South Atlantic Margin Rift Basin Asymmetry and Implications for Pre-Salt Exploration*

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Search and Discovery Article #30112 (2010)
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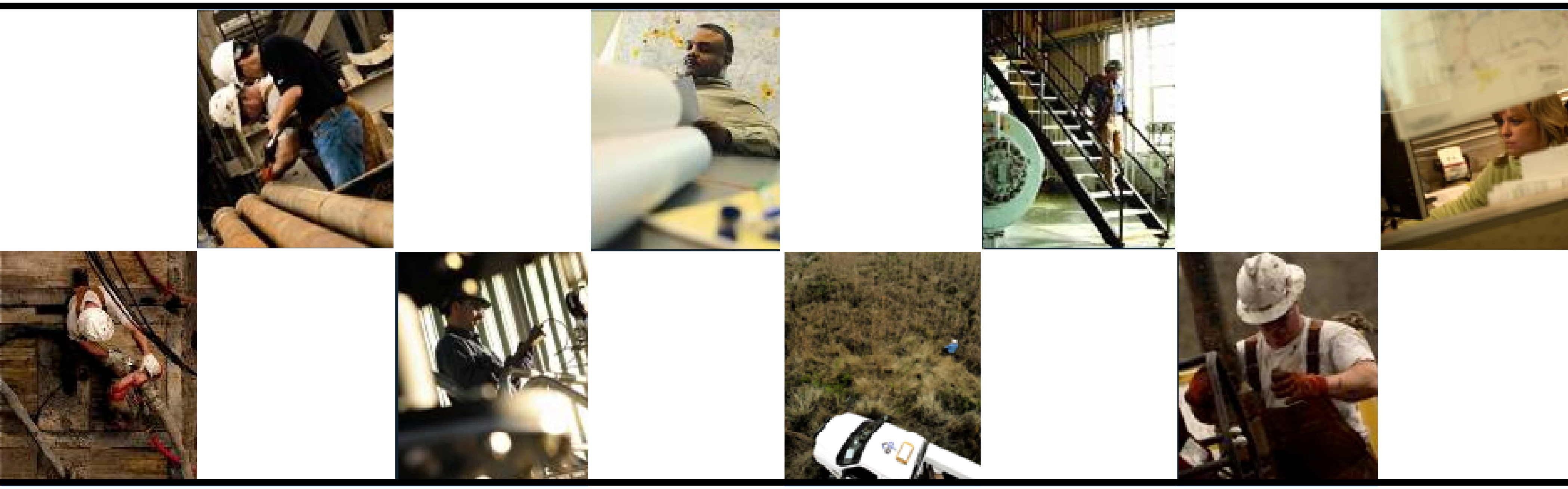
Abstract

The South Atlantic margins of West Africa and South America are composed of a diverse range of conjugate margin pairs and associated failed rifts (aulacogens), each with its own tectonic and stratigraphic expression. Such diversity is caused by a fundamental underlying structural asymmetry, derived from each basin's distinct rift, continental margin break-up, and drift phases in its history. The results are evident in the current day configuration of the Aptian Salt Basin's outer continental shelf (OCS) margin, where both wide and narrow margin segments can be observed. Wide OCS margins can be reconstructed with their narrow Afro-Brazilian conjugate pair. This observation is also confirmed by examination of the regional geologic, seismic, gravity-magnetic, and other geoscience data.

The asymmetry of these successful rift-to-drift continental-margin basins can be traced to their early architectural configuration, where the location and polarity of fundamental rift half-graben units are significantly shaped by pre-rift structure (anisotropy). Such inherited asymmetry, when reactivated, also ultimately determines the shape, size, and polarity of the upper plate - lower plate morphology of the OCS margins, which are likely driven by crustal-lithospheric delamination mechanisms (sensu Wernicke [e.g., 1985]; Lister et al. [e.g., 1991]) until continental break-up. The thermal and isostatic history associated with post-rift uplift or subsidence, along with variable hotspot activity and salt thickness variations (non-allochthonous), can also be tied to this asymmetry.

The maturation, migration, and entrapment of hydrocarbons from or within syn-rift petroleum systems in the Aptian Salt Basin are likely determined by the asymmetry inherent in any particular basin's early history. Structural and stratigraphic syn-rift play fairways arising from a basin's syn-rift and post-rift structural and stratigraphic development can also be tied to a margin's asymmetrical roots. With the advent of deep water to ultra-deepwater drilling capabilities and higher product prices, the industry is now potentially poised at the beginning of a new age of syn-rift exploration in new frontier areas.

El Paso Corporation



South Atlantic margin asymmetry and implications for pre-salt exploration

Joseph Versfelt

AAPG International, Rio de Janeiro
November 15-18, 2009

Talk Outline

Tectonic Asymmetry

- continental rift half graben architectures
- conjugate passive margins post break-up

Pre-Rift Controls

- rift zones, half graben linkage, & structural accommodation
- major pre-rift inter cratonic shears force rift & margin asymmetry
- extensional asymmetry & rift-to-drift evolution
- possible change in extensional mechanism pre breakup
- wide vs narrow margins

Possible Implications for Exploration

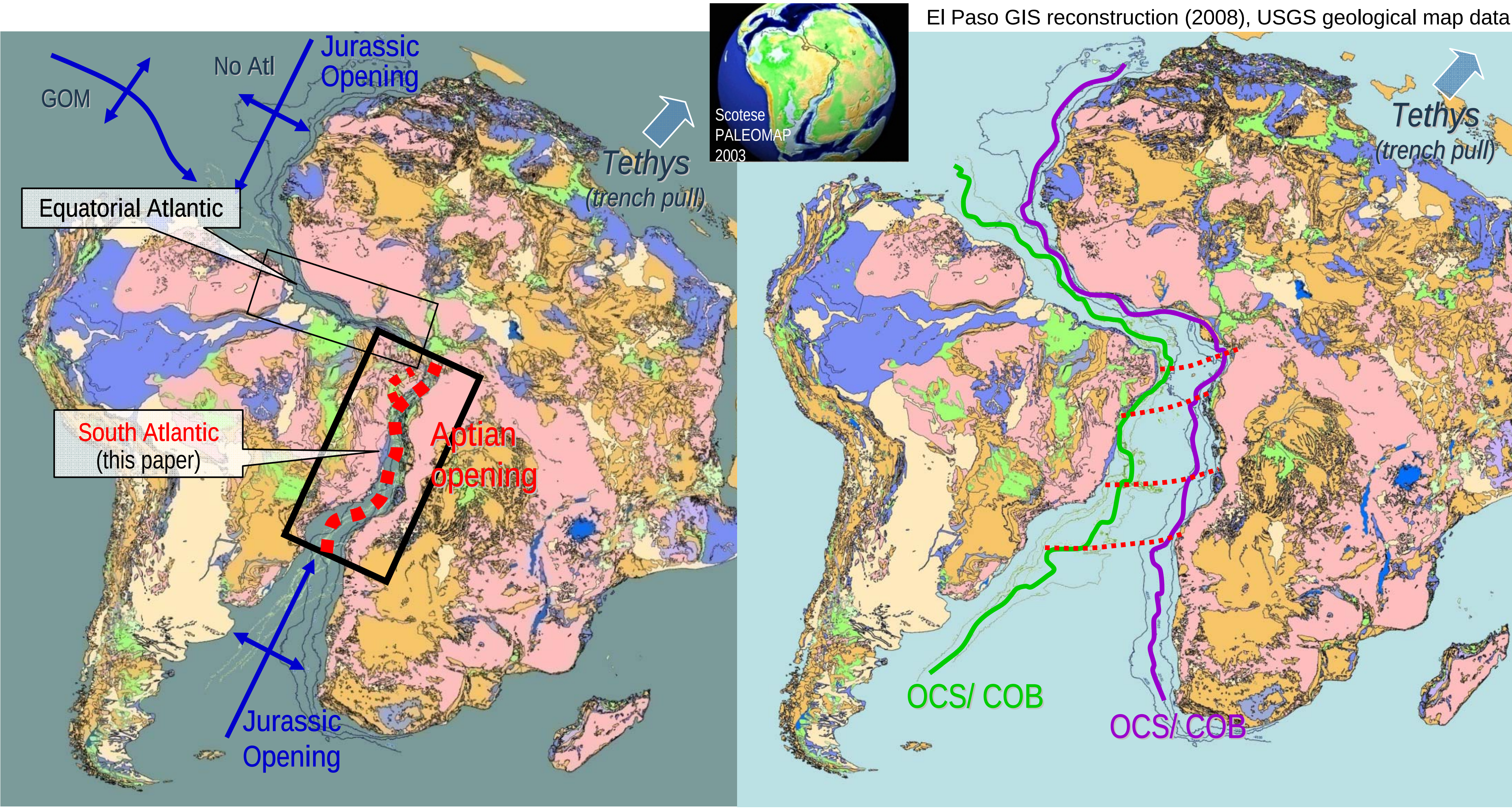
- basin history & play quality

Conclusions

View Note for Slide 3 (Page 4)

South Atlantic - Cretaceous

El Paso GIS reconstruction (2008), USGS geological map data



120 Mya Aptian **95 Mya Cenomanian-Turonian**

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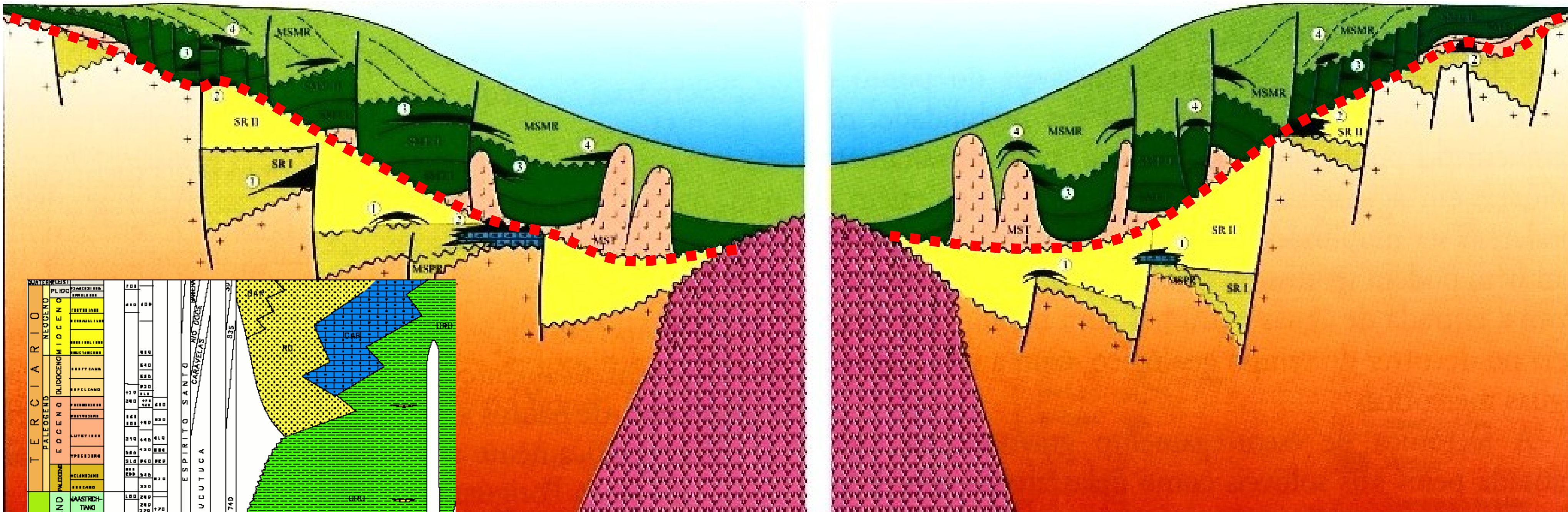
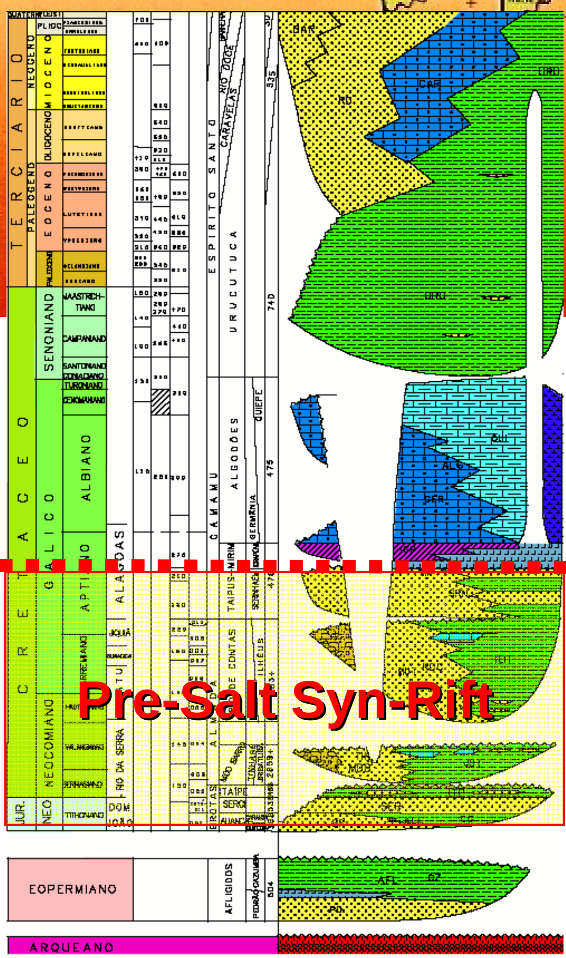
South Atlantic Pre-Salt





Mohriak, Szatmari & Anjos (2008)
after Leyden (1976), Kumar & Gamboa (1979)

- **Early Cretaceous age** (Barremian-Neocomian to mid Aptian)
- **Syn-Rift continental to marine environments of deposition**
- **Sub-salt/ evaporites** (m-l Aptian)
- **Pre-continental break-up**

