The Pillow Fold Belt: A Key Subsalt Structural Province in the Northern Gulf of Mexico*

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Abstract

Conventional fold belts have easily recognizable folds and thrusts, but pillow fold belts are harder to recognize because shortening is subtle and superposed. Pillow fold belts contain (1) preshortening halokinetic pillows and (2) synshortening features such as thrusts, contractional kink bands, box folds, and local, strong onlap and truncation.

The Atwater fold belt is generally thought to die out landward of the frontal high-relief folds. We propose instead that landward from the Sigsbee Escarpment, the frontal anticlines pass into a pillow fold belt that continues to the present Louisiana coastline as an ultradeep shelf play, like the Davy Jones discovery. In the pillow fold belt, pillows of irregular size, shape, spacing, and orientation grew first by halokinesis then by shortening. Polygonal salt ridges link the pillows and enclose oval minibasins. Normal faults of variable strike formed on the stretched crests of pillows. Subordinate thrusts formed during shortening. In the pillow fold belt of the ultradeep Louisiana shelf, mid-Miocene subcanopy shortening is juxtaposed with late Miocene supracanopy extension. This anomalous relationship can be explained by two hypotheses. The first hypothesis is that interior uplift and coastal tilting intensified in the Miocene, building a long basinward slope far inland from the Miocene shelf break and including the interior salt basins. This tilting drove a lower linked system detached on autochthonous salt, causing shortening over a wide area independently of the Miocene shelf break. An upper linked system detached on Miocene salt canopies which extended and advanced seaward on the upper slope. Lower and upper linked systems explain why extension above the canopy was almost coeval with shortening below the canopy. Neogene uplift of the interior is signaled by faults and onlaps on the tilted margin, volume balancing of erosion and sediments, fission-track analysis, neotectonic geomorphology, and earthquakes. As a second hypothesis, reactivated shear along crustal transfer faults striking northwest could cause shortening. But crustal shear has such a wide range of structural effects that it is difficult to prove or disprove.

A pillow fold belt and two independent detachments explain how halokinesis, shortening, and extension are juxtaposed in time and space in the subsalt play.

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Pillow Fold Belt

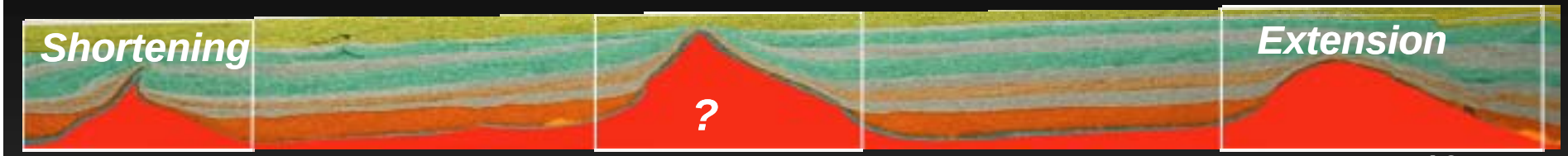
Structural province containing mildly shortened salt pillows

- **Pillow fold belts blur the distinction between fold belts and halokinetic pillows.**
- **Pillow fold belts are thus hard to recognize; so could be more widespread than realized.**

A Pillow Fold Belt

← Seaward

Physical model



Tilting begins

10 cm

Along strike

10 cm

- Stage 1: pillows grew by halokinesis from a horizontal source layer.
- Stage 2: tilting (white line) shortened Pillow A and extended Pillow C.
- Pillow B appears unshortened, but along strike was thrusted.
- Hard to distinguish halokinesis and mild shortening. Both create depositional or erosional thinning.

