Interplay of Basement Tectonics, Salt Tectonics, and Sedimentation in the Kwanza Basin, Angola*

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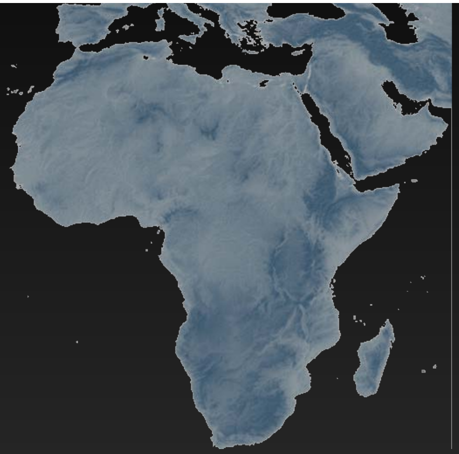
Abstract

The Lower Congo Basin has the most prolific hydrocarbon resources in West Africa. However, the basin is atypical of the region because the dominant Congo Fan masks the effects of epeirogenic basement tectonics. In contrast, other parts of the West African margin reveal how differential basement uplift has influenced basin evolution. It seems likely that basement tectonics has also affected the Lower Congo Basin but has not yet been fully appreciated.

The adjoining Kwanza Basin evolved as two different subbasins. The onshore Inner Kwanza Basin (IKB) is an interior salt basin enclosed by basement highs. It is dominated by halokinetic troughs and fold belts formed by basement shortening and uplift. In contrast, the offshore Outer Kwanza Basin (OKB) is an open continental margin that deformed by gravity spreading, resulting in ~25 km of updip extension balanced by downdip shortening. From Late Cretaceous to Miocene, advance of the Angola Salt Nappe accommodated most shortening in the OKB. Then Plio-Pleistocene burial of the nappe toe blocked its advance, which compressed the entire deepwater salt basin.

Uplift of both basins varied greatly in space and time. Where the Tertiary cover is thickest, the IKB has remained near sea level since the Eocene, which refutes the notion of a massively uplifted coastal plateau. Major uplift (2-4 km) of the Precambrian hinterland craton accelerated sediment input but had little Neogene structural effect on the deepwater OKB other than sedimentary loading. Instead, much smaller uplifts of the shelf drove spectacular Neogene deformation on a metastable slope, which radically changed basin kinematics and created or improved many structural traps.

Interplay of Basement Tectonics, Salt Tectonics, and Sedimentation in the Kwanza Basin, Angola



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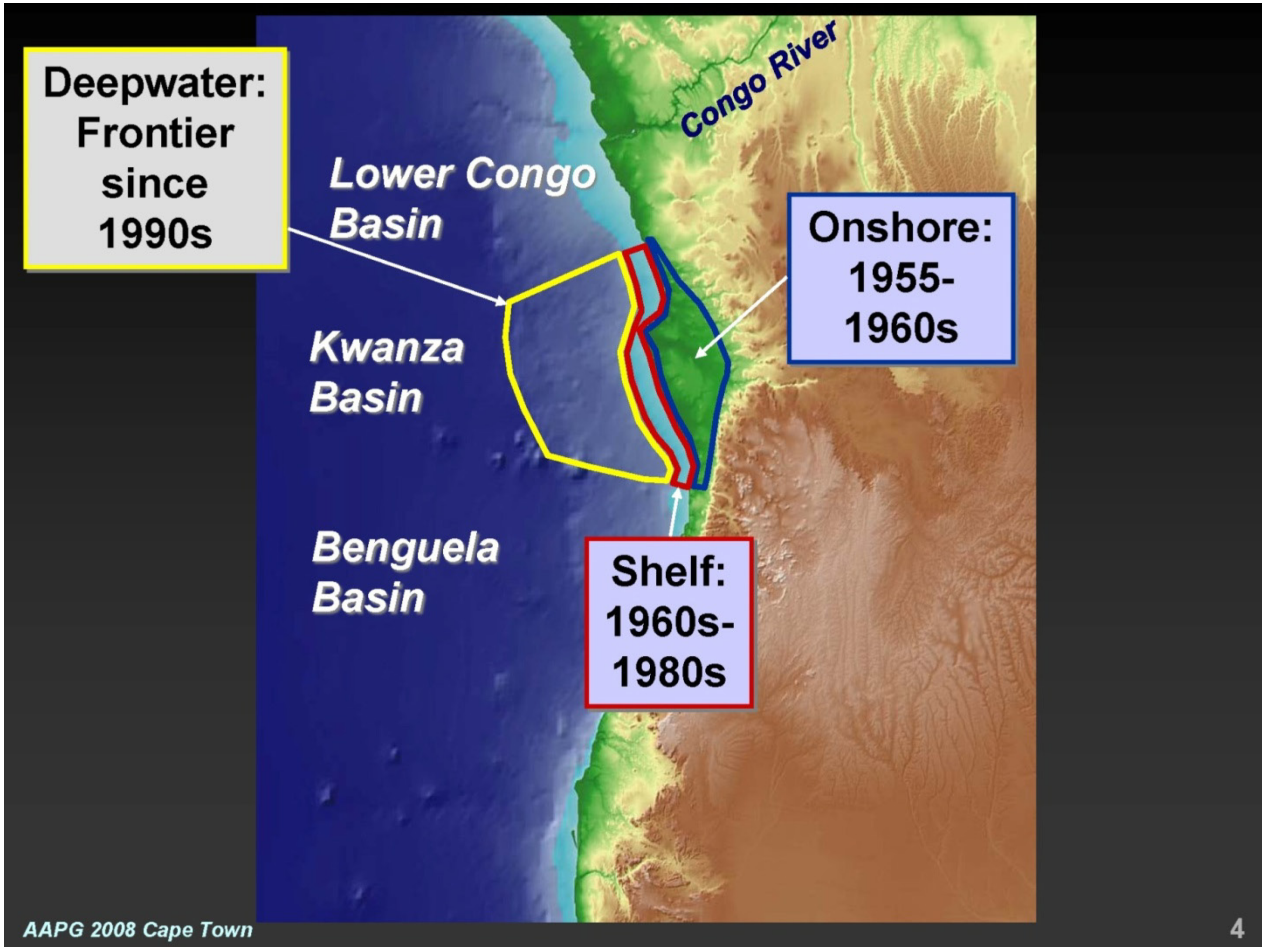
Lower Congo Basin

- Contains most-prolific hydrocarbon resources in W. Africa
- Basin is geologically atypical of W. African margin because of the Congo Fan's massive depocenter
- Thickness of this fan masks effects of post-rift, epeirogenic basement tectonics
- Other parts of W. African margin reveal how differential basement uplift in Late Cretaceous and Cenozoic interacted with sedimentation, salt tectonics, and thus influenced hydrocarbon systems
- This talk describes these basement effects in the neighboring Kwanza Basin. These effects provide clues to the types of processes that might have affected the Lower Congo Basin



Notes by Presenter:

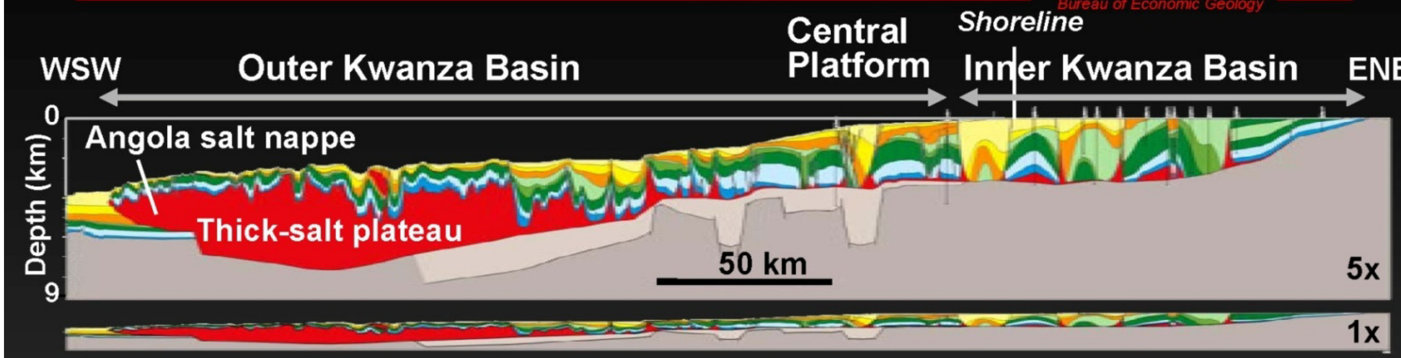
The best-known region is the extensional province on the continental shelf, which has been intensively explored for its Albian reservoirs.

To build a picture of the entire Kwanza system, we focused on its lesser known regions.

