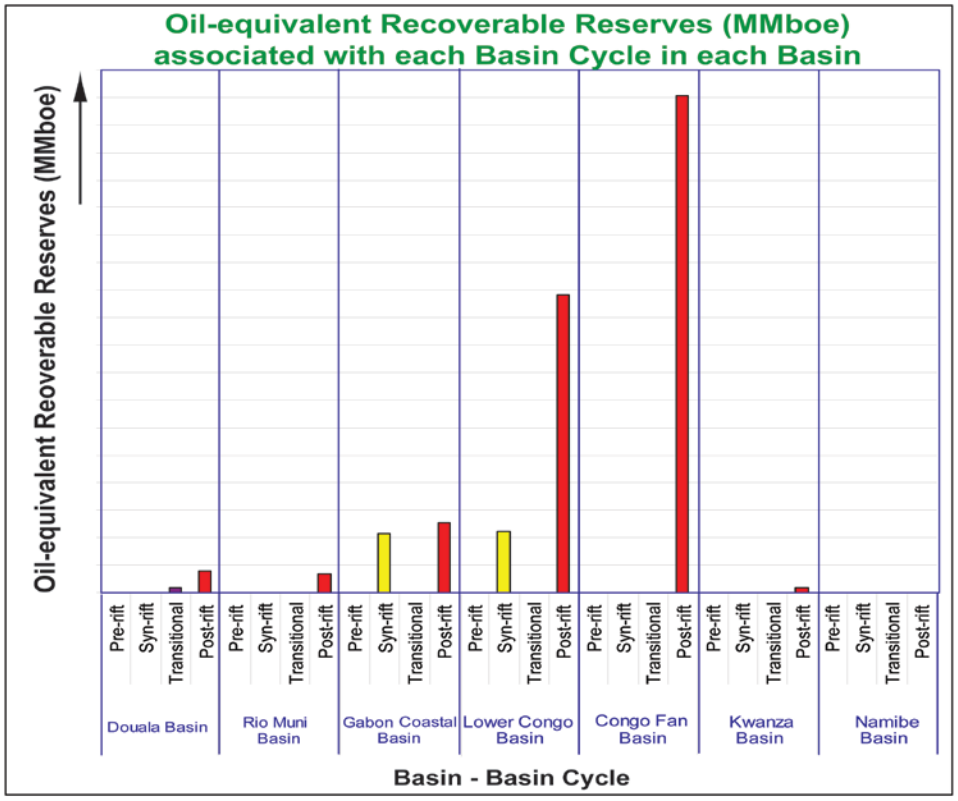
Most fields and hydrocarbon recoverable reserves are situated within the post-rift section!





Many more different types of post-rift plays than syn-rift plays:

- Increasing variety of depositional environments with basin evolution, providing more potential different reservoir lithofacies.
- Increasingly complexity of trap-forming tectonics: halokinesis.

Basin Families

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Linking petroleum system and play development to basin evolution, allows recognition of 3 basin families:

Non-Volcanic West African South Atlantic Margin			
	Basin Family I	Basin Family II	Basin Family III
Stratigraphy	* Syn-rift cycle: lacustrine. * Transitional cycle: thin fluvio-marine sands/shales + thick evaporite layer. * Post-rift cycle: shallow to deep marine.	* Syn-rift cycle: lacustrine. * Transitional cycle: thin fluvio-marine sands/shales + thick evaporite layer. * Post-rift cycle: shallow to deep marine + thick deltaic wedge.	* Syn-rift cycle: lacustrine. * Transitional cycle: shales dominating over or inter-fingering with evaporites deposited in a restricted hypersaline environment. * Post-rift cycle: shallow to deep marine.
	* Lacustrine syn-rift PST	* Lacustrine syn-rift PST	* Lacustrine syn-rift PST
Basin Example	* Gabon Coastal Basin * Lower Congo Basin * Kwanza Basin * Namiba Basin		

The recognition of basin families allows for qualitative analogue comparison between basins with a similar tectono-stratigraphic background with respect to prospectivity.