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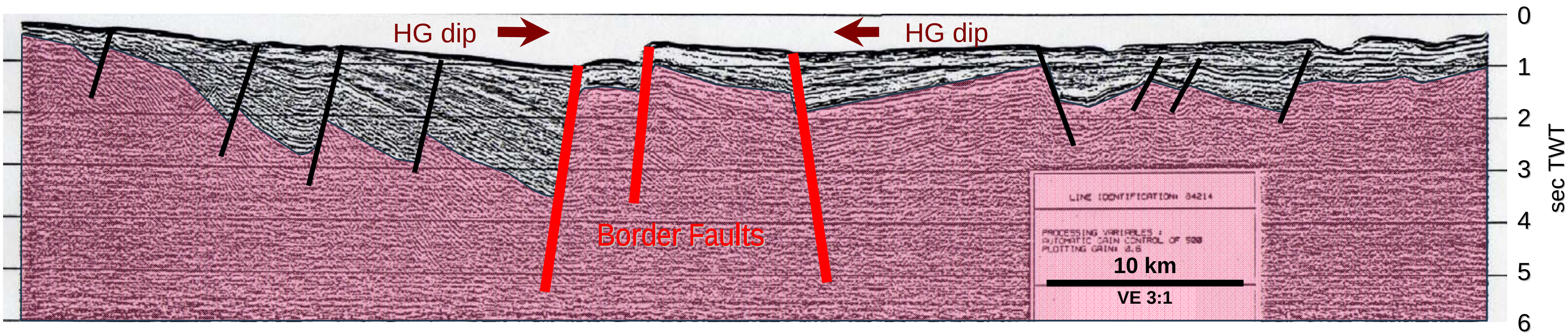
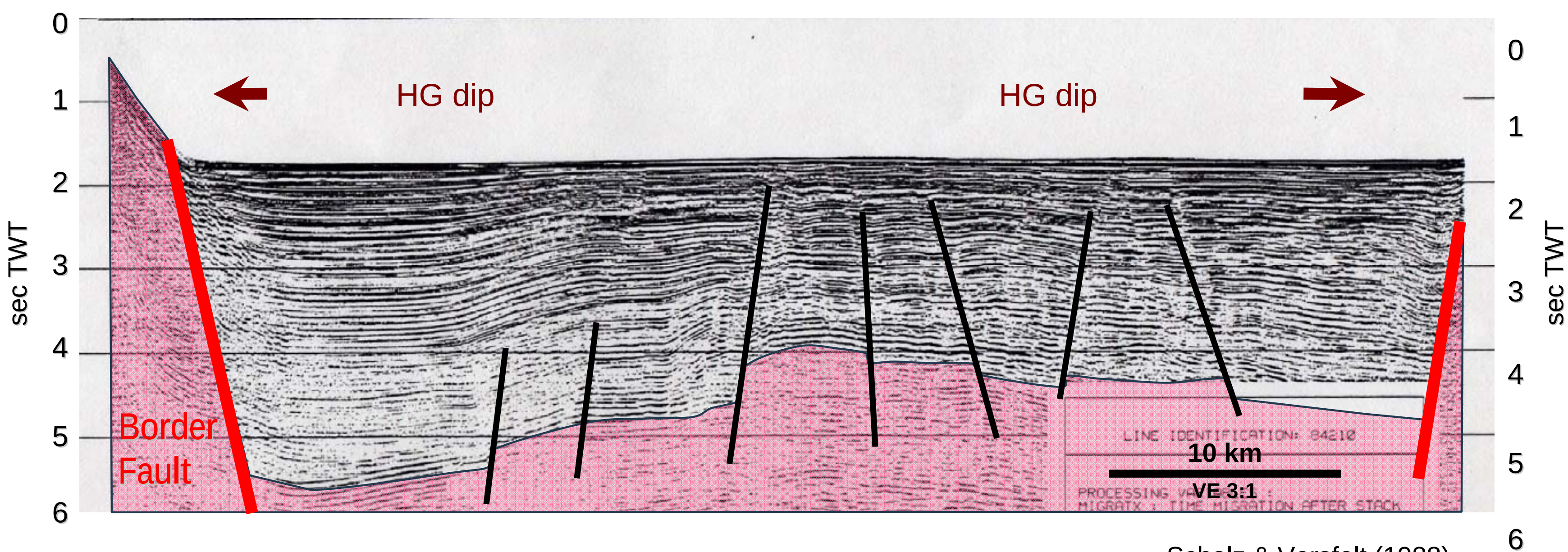
Tectonic Asymmetry

Half Graben Morphology: Lake Tanganyika, East Africa





Scholz & Versfelt (1988)

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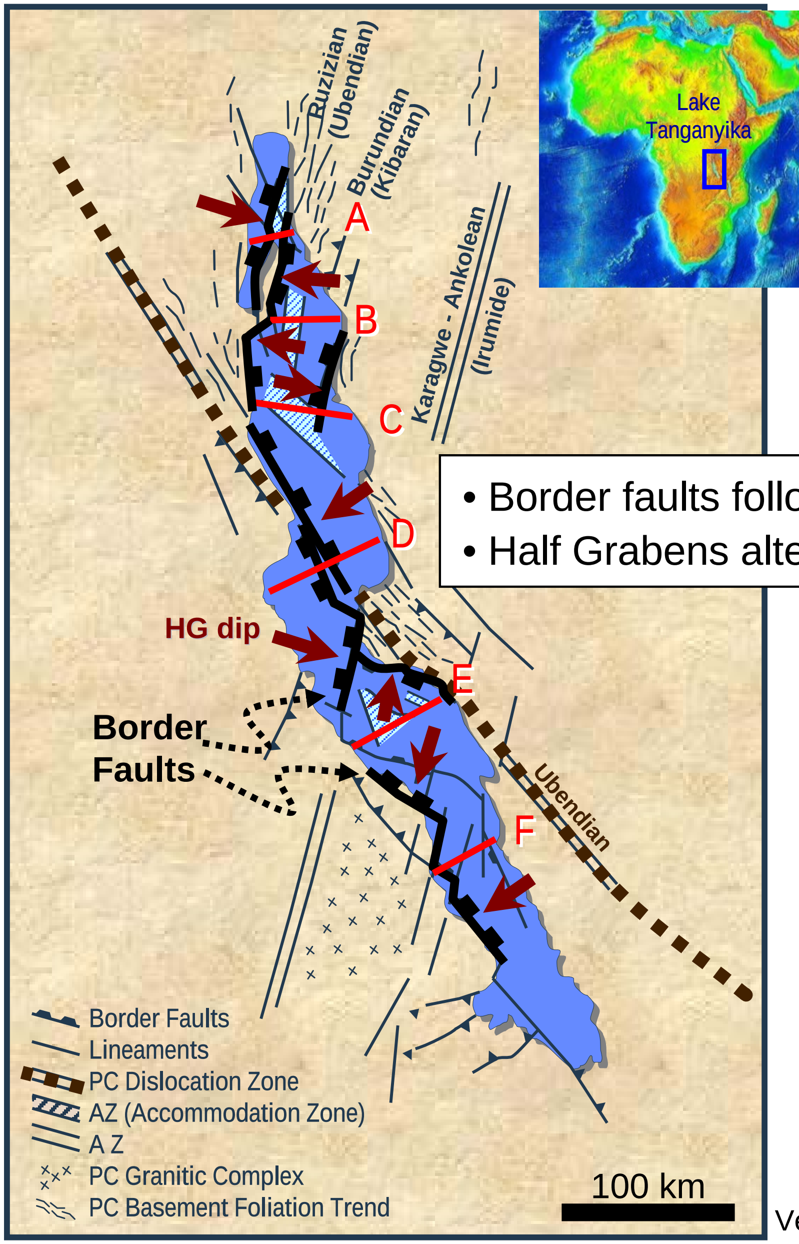
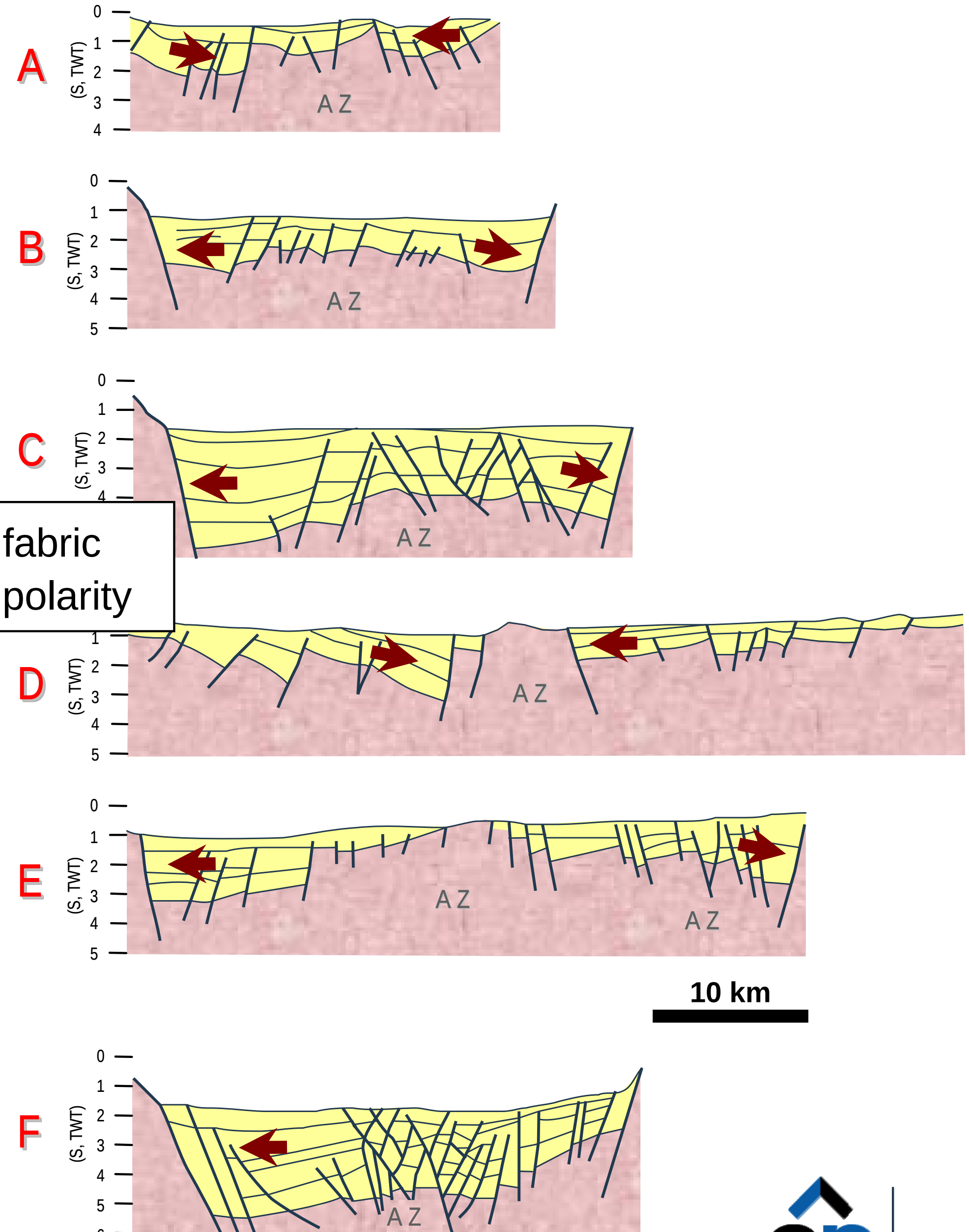
Tectonic Asymmetry

Rift Architecture: Half Graben Polarity

Lake Tanganyika



- Border faults follow pre-rift fabric
- Half Grabens alternate dip polarity



Versfelt (1988)

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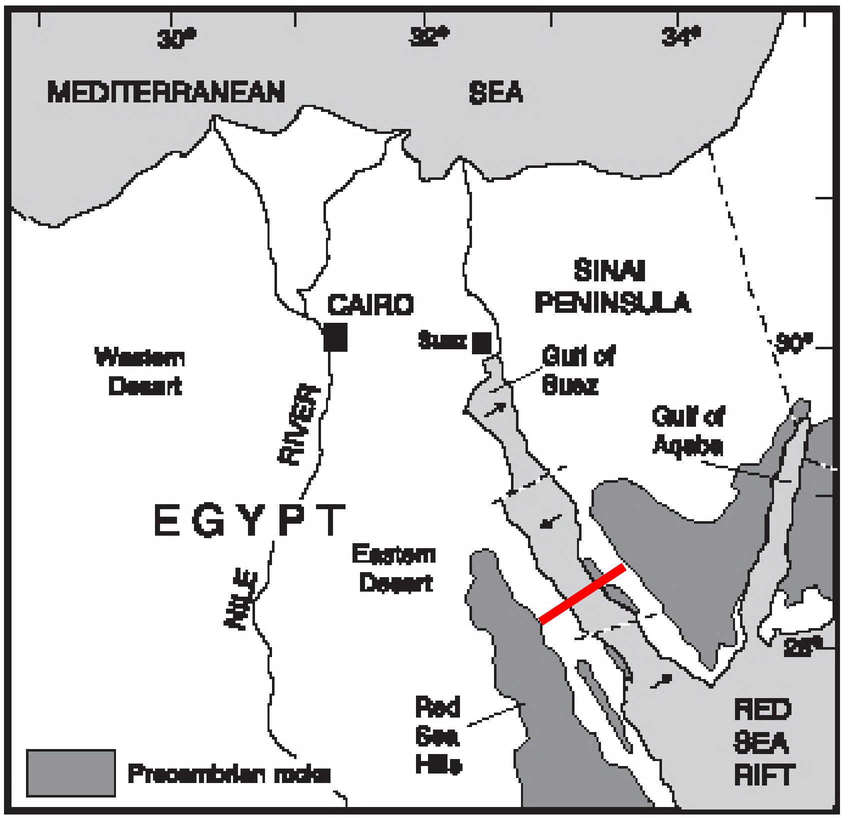
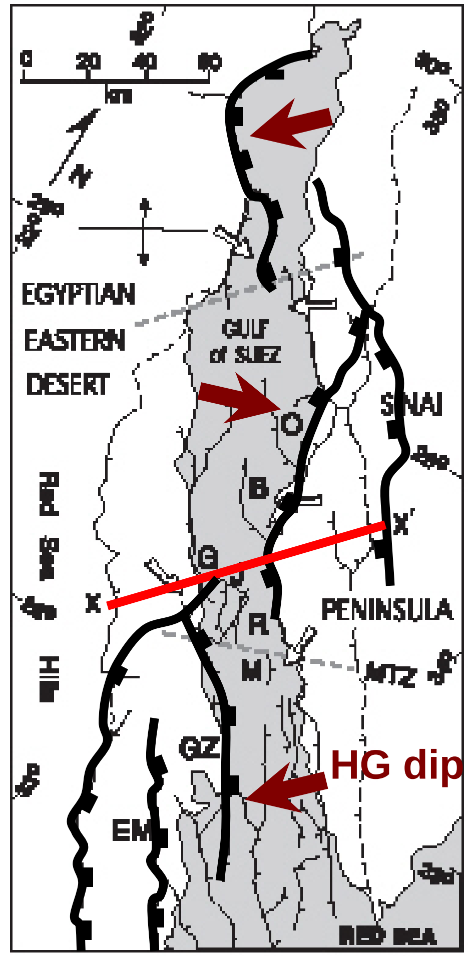
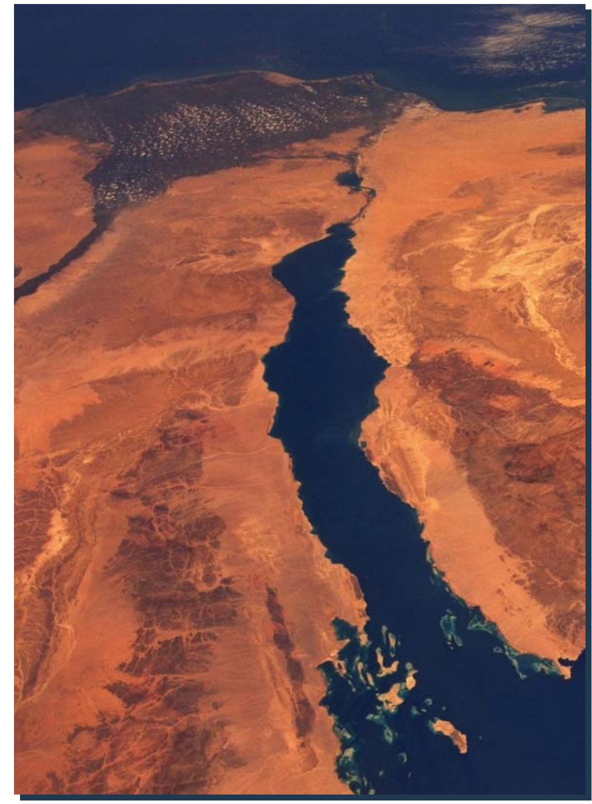
Tectonic Asymmetry