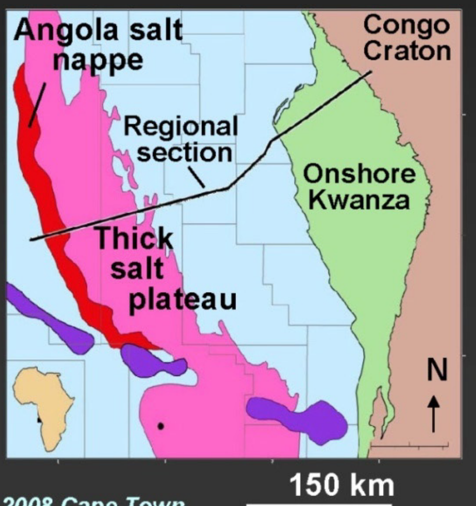
- Deep-water and ultradeep-water frontiers of the Outer Kwanza Basin, now being explored.
- Onshore: mysterious not because it is new to exploration but because it is old; it has not been explored for several decades.

The Kwanza region had a much more complex history than might be expected on a passive margin.

Kwanza Basin Overview



Kwanza Basin Map



- **Inner Kwanza Basin**
  - Interior salt basin, mostly enclosed by basement highs
  - Halokinesis dominant, minor translation
  - Shortening driven by epeirogeny.
- **Outer Kwanza Basin**
  - Passive margin
  - Gravity-spreading dominant
  - Updip extension compensated by downdip shortening.

Notes by Presenter:
The Kwanza Basin is divided into the Inner and Outer Kwanza salt basins by the Central Platform, a chain of synrift basement highs on which Aptian salt has always been thin or absent.
IKB covers all of onshore, plus fringe of continental shelf.
OKB is entirely offshore on continental slope .

Influence of Basement Tectonics, Part 1

- **Fold belts and basement uplifts in Inner Kwanza Basin**

  Outcrop evidence of basement tectonism

- **Crustal uplift in Outer Kwanza Basin**

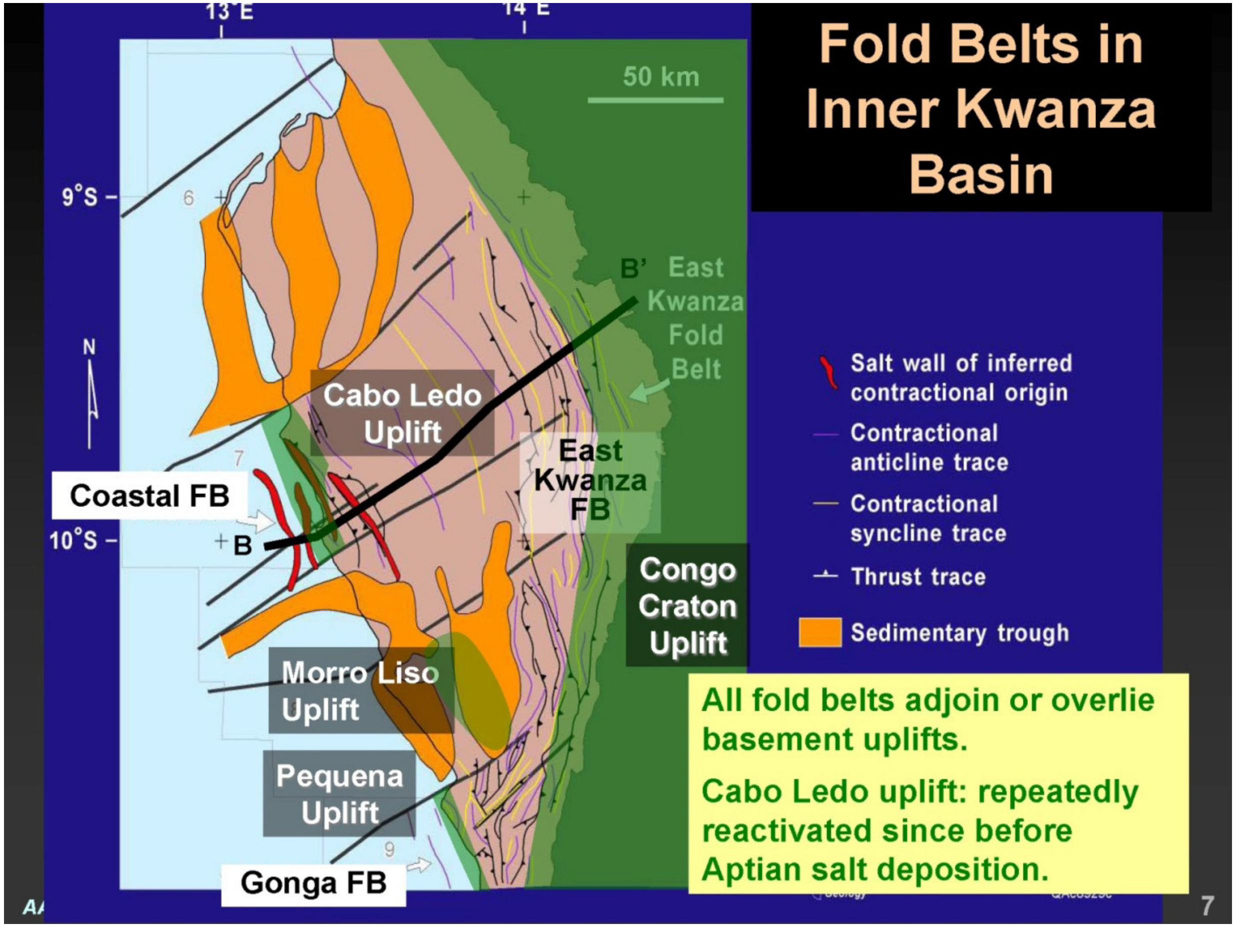
  Late Cretaceous uplift of basement in ultradeep water

- **Neogene uplift magnitude in Inner Kwanza Basin**

  Patterns of onshore uplift in basin and hinterland

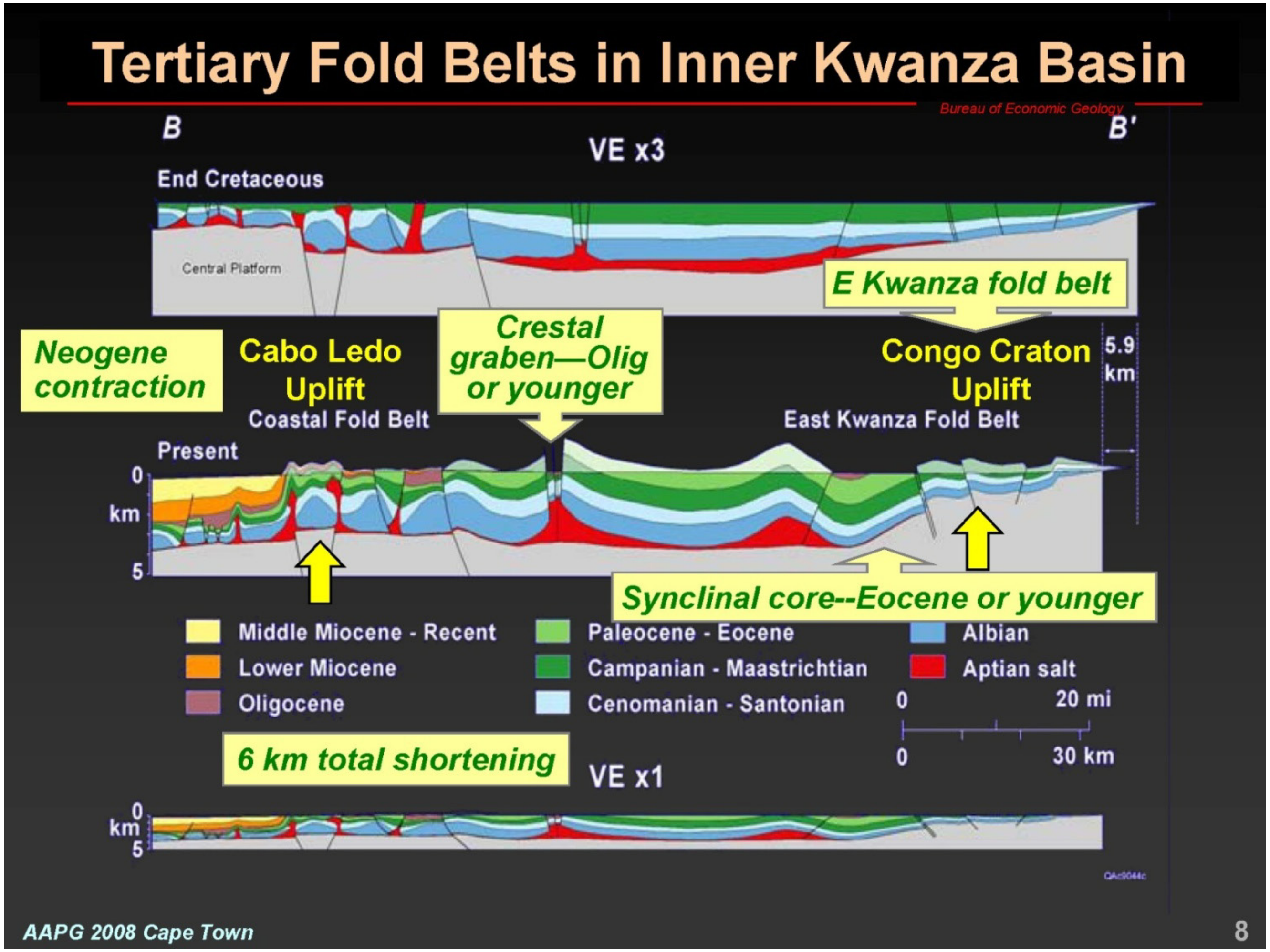
- **Neogene uplift results in Outer Kwanza Basin**

  Effect on sedimentation and salt tectonics



Notes by Presenter:
Three fold belts in the Inner Kwanza Basin.
Coastal Fold Belt is detached above salt, and includes salt-cored anticlines and squeezed diapirs.
Gonga Fold Belt involves basement (Goldhammer and others, 2000).
East Kwanza Fold Belt is detached above salt in the west and basement involved in the east.
All three fold belts are located next to or above basement-block uplifts. Shortening coincided with basement uplift.
Inner Kwanza Basin is segmented by northeast-striking transfer zones formed during Neocomian rifting.