Frontal Fold Belt

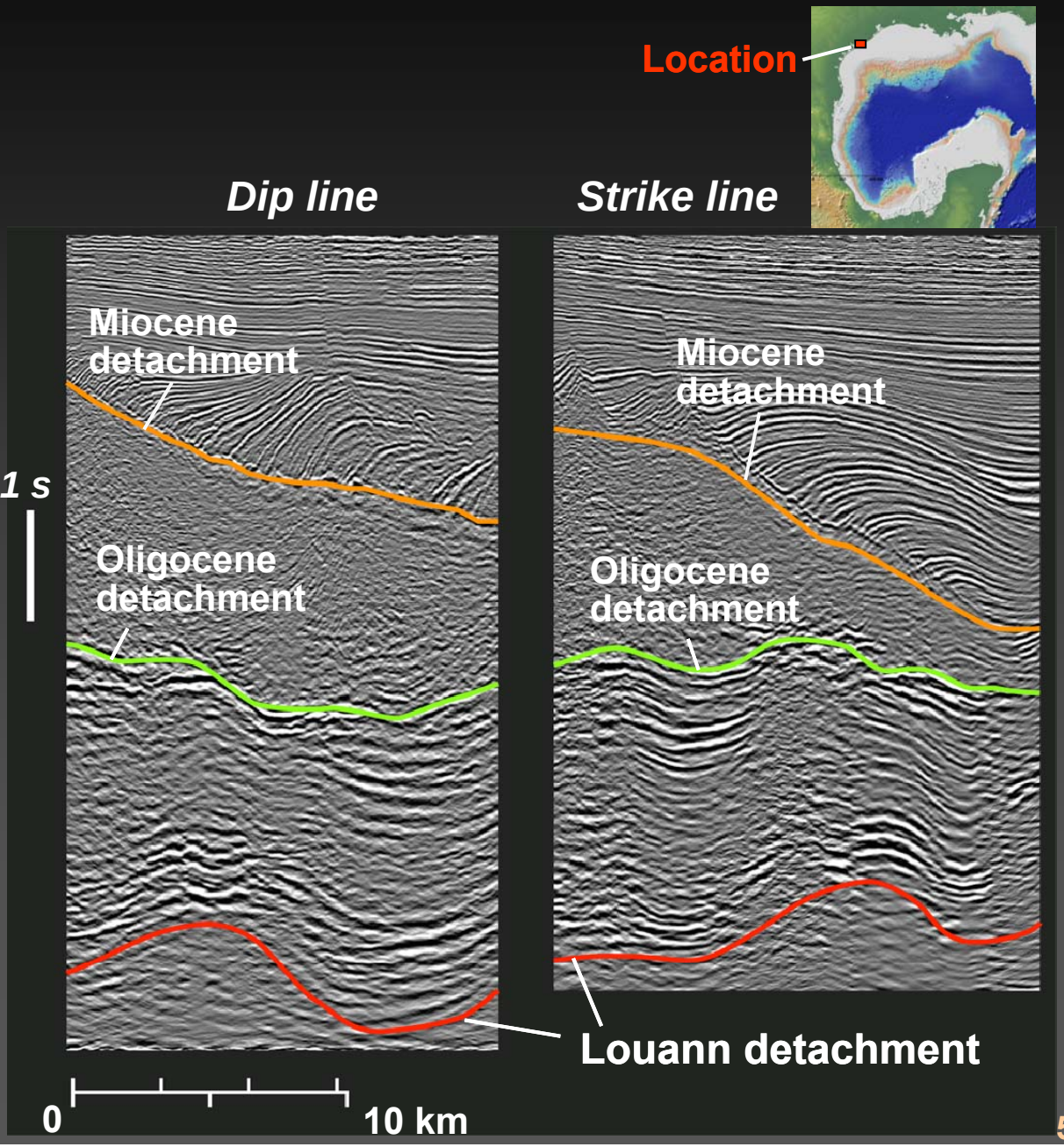
Wide-Azimuth Data

WesternGeco

- Below Sigsbee Escarpment, frontal folds in Atwater fold belt are easy to recognize if:
  - (1) seismic data are excellent
  - (2) shortening is strong.
- How far landward does shortening continue? A long way.

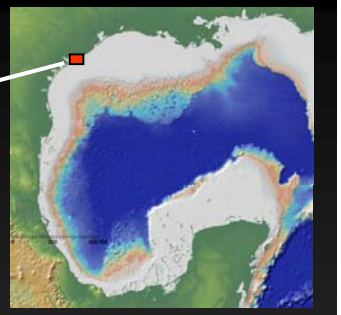
Pillow Fold Belt on Ultradeep Texas Shelf

- Miocene and Oligocene detachments overlie a pre-Oligocene pillow fold belt detached on Louann Salt.
- Pre-Oligocene halokinesis recorded by growth thickness variations.
- Oligocene shortening folded Oligocene detachment and older strata.
- Strike and dip profiles are similar.