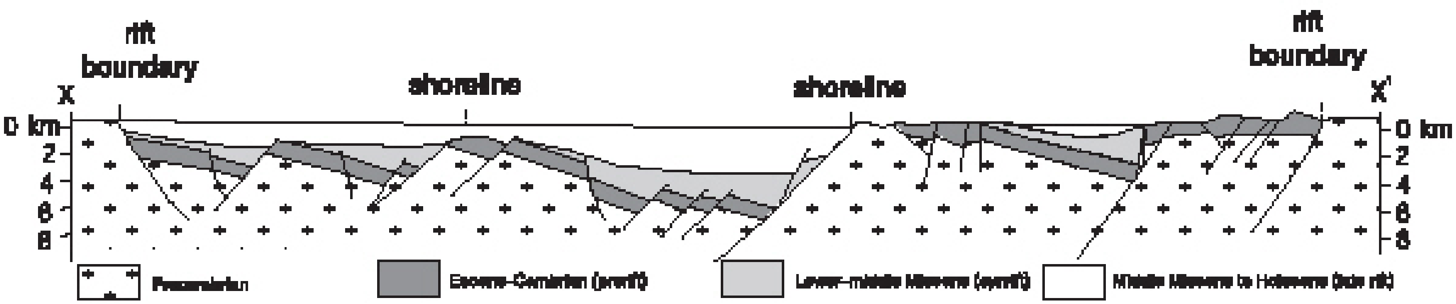
Alternating Half Grabens: Gulf of Suez, Egypt





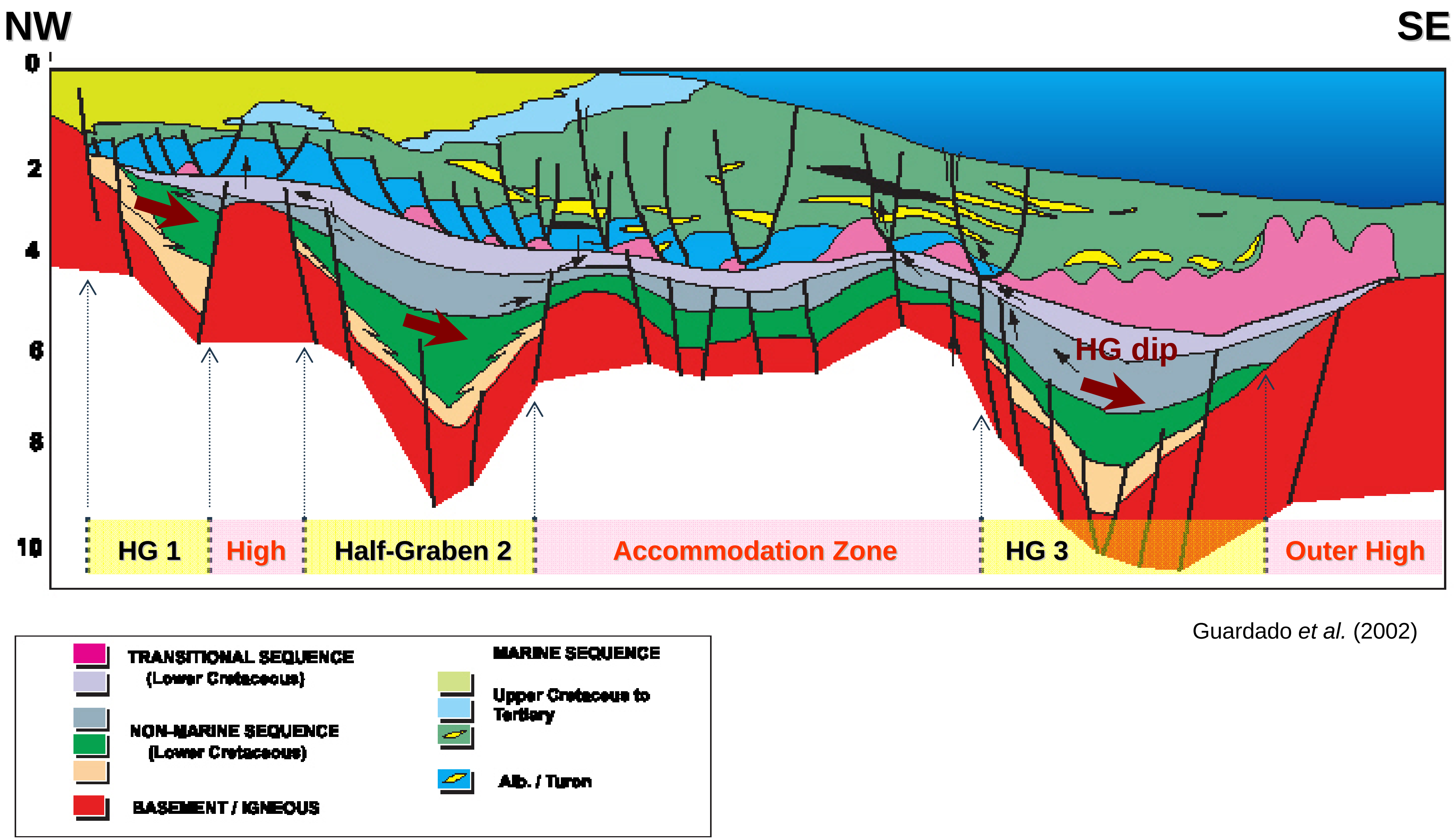


Privnik *et al.* (2003)



Tectonic Asymmetry

Side-by-Side Half Grabens: Campos Basin, Brazil



Guardado *et al.* (2002)

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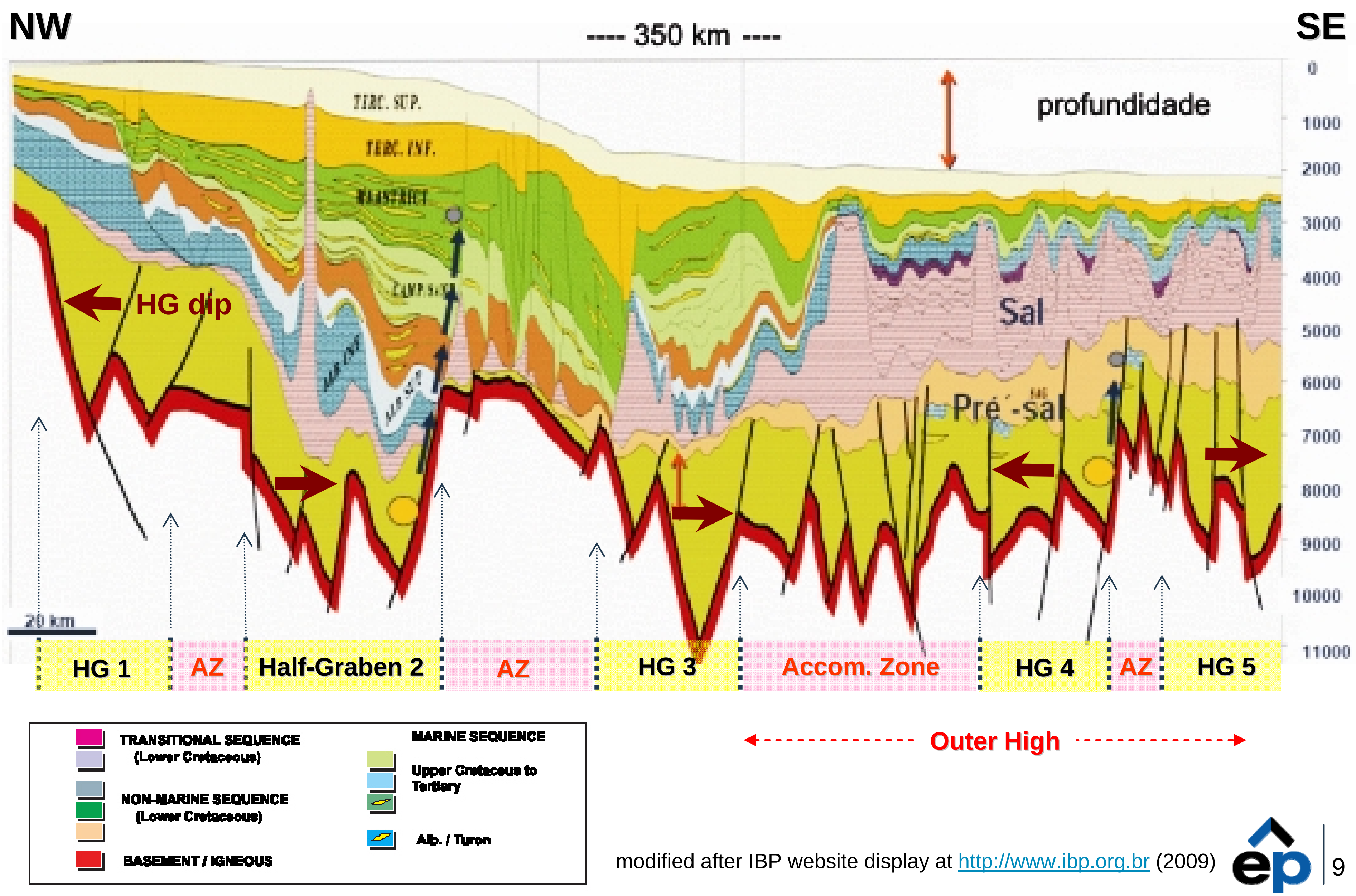
Tectonic Asymmetry

Side-by-Side Half Grabens: Santos Basin, Brazil



modified after IBP website display at http://www.ibp.org.br (2009)