Provinces lacking buttressing coastal uplifts had an early phase of basinward detached extension, which formed megawalls. Later withdrawal of salt from megawalls formed the large depotroughs for which the basin is famous.



Notes by Presenter:
Top: Restoration to End Cretaceous through central part of IKB. Cabo Ledo was high relative to IKB, but low relative to OKB.
Bottom: Present-day cross section shows 2 fold belts:

- Coastal fold belt on top of Cabo Ledo basement uplift, but partly detached on salt
- East Kwanza fold belt: above uplifted Congo Craton, partly detached on basement and partly on salt.
- Least folding in lowest, thickest part of basin, and concentration of shortening above basement highs indicates not driven by gravity
- Age of folding is post-Eocene-Oligocene but more refined age not stratigraphically discernable because uplift removed younger cover

Influence of Basement Tectonics – Part 2

- **Fold belts and basement uplifts in Inner Kwanza Basin**

  Outcrop evidence of basement tectonism

- **Crustal uplift in Outer Kwanza Basin**

  Late Cretaceous uplift of basement in ultradeep water

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Nappe Breakout: Albian-Eocene

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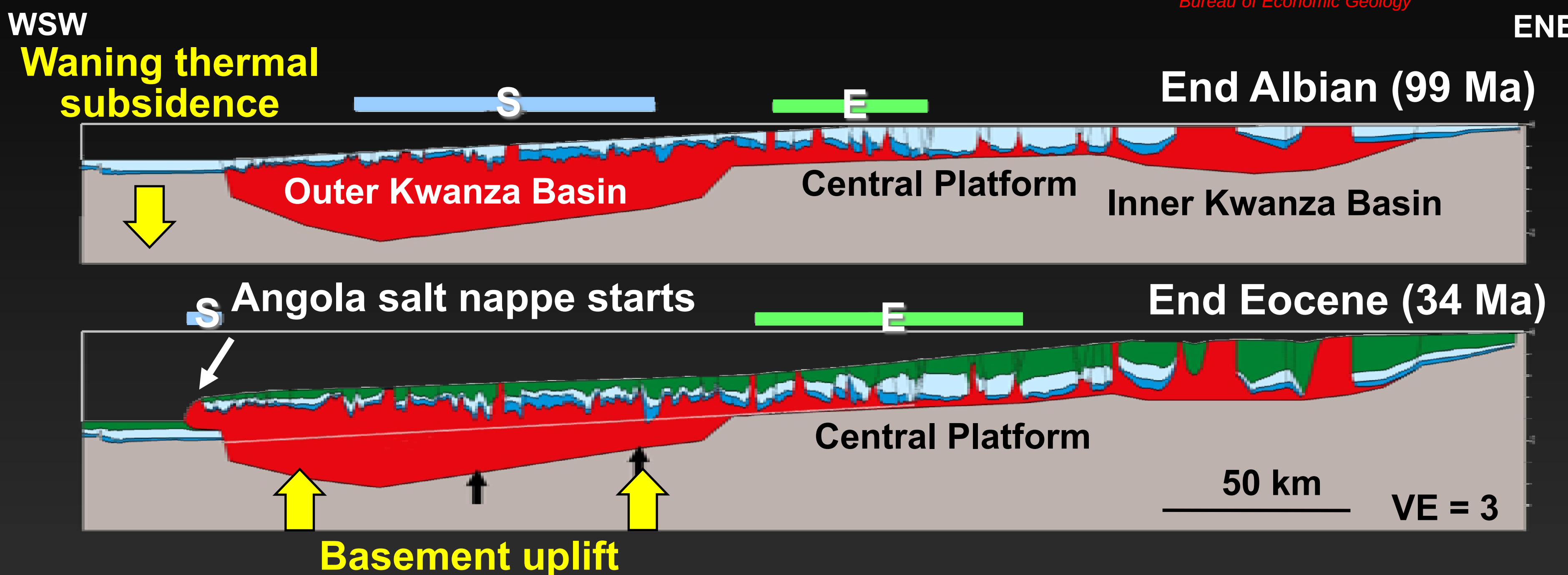
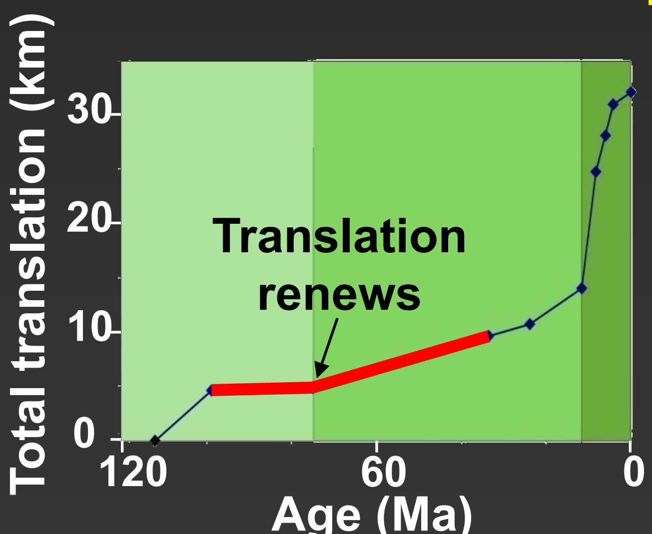
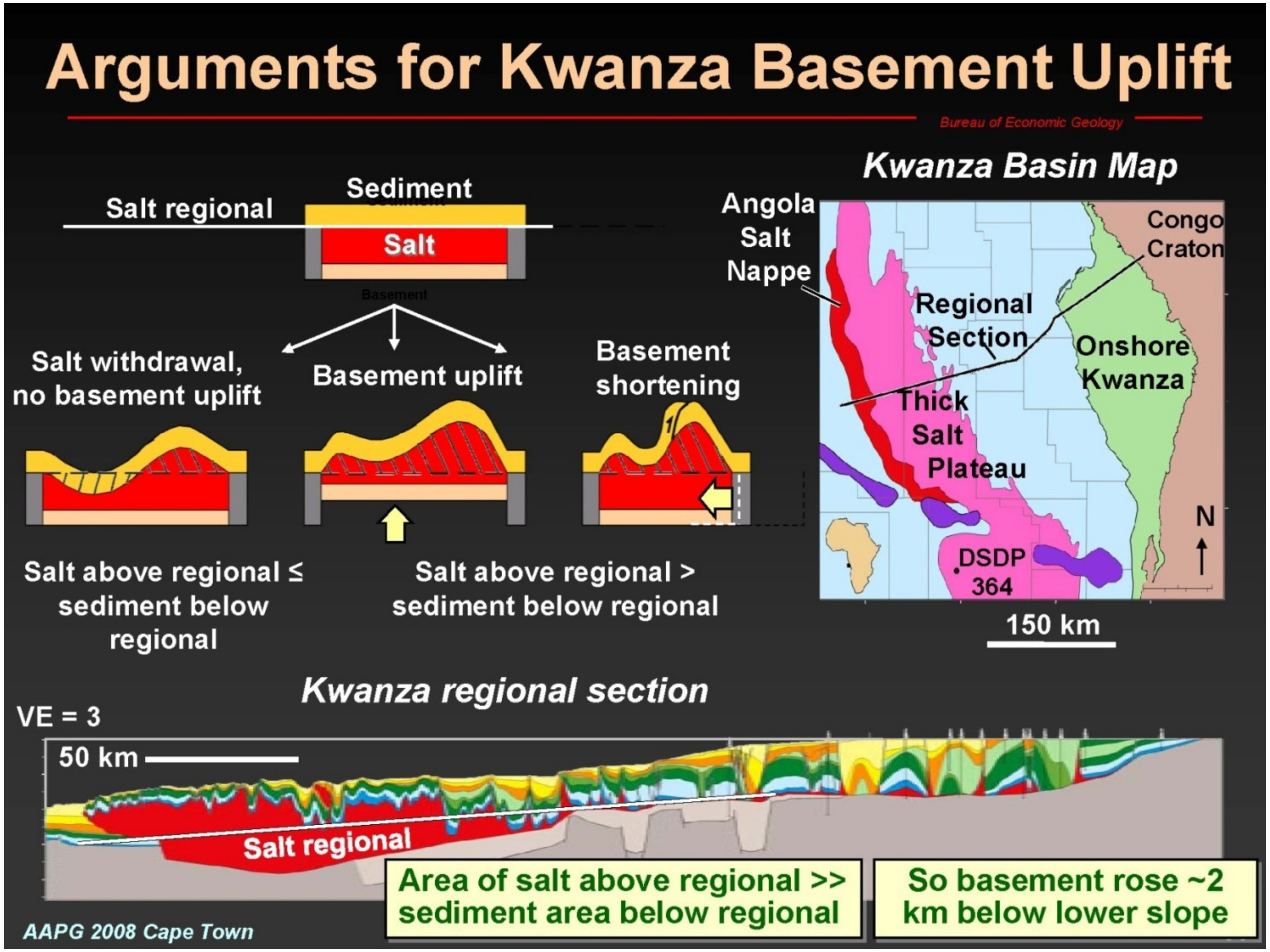