McDonnell et al., 2009

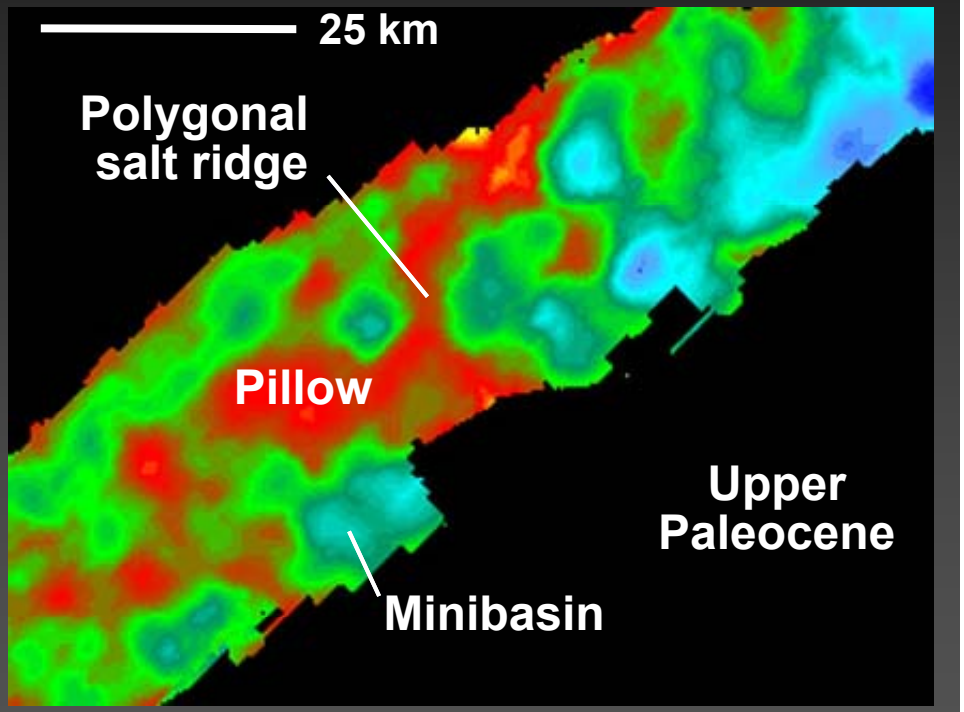
Pillow Fold Belt on Ultradeep Texas Shelf



1. Pillows have irregular size, shape, and orientation.
2. Polygonal salt ridges connect pillows.
3. Oval or coalesced minibasins between salt ridges.

- Pillow fold belts are hybrid structures.
- "Fold-belt" profiles emphasize shortening.
- "Egg-carton" map views emphasize halokinesis.