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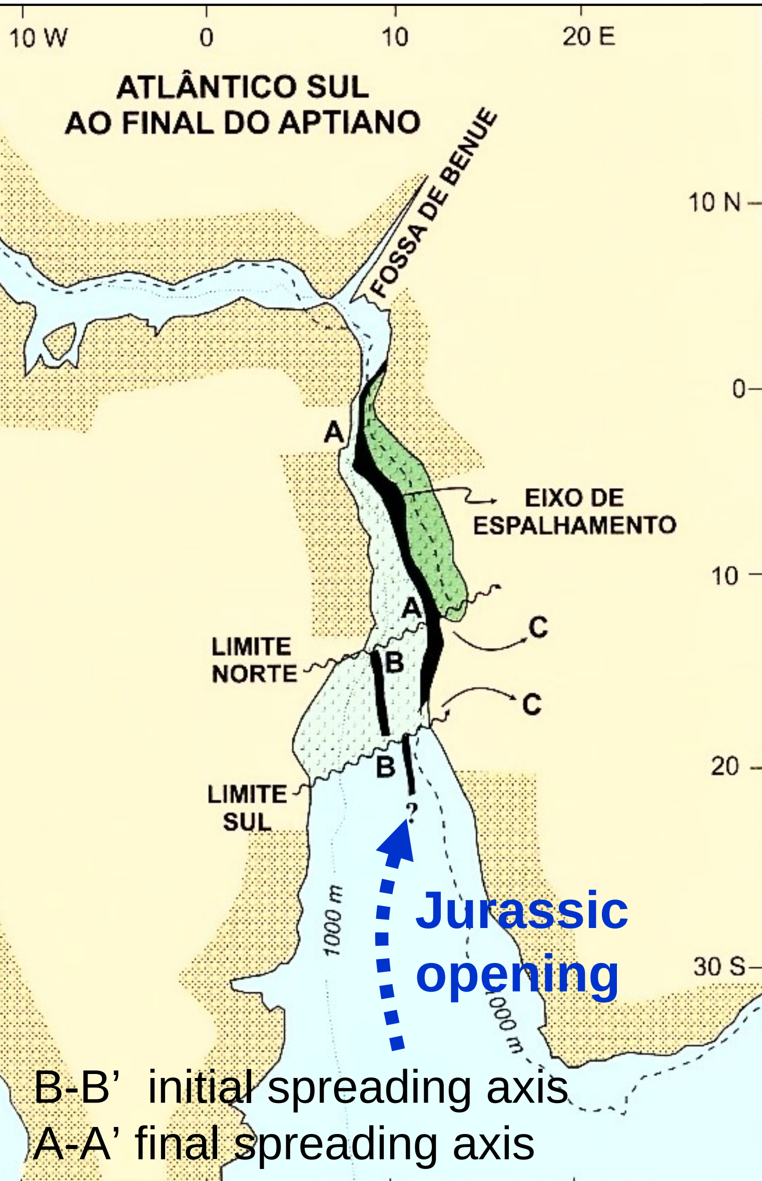
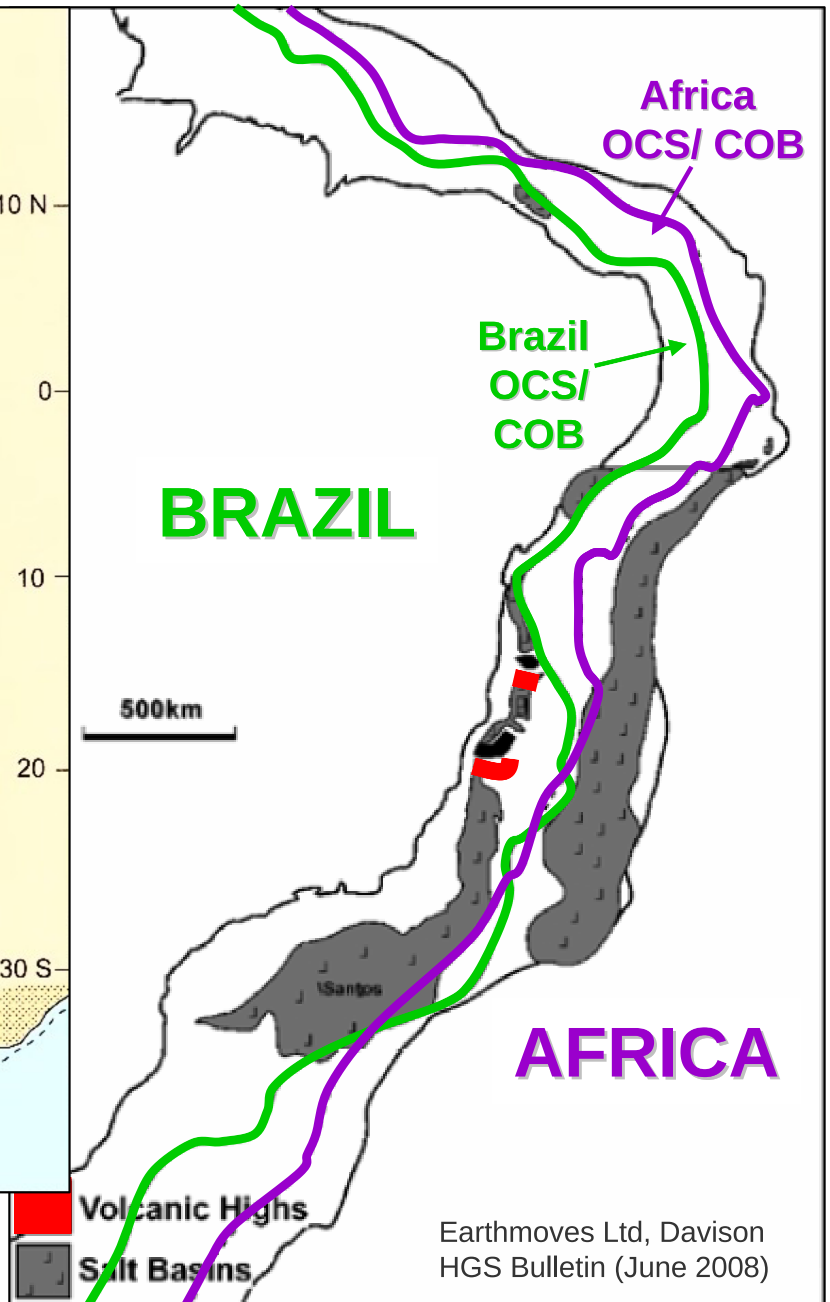
Tectonic Asymmetry

Asymmetric South Atlantic Margin Breakup (*ca.* 116 Mya, Aptian)



Gamboa et al, in Mohriak, Szatmari & Anjos (2008)
after Leyden (1976), Kumar & Gamboa (1979)



Earthmoves Ltd, Davison
HGS Bulletin (June 2008)

Observations:

- Conjugate margins track each other (OCS)
- Narrow vs wide margins
- Overlaps vs gaps (data & Beta)
- Unclear segment linkages

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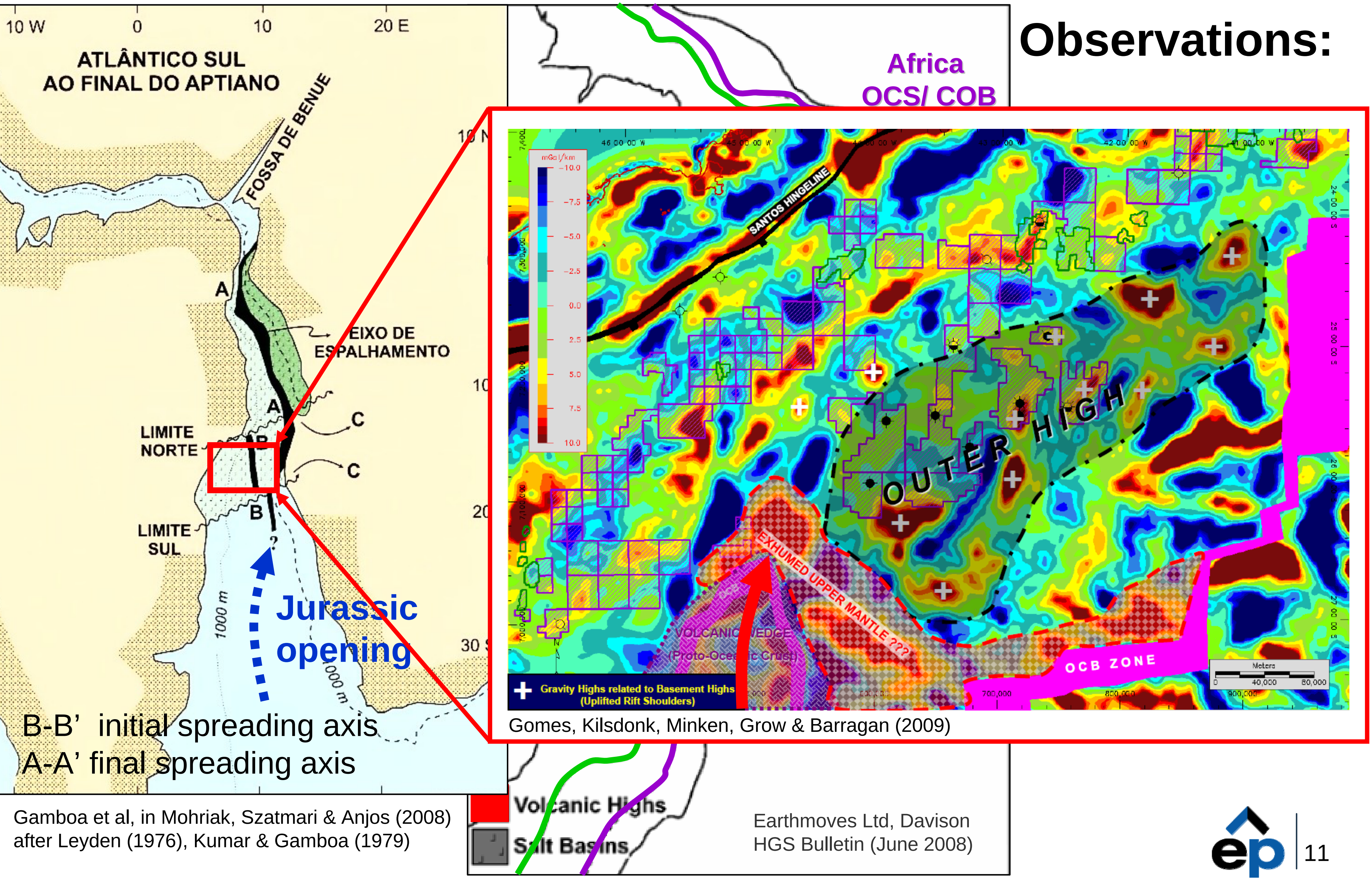
Tectonic Asymmetry

Asymmetric South Atlantic Margin Breakup (*ca.* 116 Mya, Aptian)



Gamboa et al, in Mohriak, Szatmari & Anjos (2008) after Leyden (1976), Kumar & Gamboa (1979)

Earthmoves Ltd, Davison HGS Bulletin (June 2008)

Observations:

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Pre-Rift Controls

Tectonic Memory

- **Basement:** Pre-Cambrian mobile belts preferentially weakened under extension
- **Half-Grabens:** Original border fault & half-graben dip polarity begets regional décollement & deep extension-delamination
- **Forcing of Pre-Rift Shears:** Rift basin half-graben dip polarity flips forced by major pre-rift heterogeneities (basement shear zones & associated fabrics)
- **Shears as Strain Locks:** Initially, major pre-rift shears are pin points (strain locks) in evolving South Atlantic rifting & breakup, then strain-weakened through lithospheric pure shear.
- **Shears to Transforms:** Pre-rift shears guide synrift accomodation zones & evolve into slip lines (transforms) for alternating UP-LP margins along strike during break-up

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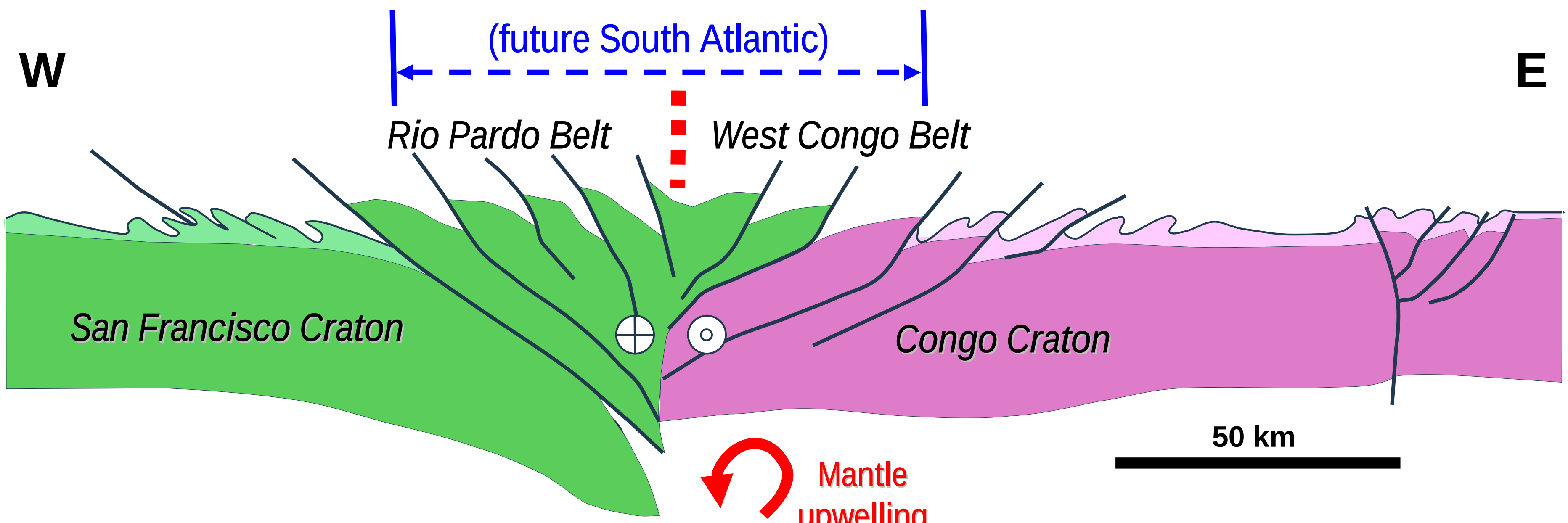
Pre-Rift Controls

South Atlantic: Rift Zone Structural Inheritance

- Late Pre-Cambrian Mobile Belts are primary control (avoid cratons)
- Initially depressed Lithosphere focuses Mantle upwelling
- Long term elevated geotherms, anatexis, extension
- MB shears & thrusts ductile-brittle fabrics pervade
- Reactivation of prevalent fabric as Border Faults & detachments



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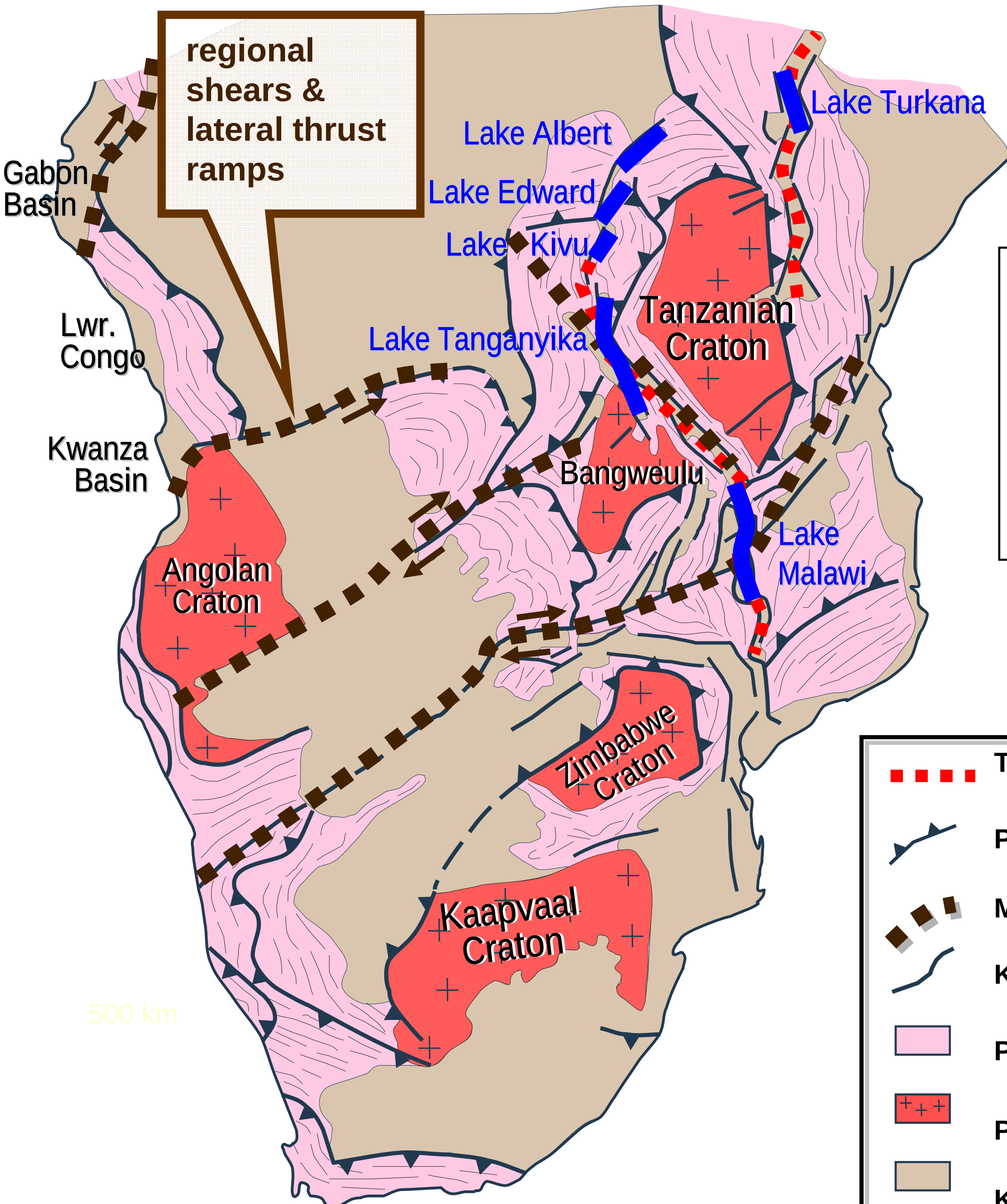
Pre-Rift Controls