- Angola Salt Nappe rejuvenated basinward translation
- Uplift of basement beneath Outer Kwanza Basin triggered nappe breakout. Uplift created an escarpment, which salt pierced to flow over abyssal plain, forming the Angola salt nappe
- What is the evidence for uplift?



Notes by Presenter:

A regional elevation for salt can be defined by connecting the two edges of the original salt basin by a straight line. Salt can only rise above this line in three ways.

(1) Salt may rise when displaced by sediment sinking in a withdrawal basin. If no salt is lost to dissolution, then volume of salt above regional = volume of sediment below regional. If salt is dissolved from upwelling, then salt above regional < sediment below regional. These calculations should be performed in 3D to ensure that no salt is flowing in or out of the plane of a given section.

(2) Salt may rise if the floor of the basin rises relative to the flanks during basement uplift. Salt above regional may greatly exceed sediment below regional.

(3) Salt may rise if the walls of the basin close in during basement shortening. Again, salt above regional may greatly exceed sediment below regional.

Based on well data in central platform, salt is currently 50-150 m thick beneath raft blocks.

Salt was likely never more than 100-200 m thicker than this, based on lack of tall diapirs, lack of rotation or salt-withdrawal features in raft blocks.

Because raft blocks on the Central Platform have been essentially unaffected by salt withdrawal, they can be treated as anchor points.

Timing of Kwanza Basement Uplift

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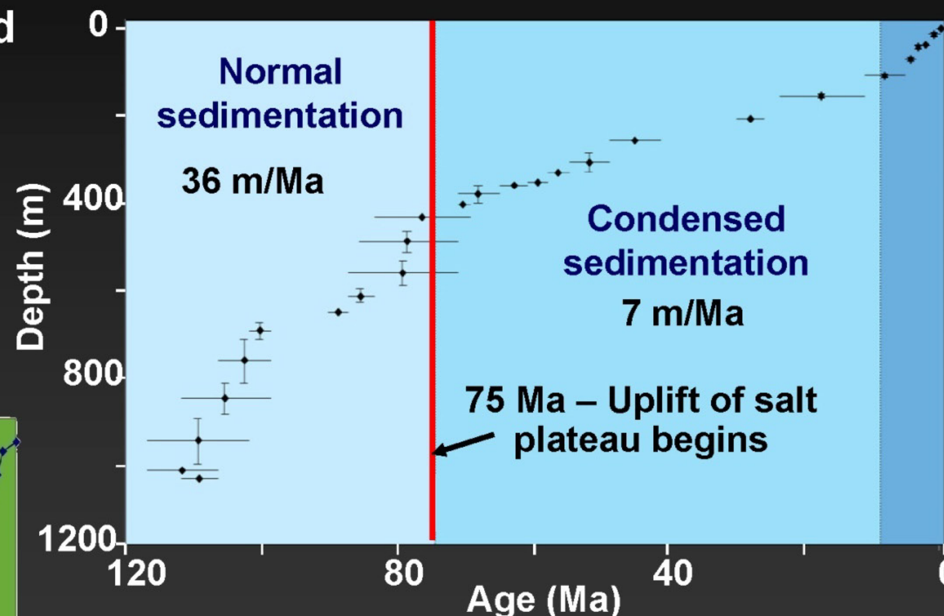
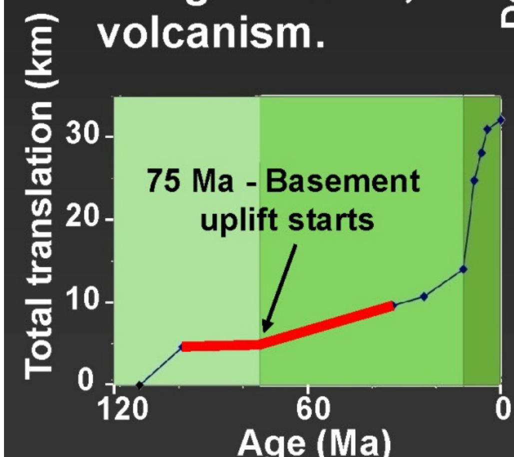
- Sedimentation rate fell to 1/5 in DSDP 364, then remained condensed.
- 75 Ma coincides with Santonian plate reorganization, volcanism.

Sedimentation rate in DSDP 364



Data from Bolli et al., 1978



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Notes by Presenter:

DSDP well 364 penetrated the full stratigraphic section above Thick Salt Plateau.

The sedimentation rate dropped from 36 to 7 m/m.y. at about 75 Ma. Coincident with a Santonian plate reorganization that caused significant deformation farther north on the African margin; also period of volcanism in the onshore Kwanza Basin.

Influence of Basement Tectonics – Part 3

- **Fold belts and basement uplifts in Inner Kwanza Basin**

  Outcrop evidence of basement tectonism

- **Crustal uplift in Outer Kwanza Basin**

  Late Cretaceous uplift of basement in ultradeep water

- **Neogene uplift magnitude in Inner Kwanza Basin**

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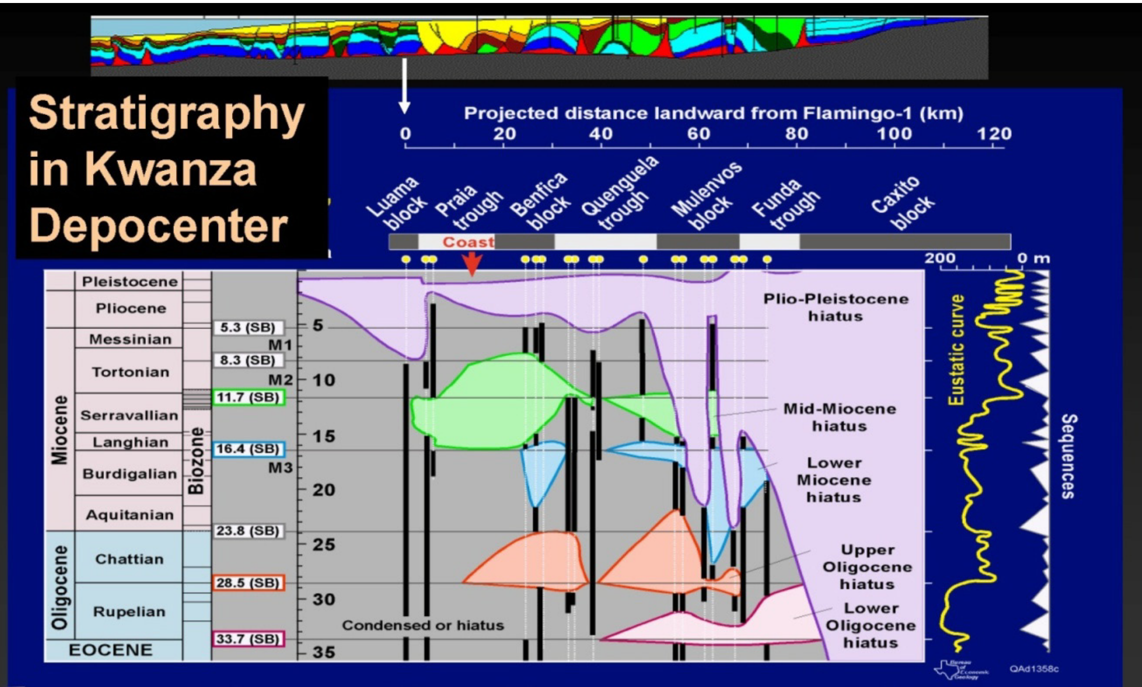
- **Neogene uplift results in Outer Kwanza Basin**

  Effect on sedimentation and salt tectonics

Stratigraphy in Kwanza Depocenter



- Between 5 hiatuses, all Oligo-Miocene strata were *marine* (planktonic forams)
- This part of Inner Kwanza Basin remained at or below sea level between hiatuses until ~5 Ma, then rose by ~150-250 m
- No high (1–2 km) coastal plateau across basin in Neogene