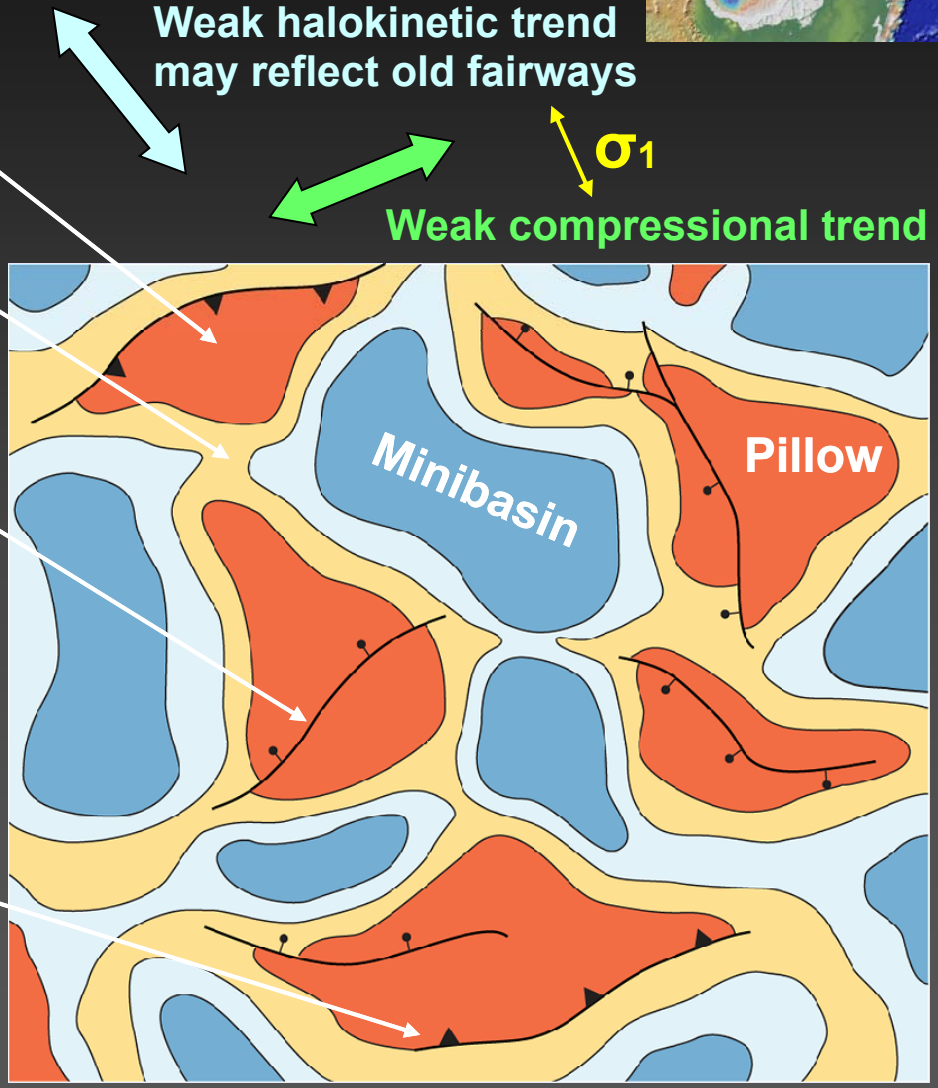
Structure map



McDonnell et al., 2009

Pillow Fold Belt on Louisiana Ultradeep Shelf

- Pillows: irregular size, shape, spacing, orientation. Geometry controlled by early halokinesis.
- Polygonal salt anticlines link pillows and enclose minibasins.
- Normal faults have variable strike. Mostly formed by arching of pillows.
- Thrusts strike roughly NE, perpendicular to Miocene compression. Forethrusts and backthrusts equally common.