South Atlantic: East African Rift Basement Control Analogue



modified after Versfelt 2008

- Rifts avoid Archean cratons
- Rift zones follow PC mobile belts
- Mobile belt shear zones force half-graben polarity flips

Tertiary rift zones

PЄ basement Mobile Belt orogenic front

Major intra-basement shear zones

Karoo + Tertiary rift faults

PЄ (Proterozoic) basement foliation

PЄ (Archean) cratons

Karoo & Tertiary sedimentary cover

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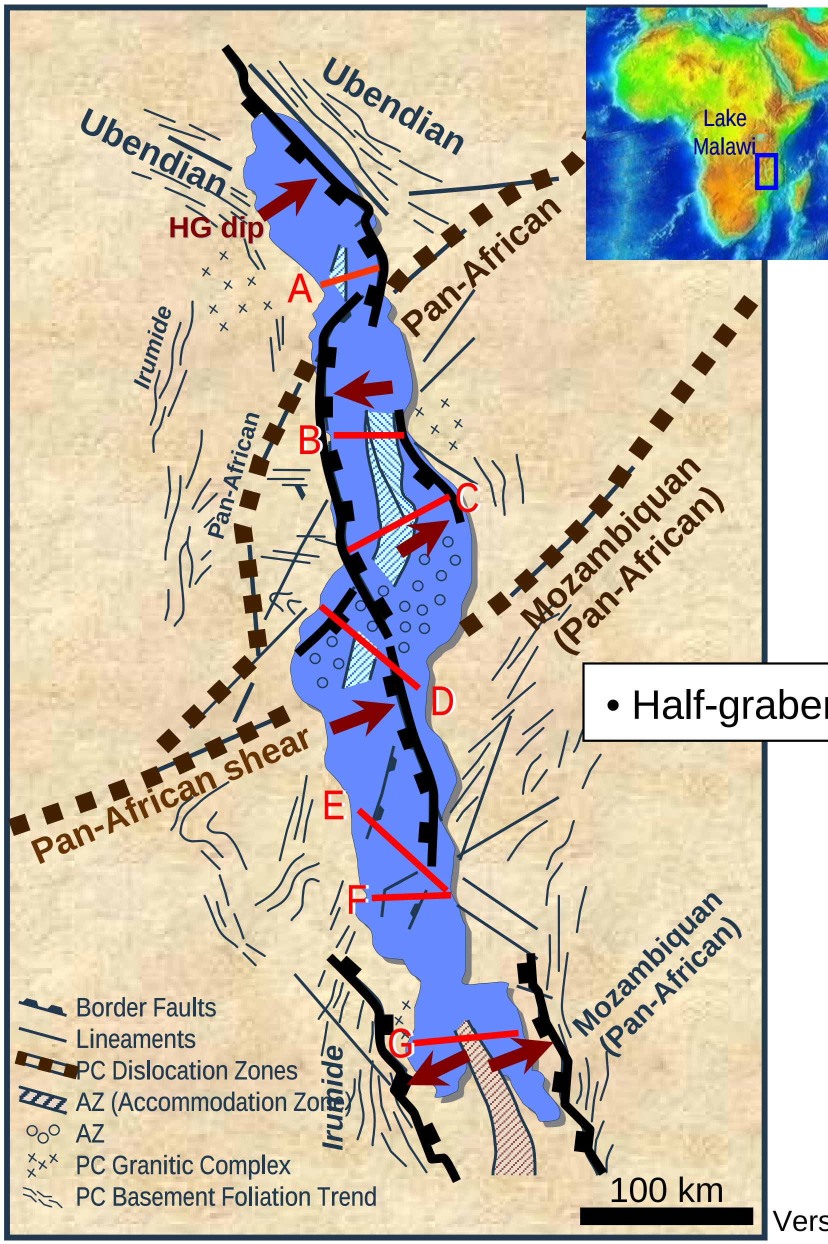
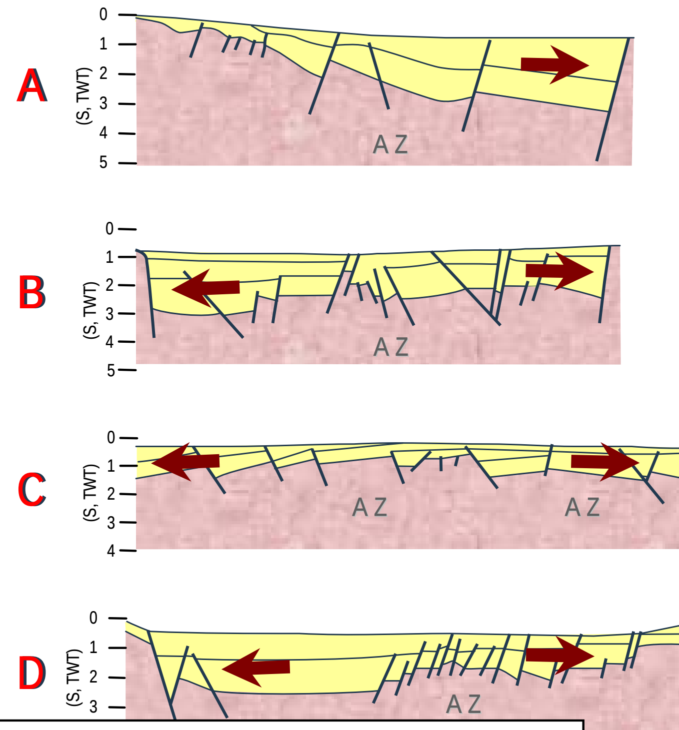
Pre-Rift Controls

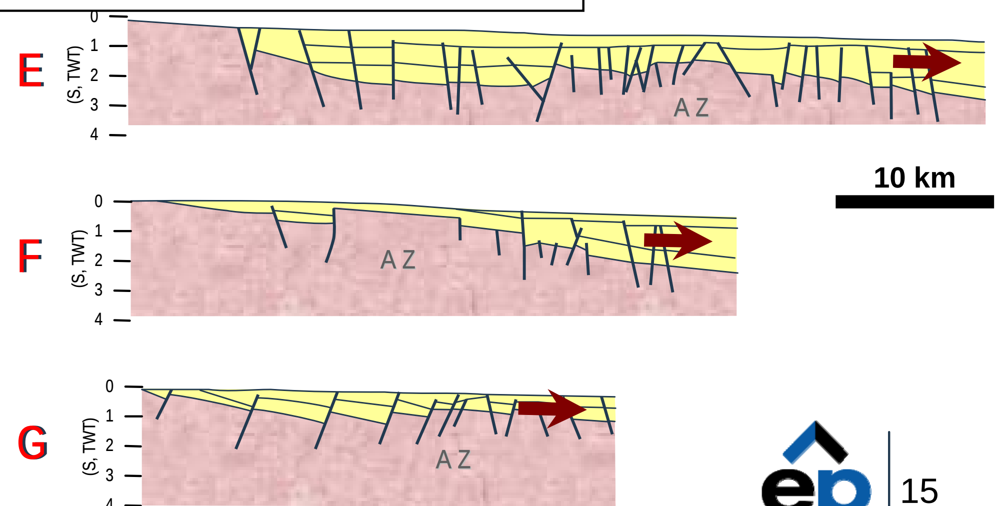
Basement Controls on Rift Architecture: Border Fault Polarity

Lake Malawi





• Half-grabens flip polarity at Basement shear zones



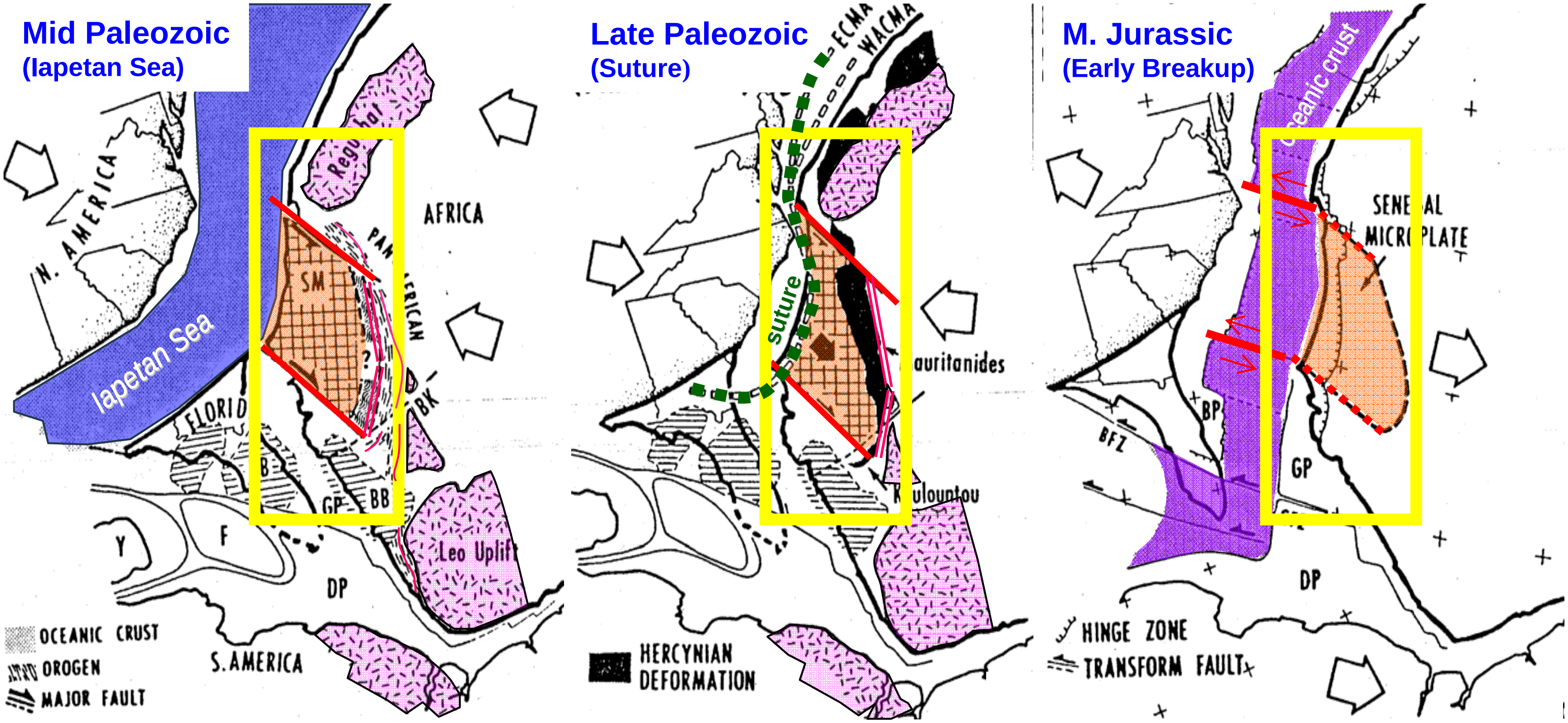
Versfelt (1988)

View Note for Slide 16 (Page 17)

Pre-Rift Controls

Basement Control on Rift-Drift Margin Segmentation

MSGBC Basin (Mauritania-Senegal-Guinea Bissau-Guinea Conakry)



Rochet (1977), Venkatakrishnan & Culver (1988)

- **Pre-Rift Basement controls along-strike rift segmentation**
  - Pre-Cambrian mobile belt lateral shear zones reactivated during rifting
  - Major rift transfer faults accommodate differential stretching along axis
  - Transfer faults lead to Transforms, segmenting the margin

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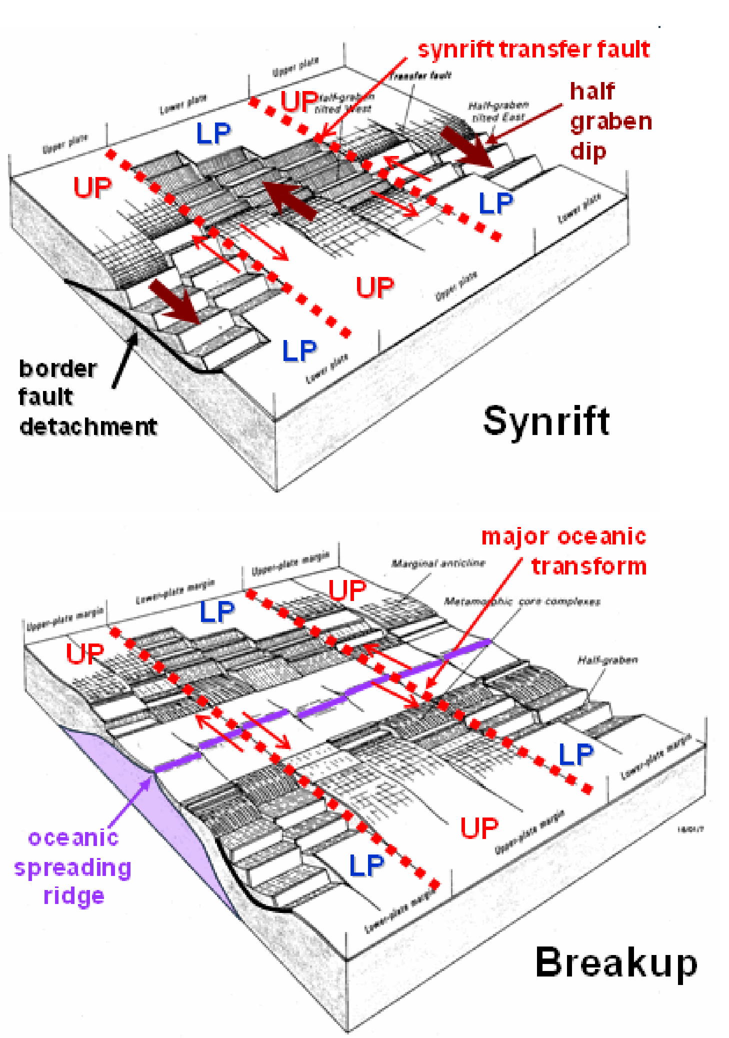
Pre-Rift Controls