Notes by Presenter:

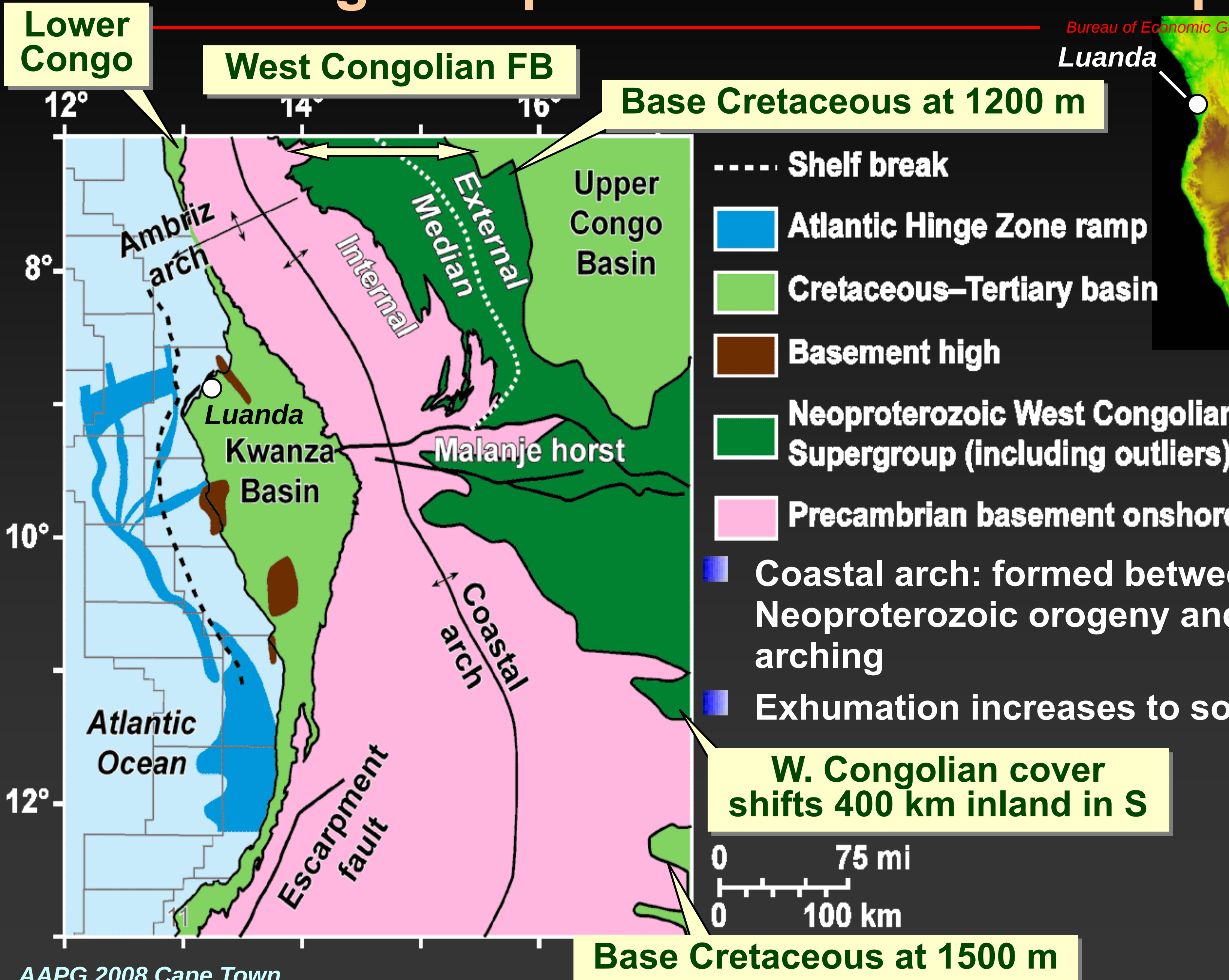
Planktonic biozones show five major hiatuses in the Oligo-Miocene and Plio-Pleistocene. Between gaps, Oligo-Miocene strata accumulated under marine conditions. A marine setting refutes the idea of a 1-2 km-'high coastal plateau in the mid-Tertiary.

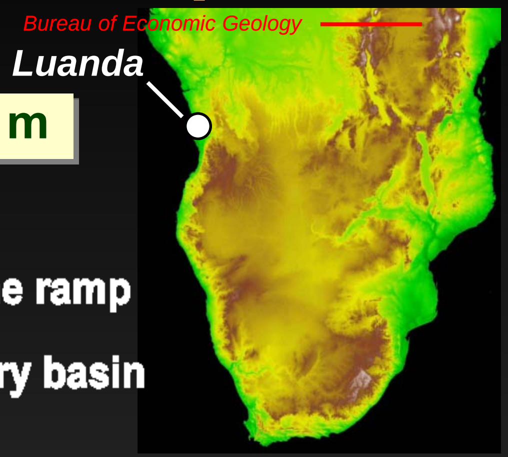
Coastal plain of N. Kwanza remained near sea level in the Tertiary until 5 Ma ago; then the plain was uplifted by ~150–250 m and thinly blanketed by continental deposits.

Mid-Miocene is the largest of all 4 hiatuses in time-space. Age is 12–11 Ma. Coincided with eustatic fall of 115 m at 11.7 Ma. Slumping began on the shelf at 15-10 Ma (Lunde et al. 1992). Erosion was deep enough to cut all 3 main depotroughs (white bar), not just the highs (charcoal bar) in the inner basin.

This hiatus ended marine conditions in the E of the basin. Marine conditions returned in the W of the basin.

Geologic Map Reveals Differential Uplift





- Coastal arch: formed between Neoproterozoic orogeny and Tertiary arching
- Exhumation increases to south

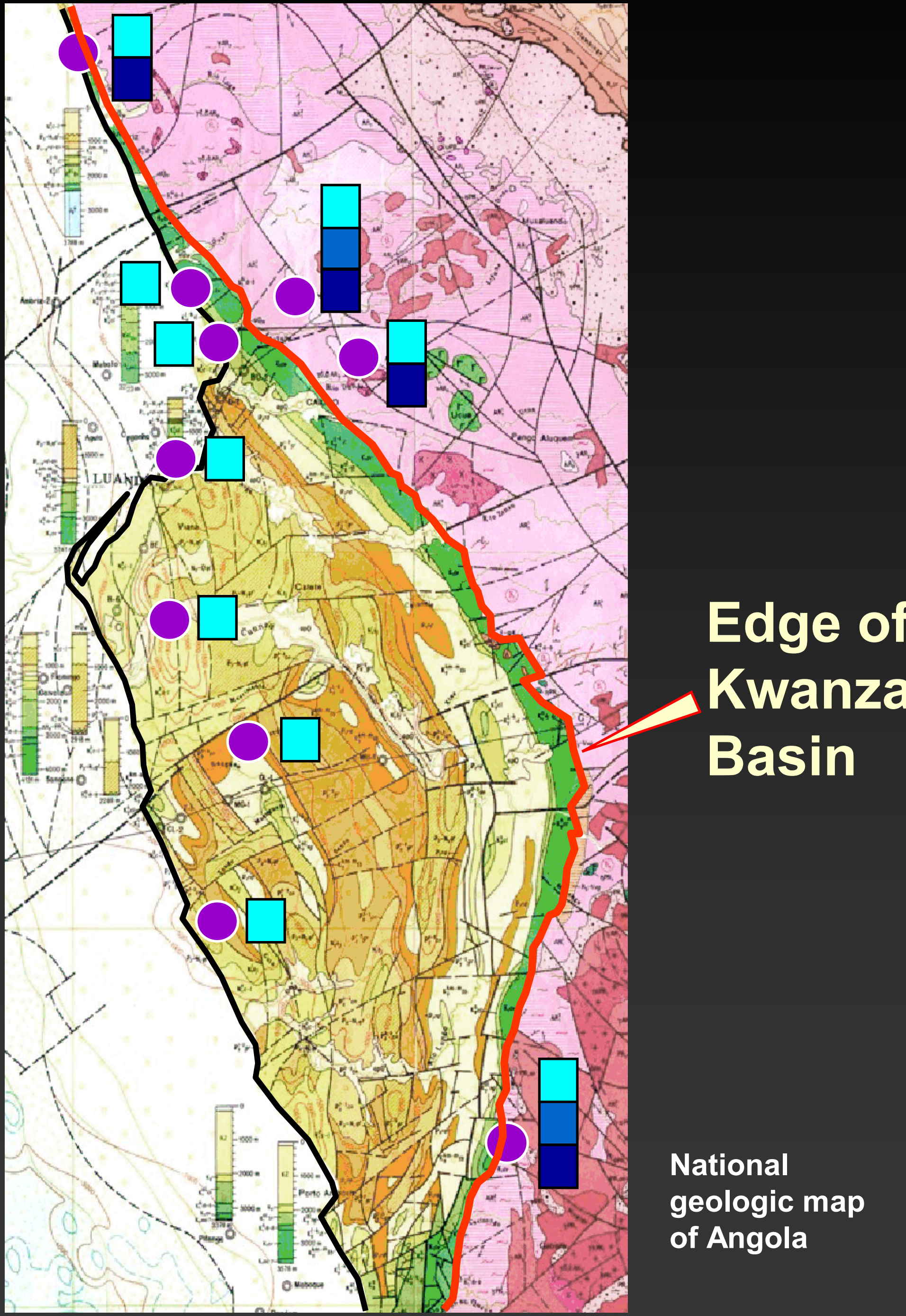
Apatite Fission-Track Analysis

Fission tracks form by decay at uniform rate. Destroyed by heating.