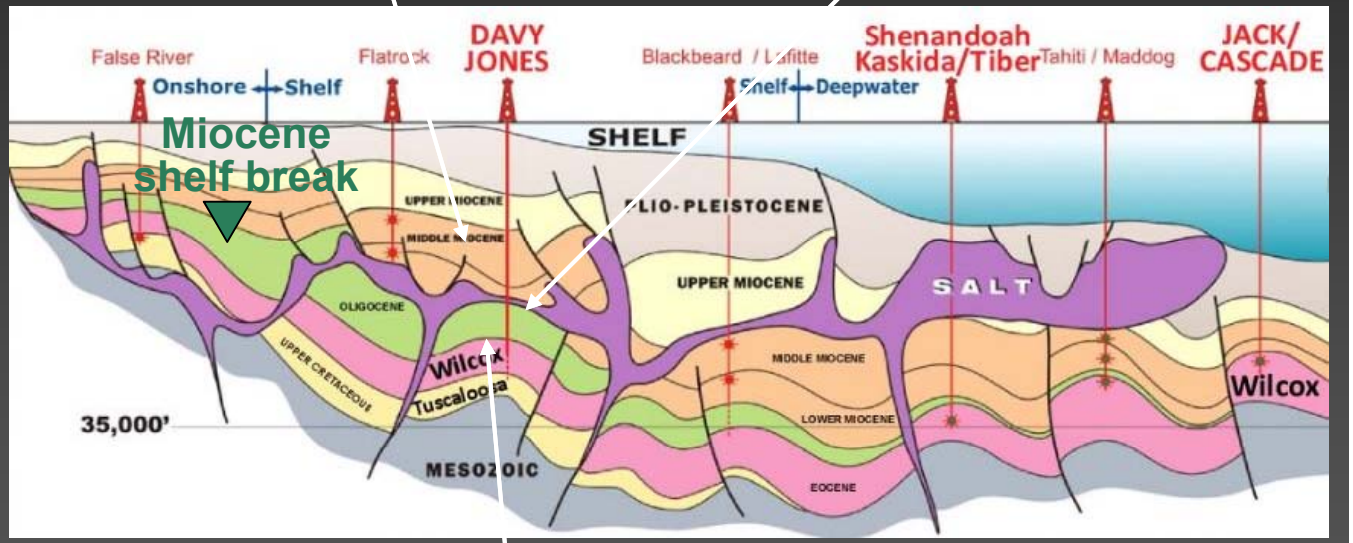
Not to scale

Pillow Fold Belt on Louisiana Ultradeep Shelf

- Growth strata in pillow folds indicate Paleogene halokinesis.
- Below canopy, shortening began in middle Miocene as canopy was eamplaced.
- Above canopy, extension began in late Miocene and mostly ended by end-Miocene.
- Highly anomalous juxtaposition of shortening and extension.

Mid-late Miocene extension above canopy

Mid-Miocene partly welded salt canopy



McMoRan Exploration website

Mid-Miocene pillow fold belt below canopy

Mystery 1

Why mid-Miocene shortening near Miocene shelf edge?

Shortening is normally in toe of slope.

Mystery 2

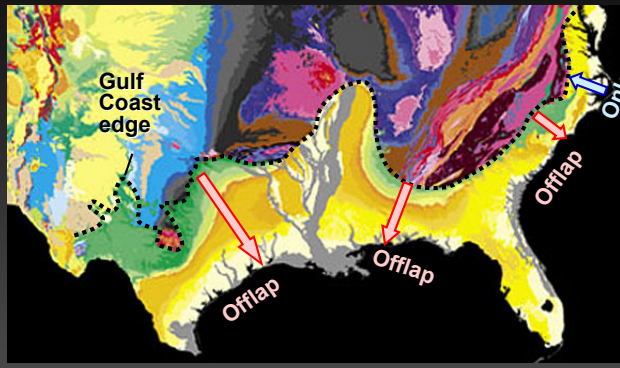
Why was middle Miocene shortening below canopy almost coeval with late Miocene extension above canopy?

Zones of extension and shortening are usually widely separated.