Rift to Drift: Upper Plate - Lower Plate Segmentation

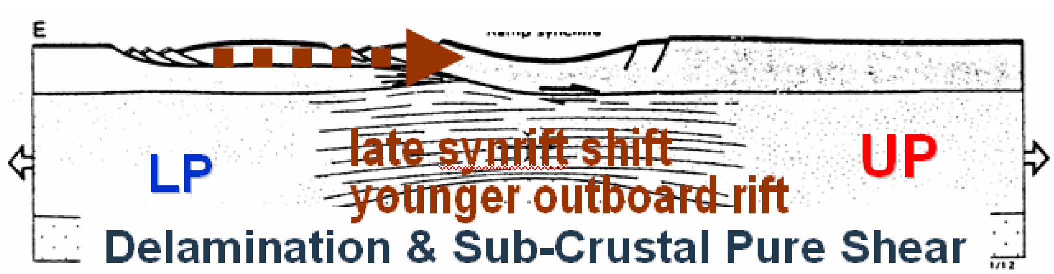


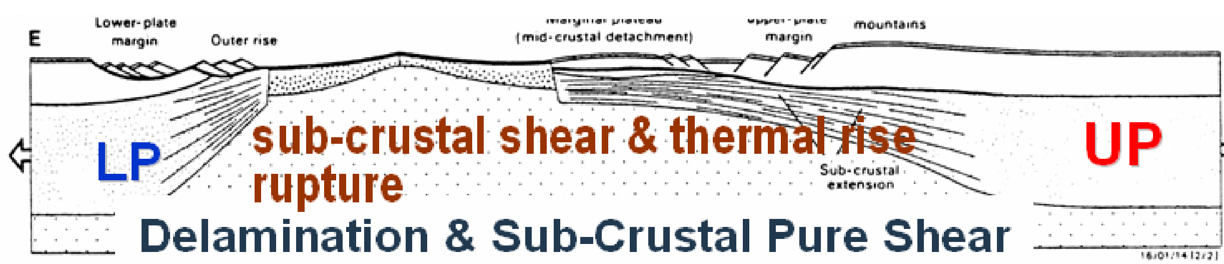
UP = Upper Plate
LP = Lower Plate

Lister, Etheridge, & Symonds (1986)

- **Asymmetry along strike (margins)**
  - Upper Plate - Lower Plate
- **Compartments bound by transfers/ transforms**
  - Basement control (pre-rift shear zones)

Mechanism for Asymmetrical Margins





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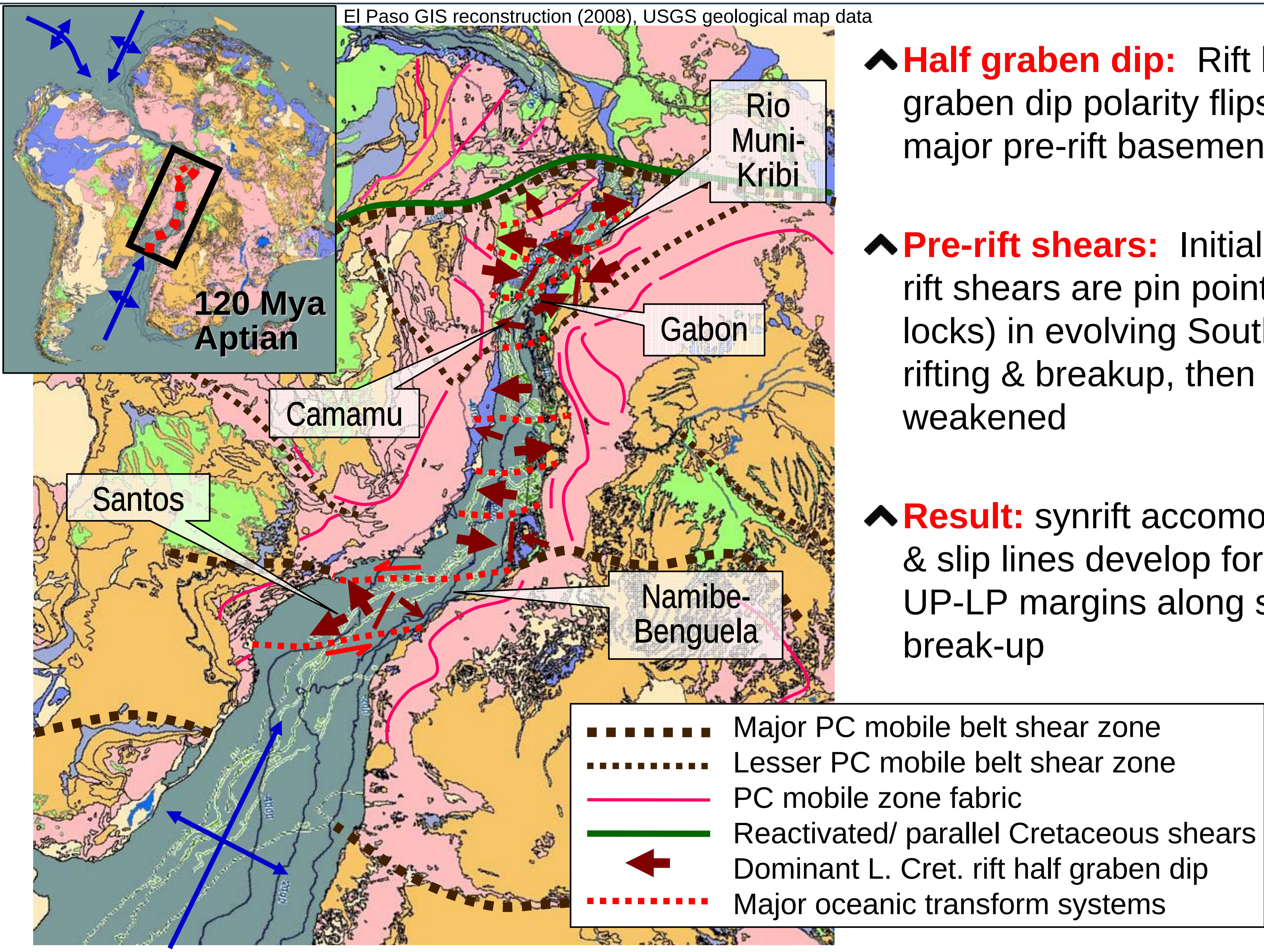
Pre-Rift Controls

South Atlantic Mega-Rift Architecture



- **Half graben dip:** Rift basin half-graben dip polarity flips forced by major pre-rift basement shear zones
- **Pre-rift shears:** Initially, major pre-rift shears are pin points (strain locks) in evolving South Atlantic rifting & breakup, then strain-weakened
- **Result:** synrift accomodation zones & slip lines develop for alternating UP-LP margins along strike during break-up

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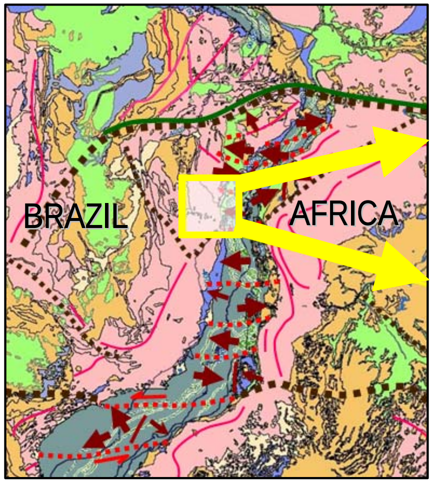
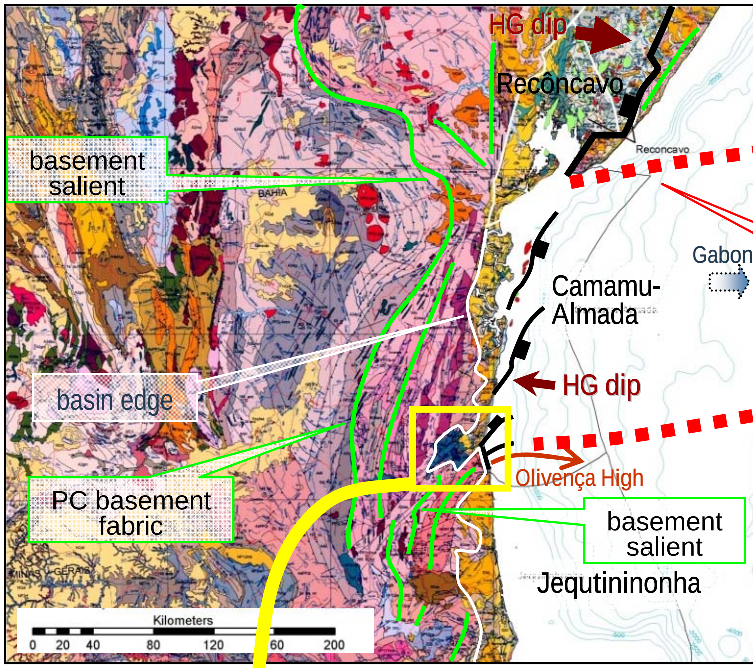
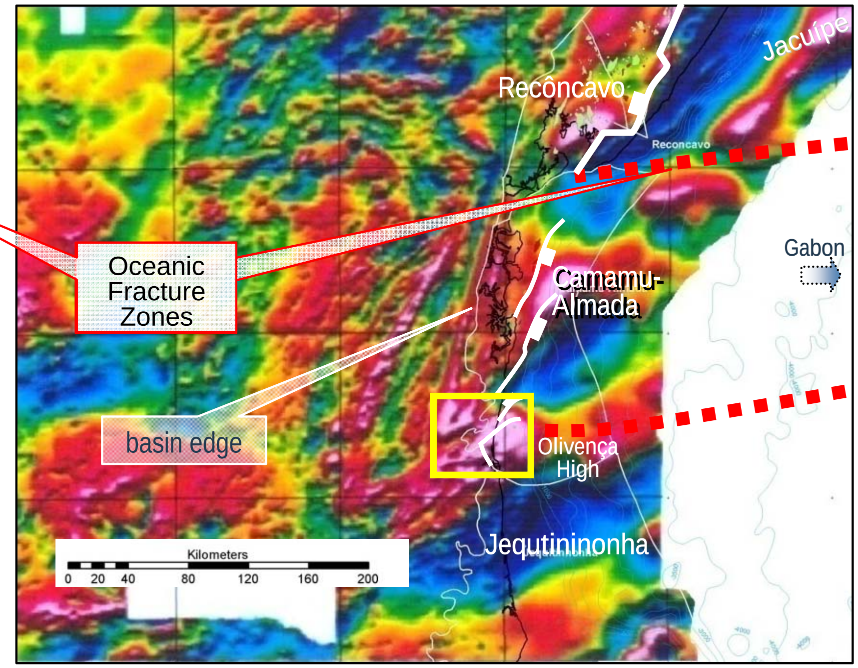
Pre-Rift Controls

Border Fault Basement Reactivation: Camamu-Almada

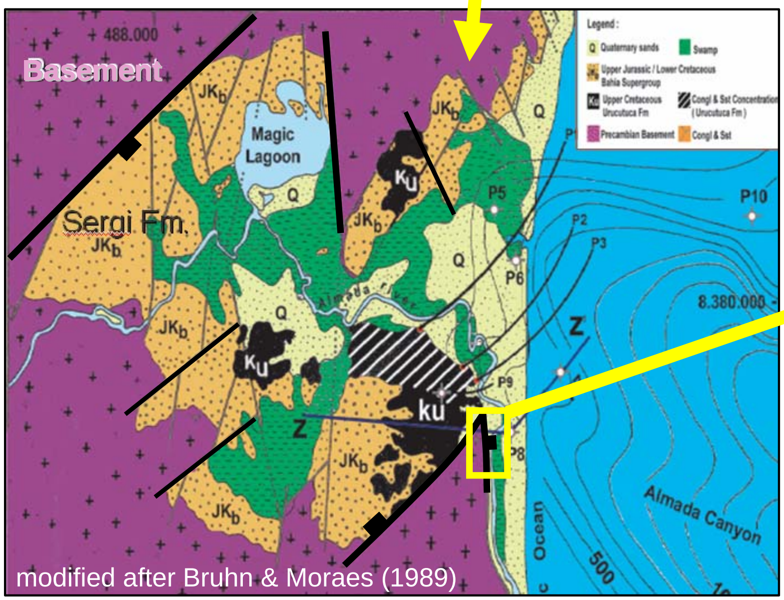




CPRM, Geological Map Brazil - sheet 24 (2004)



CPRM, Magnetics RTP IGRF - sheet 24 (2004)



HRT-El Paso field trip, Nilo Azambuja Filho (2009)