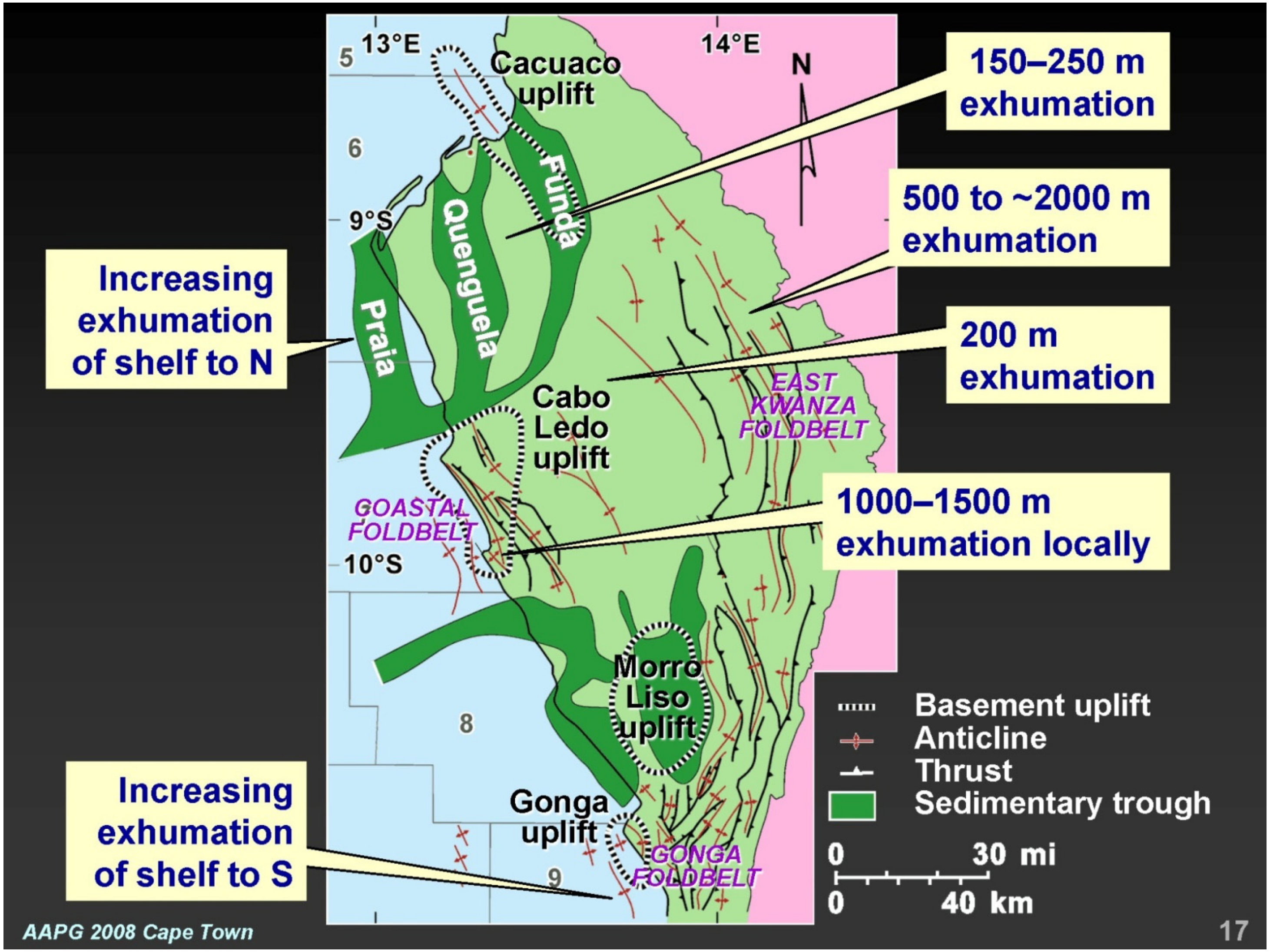
3 Thermal Events

- Neogene, 20–10 Ma
- Cretaceous, 100–70 Ma
- Jurassic, ~150 Ma

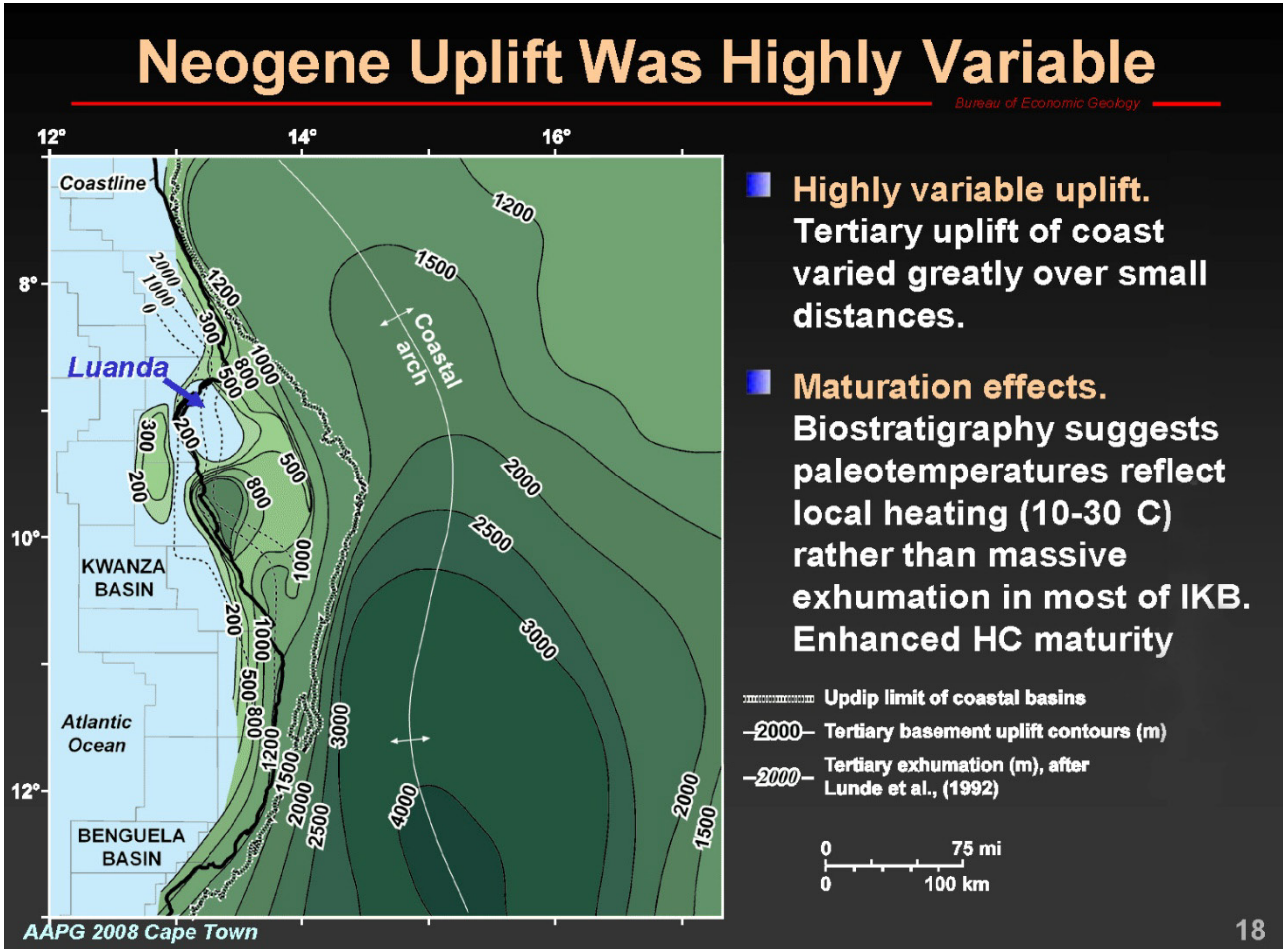
- Sample location



National geologic map of Angola



Notes by Presenter:
Mid-Miocene thermal event affected hydrocarbon maturation. Thermal effect in Kwanza coastal plain was not due to massive exhumation. Instead, probably caused by advection of hot fluids or increased geothermal gradient. This conclusion fits with previously reported Miocene heating of 30–40°C on the north Angolan margin.