Notes by Presenter:
Putting all this information together, and linking petroleum system and play development to basin evolution, I have recognized three different basin families which are essentially similar.
Basin family I is characterized by a lacustrine syn-rift, a fluvio-marine and restricted hypersaline transitional cycle and a shallow to deep marine post-rift. The PSTs which develop in such a basin family include the lacustrine syn-rift PST, fluvio-marine transitional PST and marine post-rift PST. (Notes continued on next slide)

(Notes continued from previous slide)
Basin family II is characterized by the same basin evolution as basin family I, except for the development of a thick deltaic wedge during the late post-rift. The same PSTs develop, except for an additional deltaic post-rift PST.

Basin family II also has the same basin evolution as basin family I, but the transitional cycle was dominated by shales instead of evaporites, and these shales are responsible for an extra PST, namely the restricted hypersaline transitional PST.

Basin Petroleum Volumes

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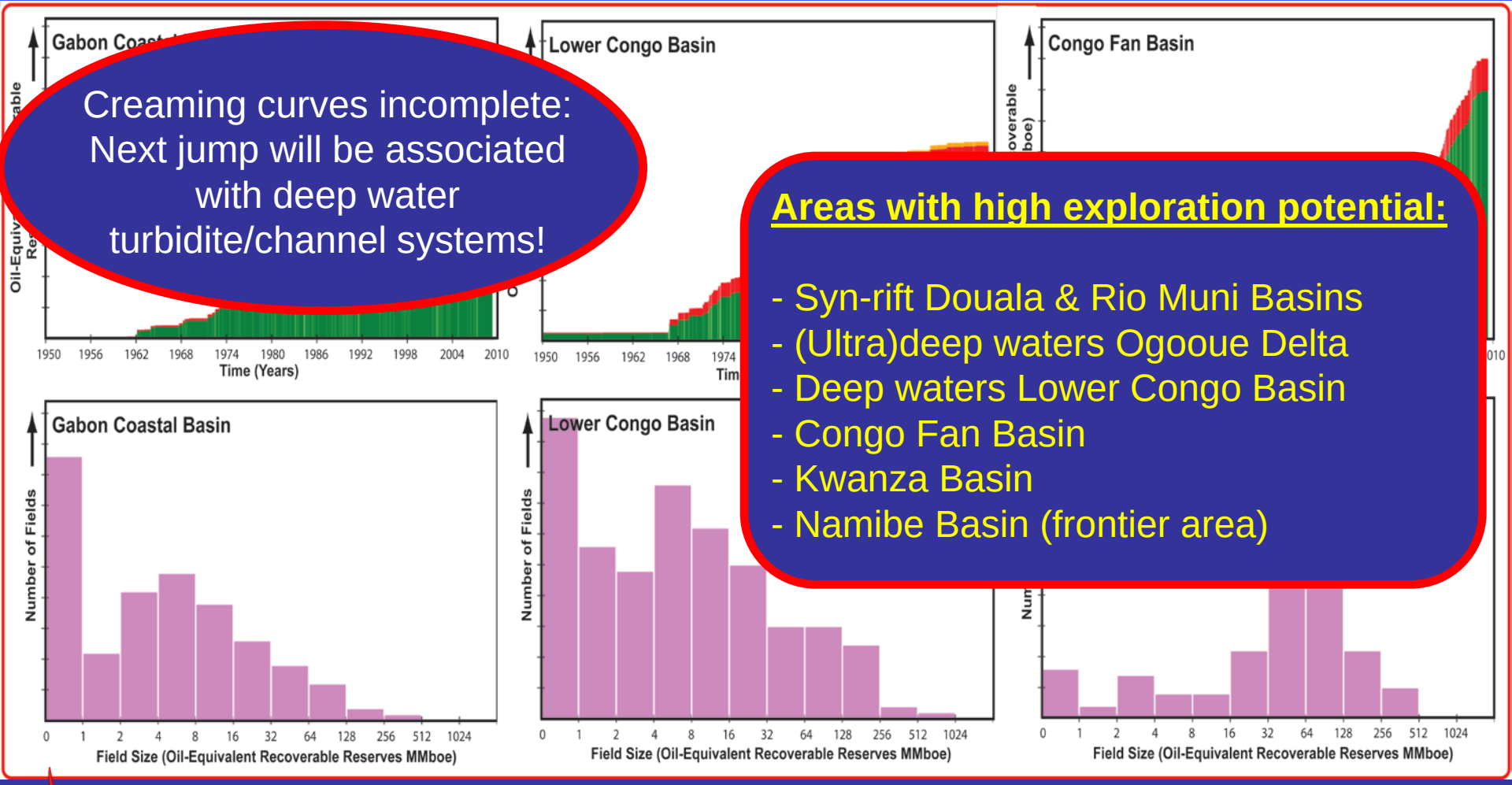
Creaming Curves & Field Size Distribution Diagrams