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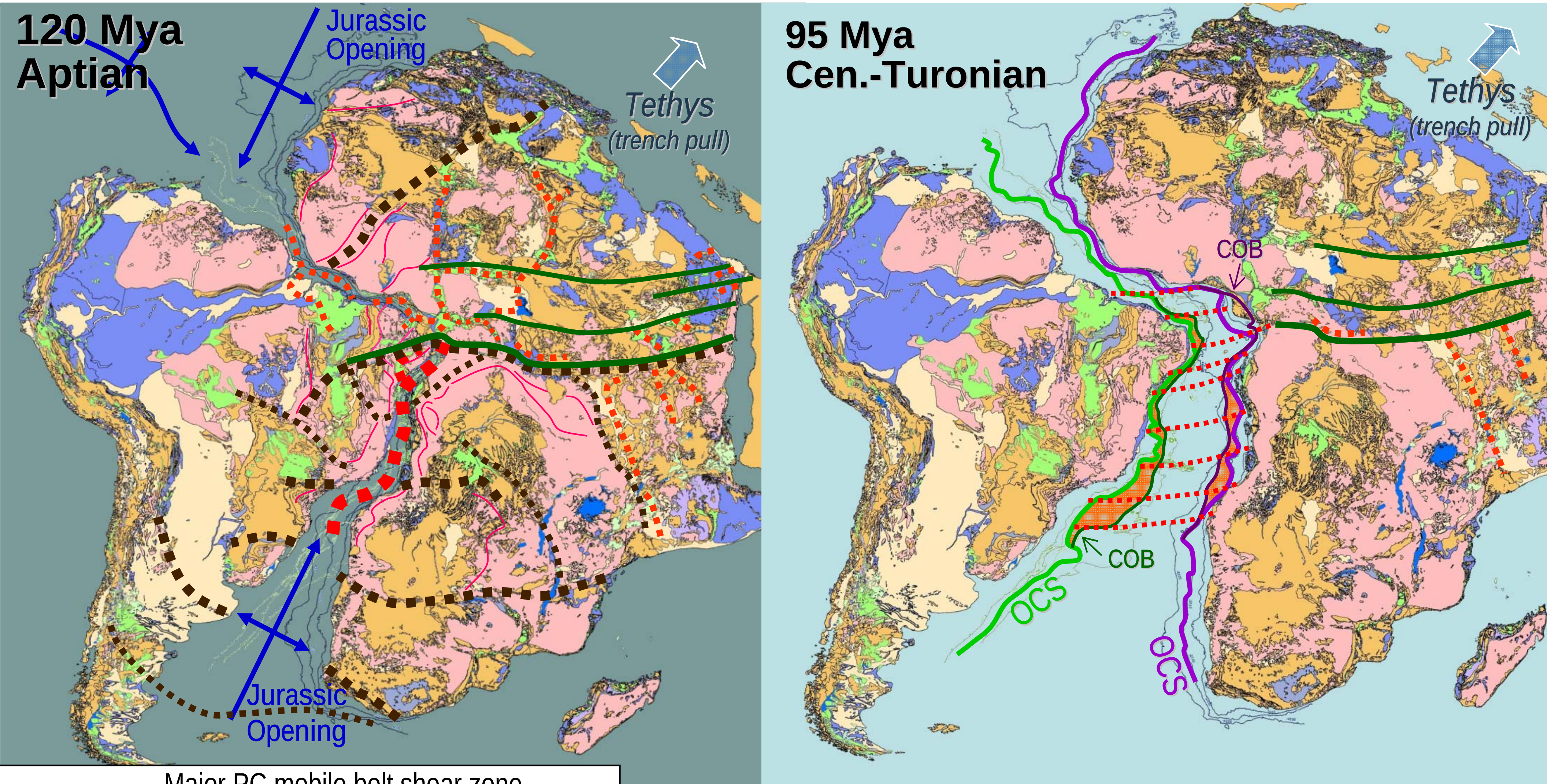
Pre-Rift Controls

South Atlantic: Rift to Drift Configuration



- Major PC mobile belt shear zone
- Lesser PC mobile belt shear zone
- Mobile PC belt fabric
- Reactivated/ parallel Cretaceous shears
- Lwr Cretaceous rift
- Middle-Upper Cretaceous rifts

El Paso GIS reconstruction (2008), USGS geological map data

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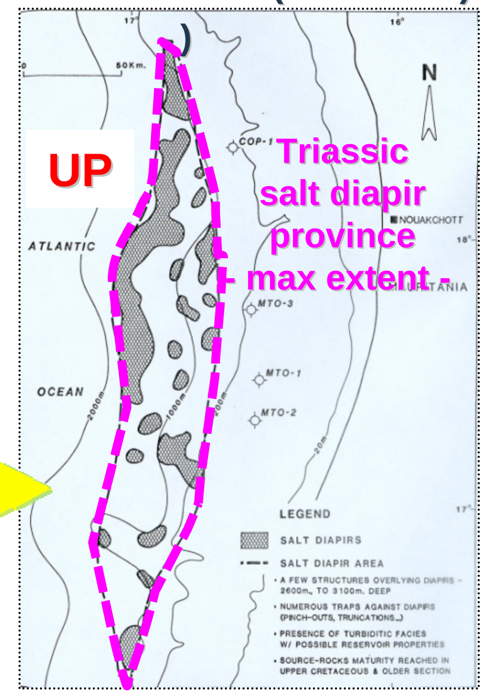
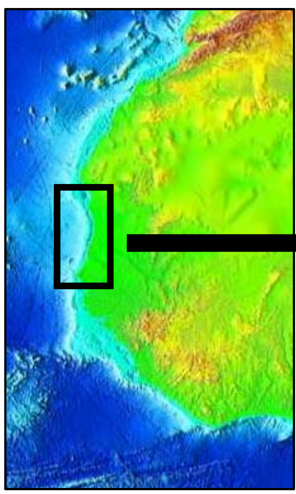
Possible Implications for Exploration

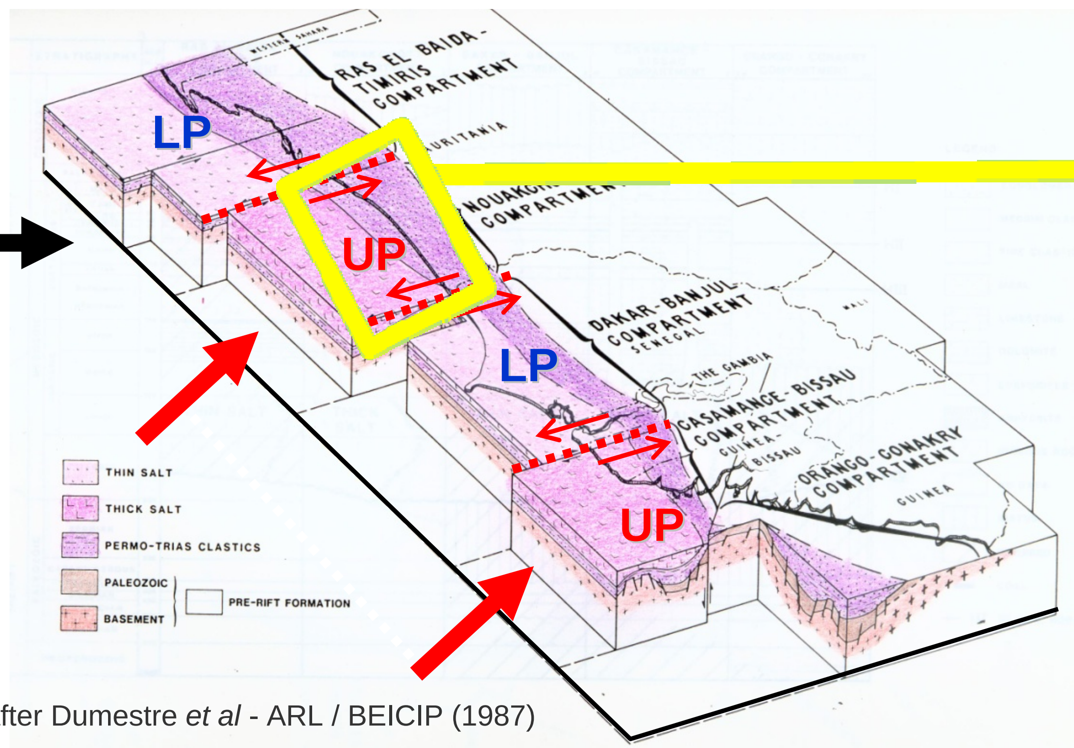
Rift to Drift Margin Segmentation Impact on PS!

- **Basin & salt thickness**
  - **UP** – thick, rift & drift inboard of COB
  - **UP** – thick salt & evaporites, thin to absent in **LP**
- **Source rock maturity**
  - Elevated maturity in post-salt SR’s
  - Suppressed maturity in pre-salt (syn-rift) SR’s, oil prone
- **Reservoirs**
  - Quality preserved in pre-salt due to lowered temperatures

Mauritania Salt Diapirs
Nouackchott (Mauritania)







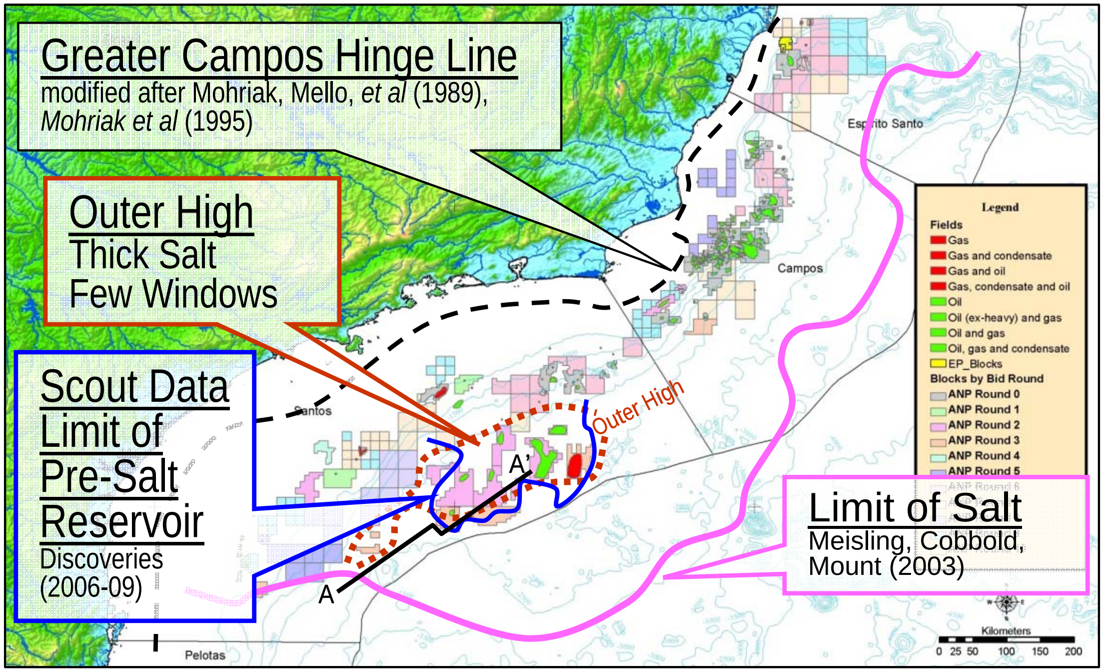
after Dumestre *et al* - ARL / BEICIP (1987)

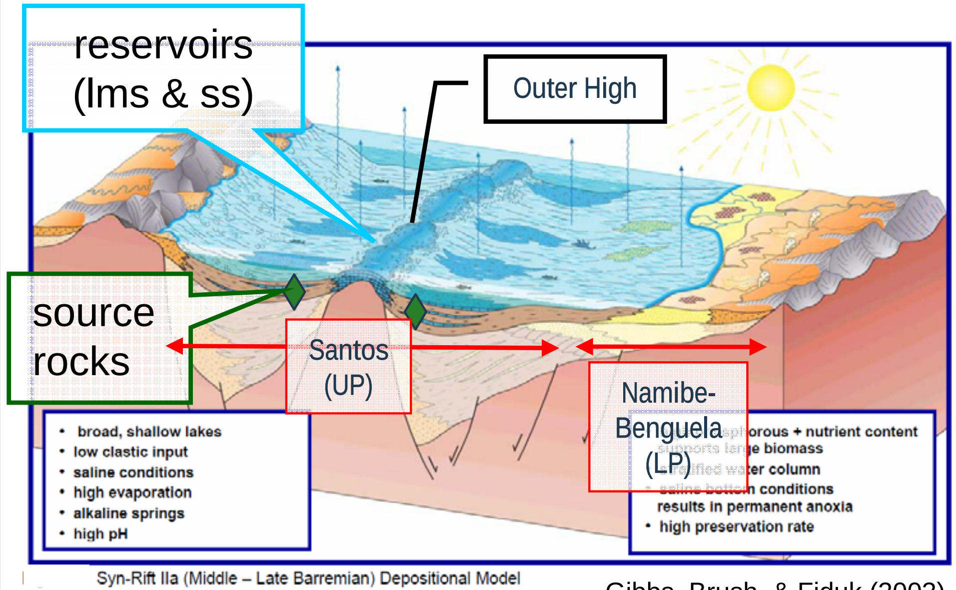
UP = Thick Salt
LP = Thin / No Salt

View Note for Slide 22 (Page 23)

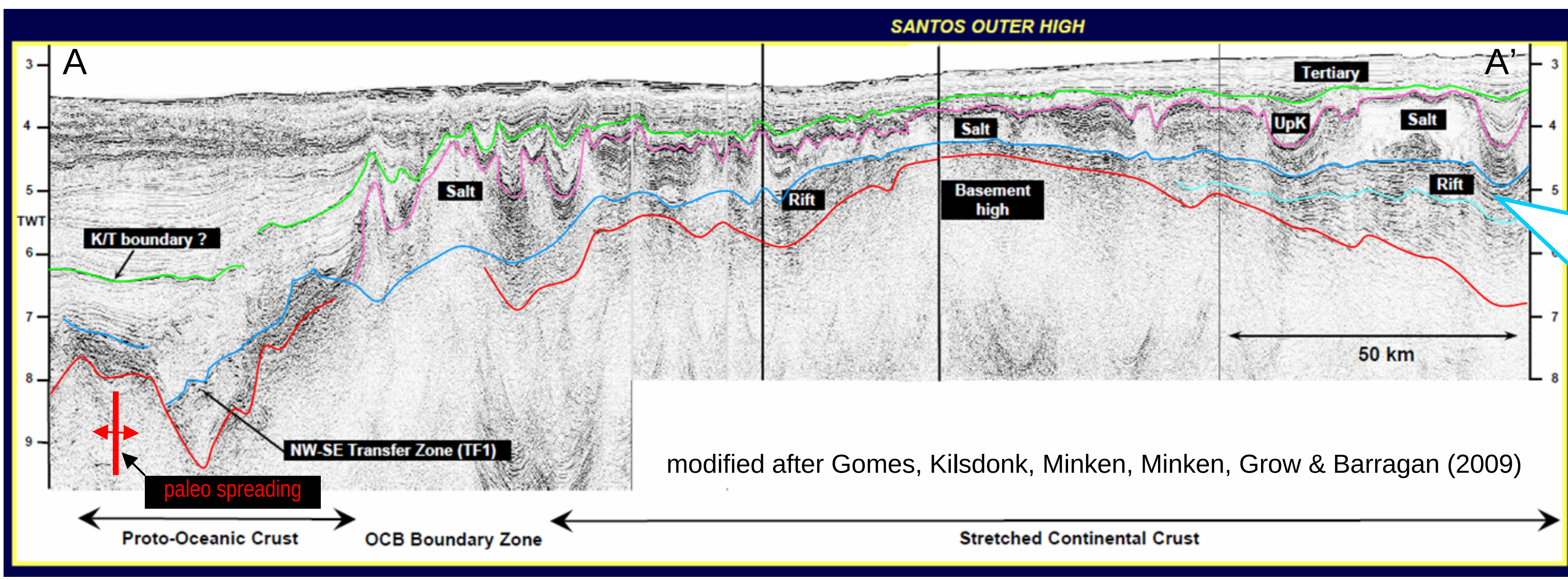
Possible Implications for Exploration

Santos (UP) Wide Margin Salt & Maturation





Gibbs, Brush, & Fiduk (2003)



modified after Gomes, Kilsdonk, Minken, Minken, Grow & Barragan (2009)

Pre-Salt source rock & reservoir mega-sequence

View Note for Slide 23 (Page 24)

Conclusions

- **Tectonic asymmetry is memory and survives**
- **All margins are not created equal**
  - UP = wide margin, LP = narrow margin
- **Diversity of Synrift structural styles & plays**
  - UP & LP margins will have different play style combinations

View Note for Slide 24 (Page 25)

Acknowledgements

- AAPG
- Marcio Mello
- El Paso Corporation

Notes Accompanying Slides

Slide 2 of 24 (Page 3 of 34)

Today's presentation surveys prior work and presents some new observations and ideas on the evolution of the South Atlantic Aptian Salt Basin.