Notes by Presenter:
Massive Neogene uplift of hinterland. The Kwanza rim and Precambrian hinterland were exhumed 1–4 km, but tilting did not appreciably affect the northern coastal plain of the Kwanza Basin. No coastal high plateau existed in the Neogene.

Largest Neogene uplift was in the Precambrian hinterland: 2–4 km uplift

Large Neogene uplift of Cabo Ledo: ~1000–1500 m uplift of the coast and shelf.
Probably had a major tectonic effect (not quantified.)
Small Neogene uplift on the shelf: ~150–250 m uplift tilted shelf and upper slope seaward.

This uplift had a major effect on deep-water salt tectonics. Hudec & Jackson (2004) estimated ten-fold increase in seaward translation rate in the Miocene.

Implications for hydrocarbon maturation .Biostratigraphy in N. Kwanza precludes significant paleoburial (except the E rim). Thus, Neogene heating (20 – 60°C) in the coastal plain is likely due to local advection of hot fluids or to increase in the paleogeothermal gradient. Both processes introduce heat, which could enhance maturation of post-salt source rocks.

Walgenwitz et al. (1990) reported Miocene heating of 30 – 40°C on Angolan margin farther N.

Neogene rise of the Precambrian hinterland supplied a massive sediment dump, which enhanced hydrocarbon maturity in the deep-water region.. Mid-Miocene thermal event has implications for hydrocarbon maturation.

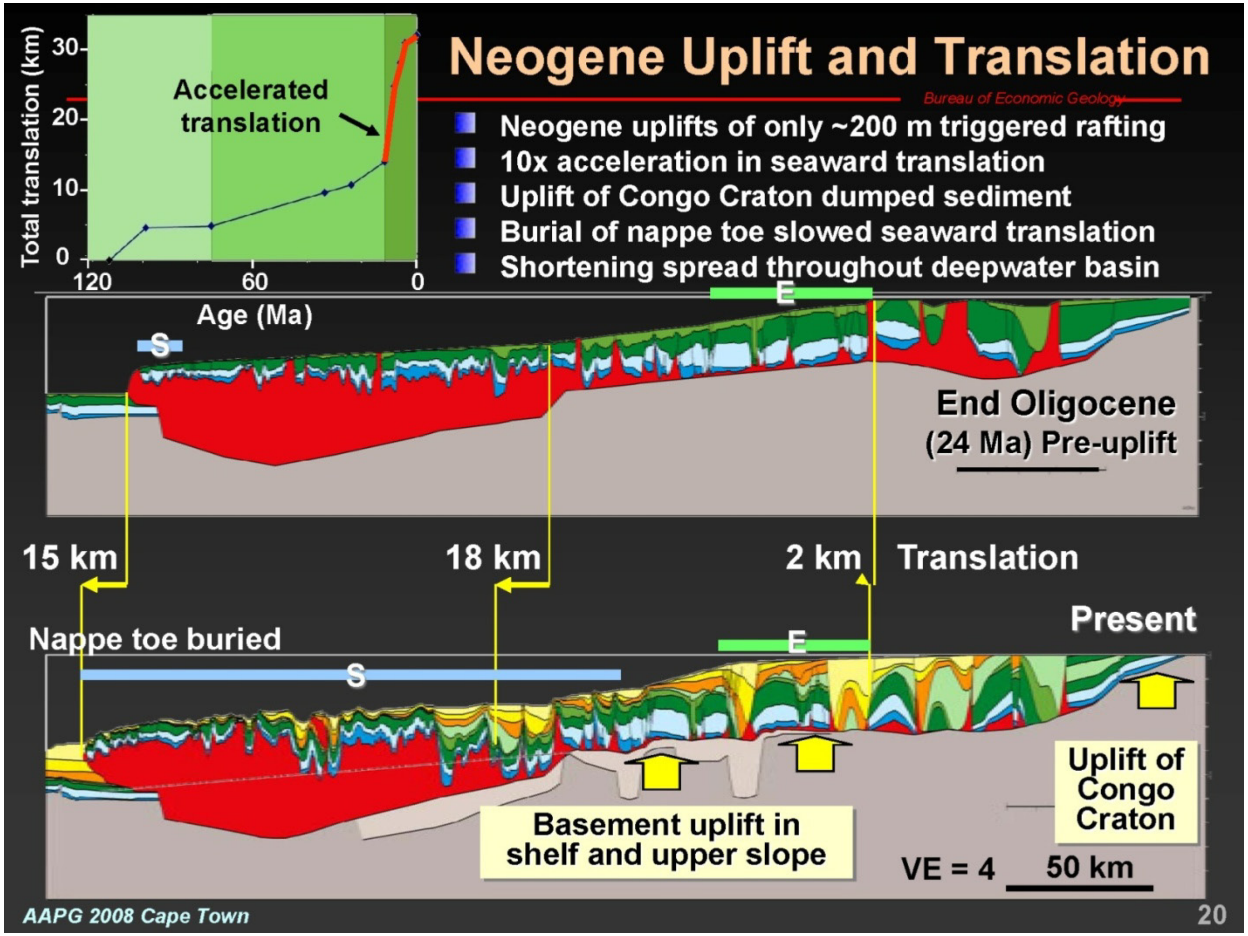
Influence of Basement Tectonics – Part 4

- **Fold belts and basement uplifts in Inner Kwanza Basin**
  Outcrop evidence of basement tectonism

- **Crustal uplift in Outer Kwanza Basin**
  Late Cretaceous uplift of basement in ultradeep water

- **Neogene uplift magnitude in Inner Kwanza Basin**
  Patterns of onshore uplift in basin and hinterland

- **Neogene uplift results in Outer Kwanza Basin**
  Effect on sedimentation and salt tectonics



Notes by Presenter:

Craton uplift shed a mass of Neogene sediments onto the continental margin without major rivers.

Minor ~200 m uplift of shelf ands upper slope was important. Triggered Neogene gravity spreading of the Kwanza margin and Phase 2 extensional rafting.

Patterns of onlap and truncation suggested instead that the basin was destabilized by tilting and minor uplift of small basement blocks. Most blocks are 10–20 km wide, and maximum uplifts were on the order of a few hundred m.

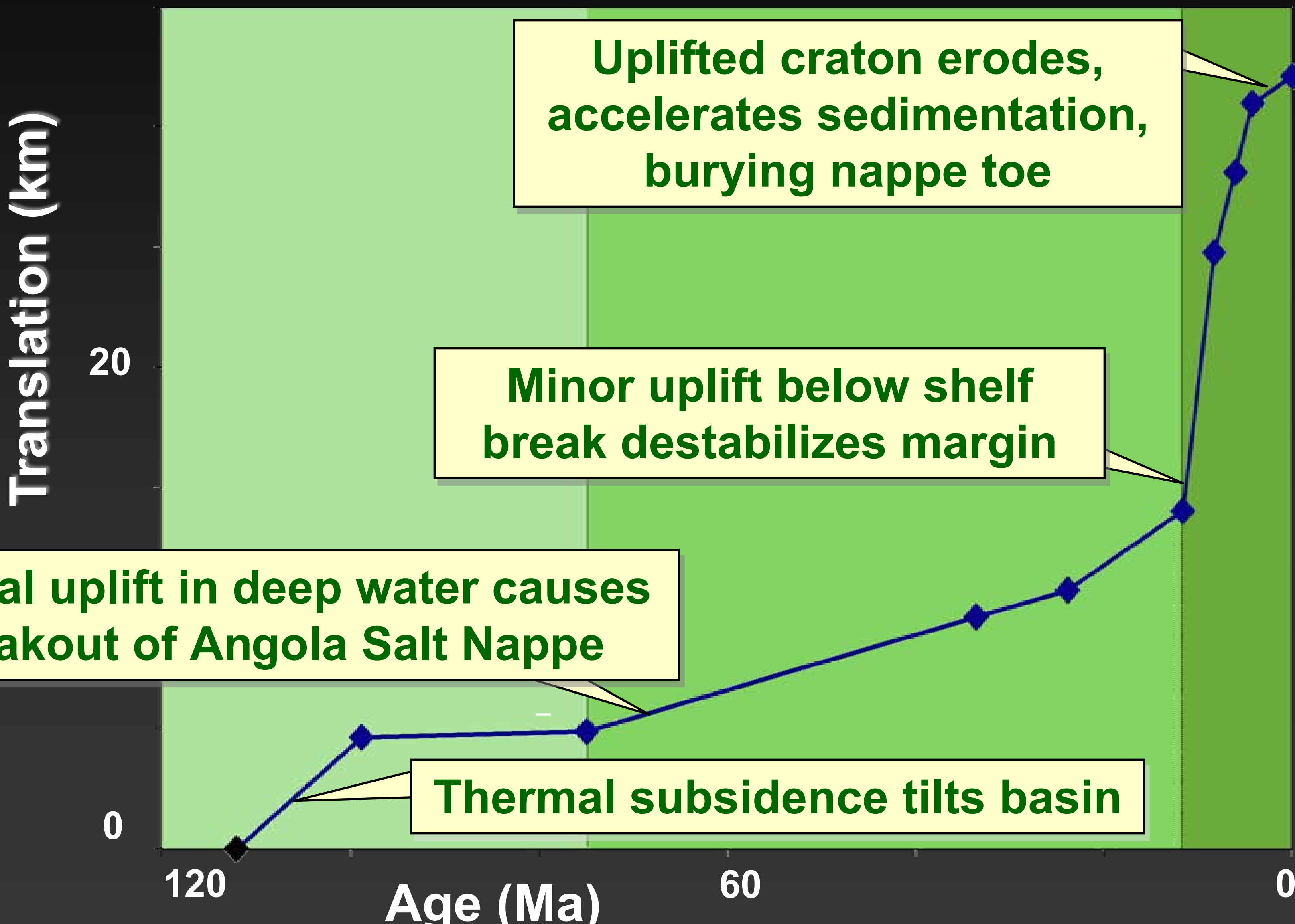
The fact that such small uplifts could have such a major effect on translation rates suggests that the margin was only metastable prior to uplift There appears to be a delicate balance between driving and resisting forces.