Creaming curves incomplete: Next jump will be associated with deep water turbidite/channel systems!

Areas with high exploration potential:

- Syn-rift Douala & Rio Muni Basins
- (Ultra)deep waters Ogooue Delta
- Deep waters Lower Congo Basin
- Congo Fan Basin
- Kwanza Basin
- Namibe Basin (frontier area)

- Gabon Coastal & Lower Congo basins seems to become mature with respect to exploration.
- Explosive exploration success in Congo Fan: no sign of maturing exploration.

Conclusions

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Similar tectonic and sedimentary evolution has led to the development of similar PSTs and plays in the West African South Atlantic basins.

- 4 Basin cycles, each associated with at least one PST:
  - *2 Regionally extensive & very productive.*
  - *3 Developed locally.*

Basin Cycle	Petroleum System Type
Post-rift	Deltaic Post-rift PST
	Marine Post-rift PST
Transitional	Restricted Hypersaline Marine Transitional PST
	Fluvio-Marine Transitional PST
Syn-rift	Lacustrine Syn-rift PST
Pre-rift	-

- Play development is closely related to basin tectonic and sedimentary evolution.
- Number and variety of plays increases with basin evolution, as tectonic and sedimentary patterns become more complicated!
- 3 Basin families with slightly different tectonostratigraphic evolution & occurrence of different combinations of PSTs; Useful for analogue comparison purposes.

Notes by Presenter:
In conclusion: The similar tectonic and sedimentary evolution of the individual West African South Atlantic Margin basins has led to the development of similar petroleum system types and plays in these basin.

We were able to recognize 4 different basin cycles, each associated with the source rocks charging a certain petroleum system type. Two regionally extensive and very productive petroleum system types have been identified, and three minor ones.
(Notes continued on next slide)

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Further, we have seen that play development is closely related to basin tectonic and sedimentary evolution. This is especially clear in the syn-rift and post-rift section. Within the syn-rift the play level is provided by lacustrine and fluvial clastics, and trap formation is related to graben development. In the post-rift, deltaic and shallow to deep marine clastics and carbonate provide the reservoir lithofacies, and the trapping structures were able to develop due to halokinetic movements and delta development.

We have also seen that the number and variety of plays increases with basin evolution, as tectonic and sedimentary patterns become more complicated.

Further, we have identified three basin families with slightly different tectonostratigraphic evolution and occurrence of different combinations of petroleum system types.

Conclusions

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Exploration density is not uniform across the West African South Atlantic Margin.

Areas remaining with high exploration potential:

- *Deep water turbidite systems.*
- *Syn-rift sections with not too thick post-rift overburden.*

Analogue basin cycle comparison is useful tool when evaluating exploration opportunities in basins with similar geodynamic and sedimentary evolution.

Analogue comparison to:

- *South American Atlantic Margin, and*
- *Southeast Asian Tertiary Basins.*

Notes by Presenter:
And at last we have seen that exploration density is not uniform across the West African South Atlantic Margin.

Many areas still remain which are under-explored and though to have high exploration potential. The focus should especially lie on the deep water turbidite system, which are now also extensively being explored in the Congo Fan Basin.

Thank You!

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