Rifts and successor passive margin basins are inherently asymmetric, so **Tectonic Asymmetry** is a primary theme in this talk.
I will present examples of rift basins and break-up margins from around Africa and Brazil to illustrate this concept.
The primary architectural unit or building block of rift basins, **half-grabens** created by an extensional border fault, dominates the developing rift basin and later break-up between Brazil and Africa.
Pre-Rift Controls are central to Tectonic Asymmetry.
The South Atlantic Aptian Salt Basin's syn-rift (pre-salt) architecture was controlled by Pre-Rift, basement heterogeneities. You will see examples from present-day rift basins and other older rift-rooted margin basins.
Basement control in the South Atlantic continued into the pre-break-up phase, shaping and adapting the response of the crust and upper lithosphere to extension through time, resulting in **wide and narrow margins.**
I also hope to convince you that continental passive-margin asymmetry, with Upper Plate – Lower Plate geometries tied to wide and narrow margins, are rooted in the original rift-stage asymmetry and have significant **implications for pre-salt exploration**.
Then some **conclusions** to close.
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These El Paso tectonic reconstruction maps shown **(L)** at 120 mya (Aptian) near the time of continental break-up, and **(R)** at 95 mya (Cen.-Turonian) after the Equatorial Atlantic margins of northern Brazil and West Africa separated.
In the map at **L**, we will be focusing on rift-drift evolution in the central portion of the South Atlantic (bold box, dashed red).
The map on the **R** shows this interpretation of the respective margins for South America/Brazil (green) and Africa (purple).
Note the marked asymmetry between any two segment of the opposing margins.
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"Pre-Salt" is a stratigraphic term with the same meaning on both sides of the South Atlantic, Brazil and West Africa.
"Pre-Salt" is all Lower Cretaceous strata deposited in continental rift basins before the onset of regional salt-evaporite strata deposition in Early to Mid-Aptian time (in red).
They are in normal stratigraphic sequence below the autochthonous mother salt.
Pre-Salt is composed of continental lacustrine and fluvial-alluvial to paralic-marine stratigraphic sequences.
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Slide 5 of 24 (Page 6 of 34)
Examples of **Tectonic Asymmetry:**
Shown here are 2D seismic profiles from Lake Tanganyika in East Africa, a basin created by continental rifting since the Miocene.
They illustrate the primary structural architectural unit of continental rift basins, **half-grabens**.
Top line: **Back-to-back, opposite dip half-grabens** defined by major border faults (red), with a horst-form accommodation zone in between, isolating the two distinct depositional sub-basins.
Bottom line: **Facing, oppositely dipping dip half-grabens** with a faulted, low relief antiformal accommodation zone in between.
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Slide 6 of 24 (Page 7 of 34)
The same lines in Lake Tanganyika (profiles D and C) are from 2 of the 6 sub-basins in the lake basin.
Each sub-basin is a fundamental half-graben unit, created by the formation of a primary Border Fault.
These **half-grabens** alternate dip polarity along strike (note the maroon arrows for dominant HG dip).
Each half graben is typically 120-150 km in length and 30-70 km wide.
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Slide 7 of 24 (Page 8 of 34)
In Egypt, the Miocene-age Gulf of Suez rift basin is also typified by alternating half-graben architecture.
Three alternating half-grabens, with intervening accommodation or transfer fault zones, constitute the entire basin.
Dimensions are comparable to those in East Africa.
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In Brazil, the Campos Basin is underpinned by Barremian-Neocomian to Middle Aptian-age half-graben basins.
Note the 3 side-by-side, same polarity half-grabens.
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Slide 9 of 24 (Page 10 of 34)
In the Santos Basin, Early Cretaceous half-graben basins are of varying dip polarities, causing complex linking arrangements in the form of multiple **accommodation zones**.
This suggests a complex pre-rift structural arrangement and a polyphase history for the Santos Basin.
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Here are several views of the South Atlantic from the literature. Each is interesting for their recognition of overall margin asymmetry.
L – Early recognition (1970's) by Brazilian geoscientists that the South Atlantic did not open uniformly and symmetrically.
An Early Cretaceous, N-S spreading center (B-B'), extended into the Santos Basin, continuing the earlier successful Jurassic oceanic opening (<u>blue line</u>) from South of the Rio Grande Rise position of today.
It aborted and shifted east along the present-day narrow Namib-Benguela margin (C-C'), and then propagated North to open the South Atlantic (A-A').
R – Davison has also documented conjugate margin linkages, **wide vs narrow margins**, noting apparent overlaps or gaps.
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Gomes et al. have recently supported this early view of a **Early Cretaceous N-S spreading** axis.
Over 200+ km from current day shoreline, it caused widespread Barremian age syn-rift uplift along the NE-SW trending **Outer High**, which is the site of so many recent Pre-Salt discoveries by Petrobras.
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Several types of **Pre-Rift Controls** shape the architecture and strain evolution of South Atlantic syn-rift basins and subsequent passive margins. This is what is termed here as **Tectonic Memory**.
Pre-Cambrian **basement** mobile belts, which are old collision zones between older and thicker Archean cratons, are the preferred sites for continental extension.
Mobile belt **fabrics** control the location and orientation of extensional rift **border faults**.
Pre-Cambrian mobile belts often have major **shear zones** that:
force rift half-graben polarity flips.
are intermittent **strain locks** on the propagating South Atlantic rift.
develop into **transform** slip lines between adjacent, alternating UP-LP margins.
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Mobile Belts are the primary or **first-order control** on rifting, in that rifts preferentially develop in them, and **avoid cratons**.
How does this happen? The ancient suture and any relict subduction slab induce long-term mantle convection cells and progressively weaken the crust and lithosphere.
This combined with far-field tectonic stresses can initiate **thermal anomalies** and tensile forces in mobile belts.
In fact, Pre-rift sag basins known to have preceded several parts of the South Atlantic rift are expressions of early deep lithospheric thinning.
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This map of the Southern half of Africa delineates the known, mapped basement outcrops.
Oligo-Miocene East African rift zones (red) and the overlying deep rift lakes (blue) follow the late Pre-Cambrian **mobile belts** (light pink) and avoid the oldest Precambrian Archean cratons (in bright pink).
Intra-mobile belt **shear zones** (dark brown - dashed) allowed Late Pre-Cambrian slip between oppositely dipping mobile belts and cratons. These have been observed to directly influence or shape the modern East African rift architecture.
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The Lake Malawi rift zone in East Africa is also a Miocene rift zone, like Lake Tanganyika.
Note once again the **alternating half-graben dip architecture** here.
In Lake Malawi, Pre-Cambrian basement **shear zones** force **changes in half-graben dip polarity.**
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An older example of **basement control on syn-rift segmentation** and margin break-up can be seen in the MSGBC Basin in NW Africa.
The mobile belt salients between 2 cratons were major lateral basement shear zones (orange), and were later exploited by Triassic-Jurassic rifting as **transfer faults** and developed into oceanic **transforms**.
The passive margin was broken into Upper Plate-Lower Plate margins.
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Upper Plate (UP)

- UP is essentially the mega-hanging wall in a dominant half-graben rift basin system controlled by a major border fault decollement into the upper ductile lithosphere.

>>wider
Lower Plate (LP)
LP is basically the mega-footwall in a half graben rift basin system.
>>narrower
This sets-up fundamental asymmetry both along strike and across to the conjugate basin. Due to this early, inherent UP-LP asymmetry, it may be concluded that **passive margins do not spilt symmetrically**.
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Back to the South Atlantic.
Based on these analogues and study of seismic and gravity-magnetic databases in South Atlantic margins, the following can be observed:
1st - **Rifts** follow Pre-Cambrian **mobile belt** fabrics.
2nd - Half-graben **polarity flips** are **forced** by major pre-rift shear zones (**maroon** arrows - dominant HG dip).
3rd - Major pre-rift shear zones are **strain locks** to propagating rift (e.g., S & N ends).
4th - Major syn-rift **accommodation zones** coincident w/ pre-rift shears develop into **slip lines** for alternating UP-LP compartments along strike.
The **Santos - Namib/ Benguela** sector was the site of reorganized Early Cretaceous spreading and was a **strain lock**:

Rift refracted across a major pre-existing basement shear, and around major cratons.

Result was a wide zone of mixed styles of extension under overall sinistral shear..

The northernmost sector of the South Atlantic was also a later **strain lock**, with significant late-stage, along-axis shear.
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In the **Reconcavo** and **Camamu-Almada basins** in NE Brazil, we can see the control of basement on rift border fault orientation and half-graben polarity.
Reconcavo Basin: the Salvador Horst is one the few exposed rift border faults in the South Atlantic. It follows the Pre-Cambrian Brasiliano mobile belt fabric and demarcates an **East-dipping half-graben**.
Camamu: SE of Salvador, a major basement salient (PC shear zone) forced the **switch in the half-graben polarity** of the Brazilian syn-rift margin to **down-to-the-West** and corresponds to westward extension of the Fang oceanic fracture zone of Gabon's Atlantic margin.
Almada: 160 km farther South, the Olivenca High defines the westward extension of the next major South Atlantic fracture zone, between the Almada and Jequitinhonha basins.
Onshore, the syn-rift **Sambaituba** fault outcrop is an example of a syn-rift structural accommodation zone, where 2 fundamentally different Pre-Cambrian basement fabrics (NNE-SSW, NE-SW) intersect.
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South Atlantic Reconstruction
120 MYA Aptian late Syn-rift
1. Major pre-rift heterogeneities reflecting assembly of southern Gondwana: basement mobile belt **shear zones** (in dk brown) and dominant **mobile belt fabrics** (pink).
2. Triassic rifting and Jurassic oceanic spreading (blue) in No. Atlantic/ GOM to the North, and the South Atlantic to the Florianopolis FZ (Brazil) or Walvis Ridge (Africa).
3. Cretaceous rifting of the South Atlantic Aptian Salt Basin (red). South Atlantic **continental rupture** occurred by Mid Aptian time.

4. Wrenching occurred along the proto-Equatorial Atlantic margin and across Central and NE Africa largely along reactivated, pre-existing, nearly E-W shear systems (green).

This zone acted as a **strain lock** until Equatorial South Atlantic opened in Cenomanian-Turonian time.

95 MYA Cen.-Turonian Drift

1. Interpreted margin edges (OCS and COB) for Brazil (green) and Africa (purple) from seismic and gravity-magnetic data. Note how margin widths vary.
2. A gap (orange) of OCS and COB reflects varying extension along strike. Here wide margins are generally interpreted to be highly extended **UP margins**.
3. Major oceanic Transforms or FZ's (red) delineate major margin compartments, UP-LP

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So how does this body of data and premise potentially impact a passive margin basin's development post-rift and break-up, and what are the impacts on Pre-Salt exploration?

Salt thickness has been shown to be controlled by UP-LP tectonic control in the MSGBC basin of NW Africa.
Salt is key to understanding both source rock maturity and reservoir distribution and quality, and the South Atlantic is no exception.

Post-salt source rocks tend to be more thermally evolved due to salt conductivities and efficient heat transmission into overlying sediments

Pre-salt source rocks can remain oil prone even at great depths.

Syn-rift sand quality may be preserved due to lower temperatures below massive salt and with early oil expulsion and migration.

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The **Santos Basin** is a special case where Gondwana's basement geology pre-disposed it to become an **asymmetric and wide (UP)** rifted break-up margin, where rich late-syn-rift source rocks and thick extensive salt were deposited, especially over the Outer High of the Santos Basin.
Almost 250-300 km offshore, the **Outer High** has seen well over a dozen major discoveries during the past 3 years, with estimated reserves totaling 14 BBO 1P-2P and a possible upside range of 30-35 BBO, according to Petrobras.
Thick salt coupled with rich source rocks and potentially extensive reservoirs have produced a significant, new World Class petroleum province.
Other recent deepwater Brazilian Pre-Salt discoveries in the Santos, Campos, and Espirito Santo basins, and also in Angola, give promise to other Pre-Salt play variants throughout the South Atlantic, Brazil, and West Africa.

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Presented in this article are data and evidence of the primacy of tectonic asymmetry in rifting, shaped significantly by pre-rift heterogenities. Pre-rift shears cause major half-graben polarity flips and evolve into oceanic transforms. This imprint is "Tectonic Memory" and it survives. From rift to drift passive margins, the UP-LP asymmetry is expressed by highly extended margins adjacent to others across transfer/ transform fault zones.
Some margins are wide and others narrow. Therefore not all margins are created equal. Not good or bad, just different.
Different Exploration play combinations must be present in wide and narrow margins, due to variations in Petroleum System combinations.
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[http://www.searchanddiscovery.net/abstracts/html/2009/intl/abstracts/geetan.htm]).
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