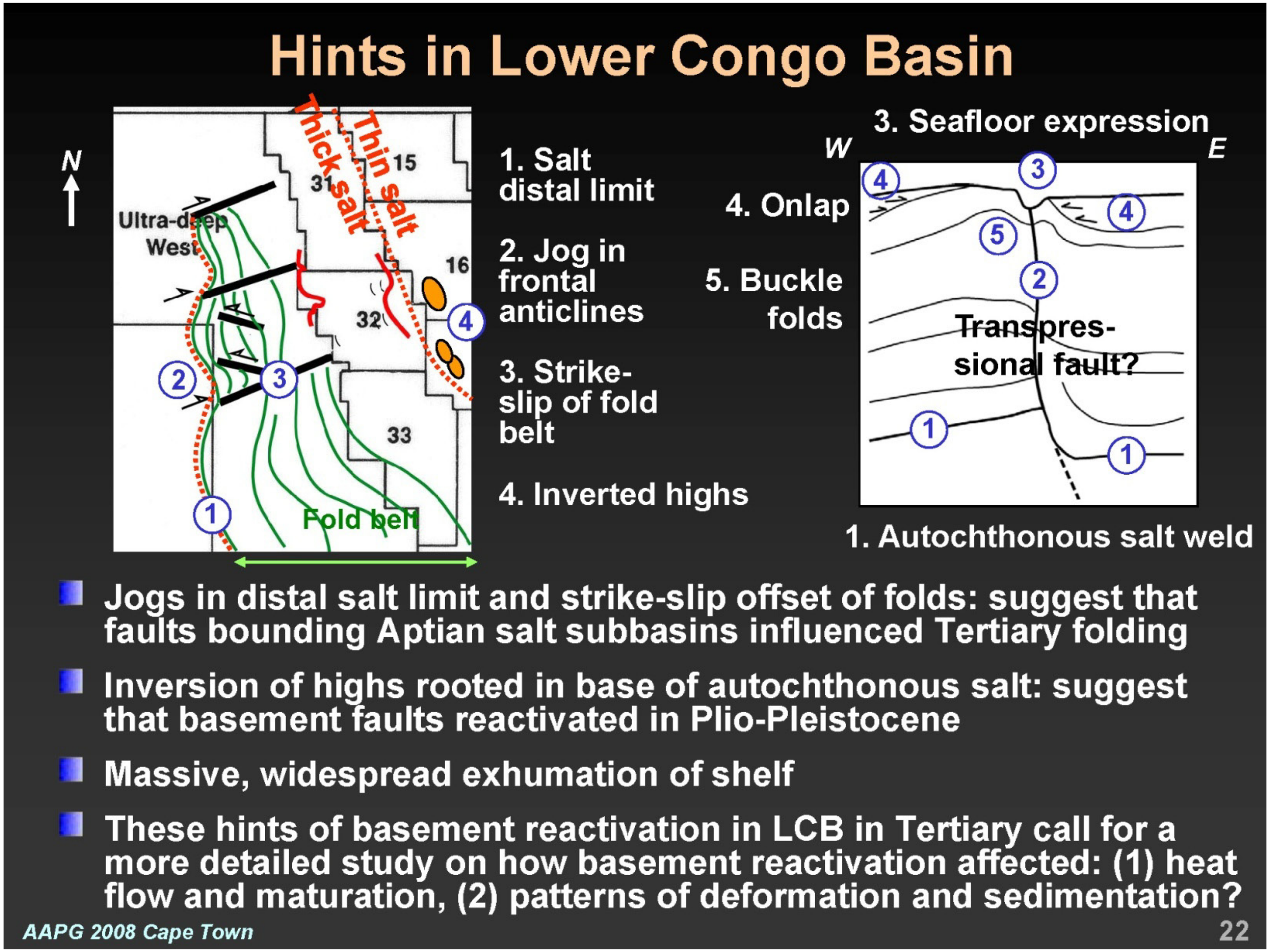
- Major extension (20 km) in central region, mostly by extensional opening of Praia depotrough, filled entirely by Neogene sediments.

- Farther downdip, 18 km of translation is recorded by onlaps over Atlantic Hinge Zone. Farther downdip still, the Angola Salt Nappe advanced by 15 km in Neogene. Again, intervening squeezed diapirs and mild buckling absorbed another 2 km of translation.

- Recent slowing of deformation due to rapid aggradation of the abyssal plain since the middle Miocene. Deposition rates on the abyssal plain have increased from 8 to 130 m/m.y.. This rapid sedimentation has: (1) buried the toe of the Angola Salt Nappe, forming a buttress at the downdip end of the system. (2) decreased the overall slope of the system by increasing the elevation of the downdip end.

Summary


Uplifted craton erodes, accelerates sedimentation, burying nappe toe
Minor uplift below shelf break destabilizes margin
Crustal uplift in deep water causes breakout of Angola Salt Nappe
Thermal subsidence tilts basin
Translation (km)
20
0
120
60
0
Age (Ma)



Notes by Presenter:

Rift architecture can influence salt-tectonic evolution in at least three ways:

1) Variations in extension magnitude lead to differential thermal subsidence, which controls dip on base of salt.
2) Highs and lows in basement can control salt isopachs.
3) Reactivation or inversion of rift-age structures can buttress basinward translation, invert older salt structures, or create new salt structures.

References

Bolli, H.M., W.B.F. Ryan, J.B. Foresman, W.E. Hottman, H. Kagami, J.F. Longoria, B.K. McKnight, M. Melguen, J.H. Natland, D.F. Proto, W.G. Siesser, 1978, Angola continental margin; Sites 364 and 365 :Initial Reports of the Deep Sea Drilling Project, v. 40, p. 357-455.

Bolli, H.M., W.B.F. Ryan, J.B. Foresman, W.E. Hottman, H. Kagami, J.F. Longoria, B.K. McKnight, M. Melguen, J.H. Natland, D.F. Proto, W.G. Siesser, 1978, Walvis Ridge, Site 362 and 363: Initial Reports of the Deep Sea Drilling Project, v. 40, p. 183-356.

Bolli, H.M., W.B.F. Ryan, J.B. Foresman, W.E. Hottman, H. Kagami, J.F. Longoria, B.K. McKnight, M. Melguen, J.H. Natland, D.F. Proto, W.G. Siesser, 1978, Cape Basin continental rise; Sites 360 and 361: Initial Reports of the Deep Sea Drilling Project, v. 40, p. 29-182.

Goldhammer, R.K., R.M. Lawrence, H. Forero, E. Hussey, and D. Gaudoin, 2000, Cretaceous tectono-stratigraphic and paleogeographic ev olution of the southern Kwanza Basin, Angola: AAPG Annual Meeting Expanded Abstracts, v. 9, p. A55.

Hudec, M.R. and M.P.A. Jackson, 2004, Regional restoration across the Kwanza Basin, Angola; salt tectonics triggered by repeated uplift of a metastable passive margin: AAPG Bulletin, v. 88/7, p. 971-990.

Lunde, G., K. Aubert, O. Lauritzen, and E. Lorange, 1992, Tertiary uplift of the Kwanza Basin in Angola, *in* R. Curnelle., ed., Geologie Africaine: Colloque de stratigraphie et de paleogeographie des bassins s dimentaires Ouest-Africains: Recueil des Communications, v. 6/8, Libreville, Gabon, p. 99-117.

Walgenwitz, F. and M. Pagel, 1990, Diagenesis of cretaceous sandstone reservoirs of the South Gabon Rift Basin, West Africa: Mineralogy, mass transfer, and thermal evolution: Journal of Sedimentary Petrology, v. 60/3, p. 471-476.

Walgenwitz, F., M. Pagel, A. Meyer, H. Maluski, and P. Monie, 1990, Thermo-Chronological approach to reservoir diagenesis in the offshore Angola Basin A fluid inclusion, 40AR-39AR and K-AR investigation: AAPG Bulletin, v. 74/5, p. 547-563.

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