Hypothesis 1

Interior Uplift Intensifies Gravity Spreading

Offlapping Gulf Coast

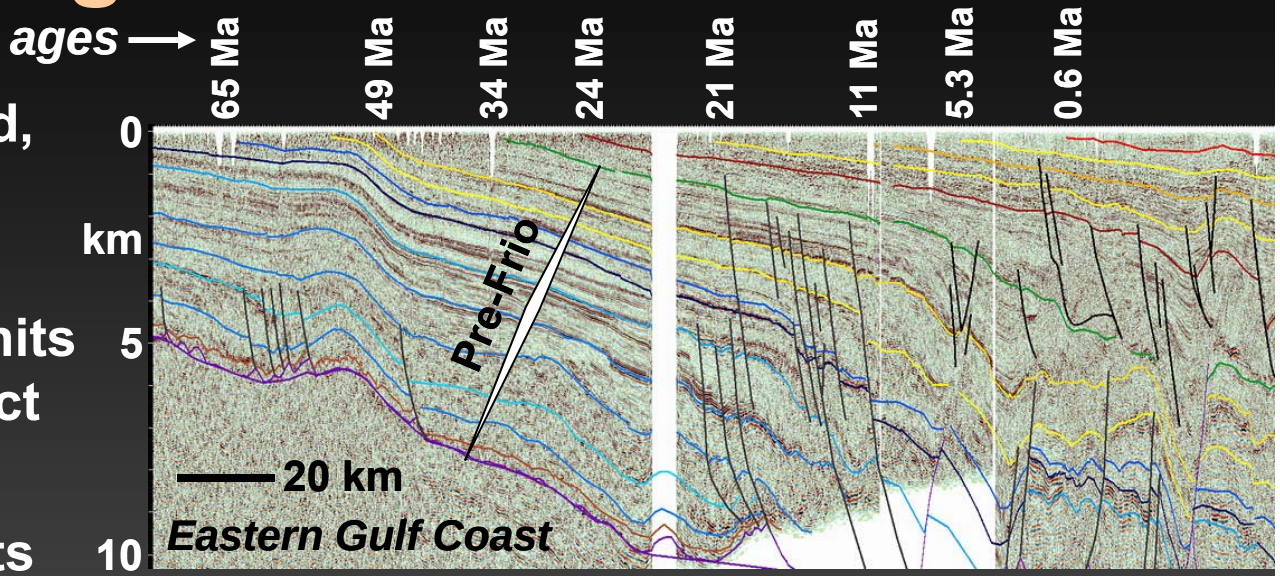


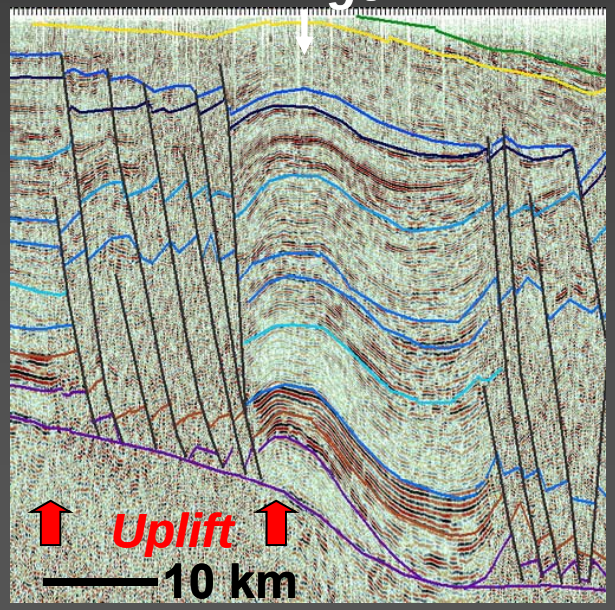
- Along most of the Gulf Coast, outcropping strata are younger seaward = offlap pattern.
- Southern U.S. Atlantic Coast has same offlap.
- Northern U.S. Atlantic Coast has onlap, where younger strata are preserved far inland.

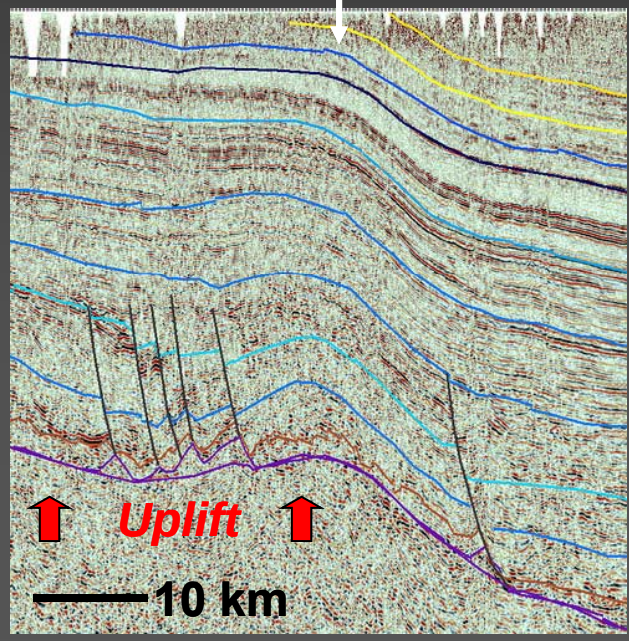
Presenter's notes: Loading of elastic crust produces onlap (steer's head model). Loading of viscoelastic crust or coastal uplift produces offlap (basin narrows over time as it becomes less rigid as flow relaxes stresses).

Uplift Hinge of U.S. Gulf Coast

- All units are truncated, younger seaward (offlap).
- Pre-Frio (>31.5 Ma) units are parallel and project landward infinitely.
- Frio and younger units (<31.5 Ma) wedge landward.
- Thus coastal uplift began at ~30 Ma.
- Uplift created Gulf Coast hinge separating uplifted interior from tilted continental margin.





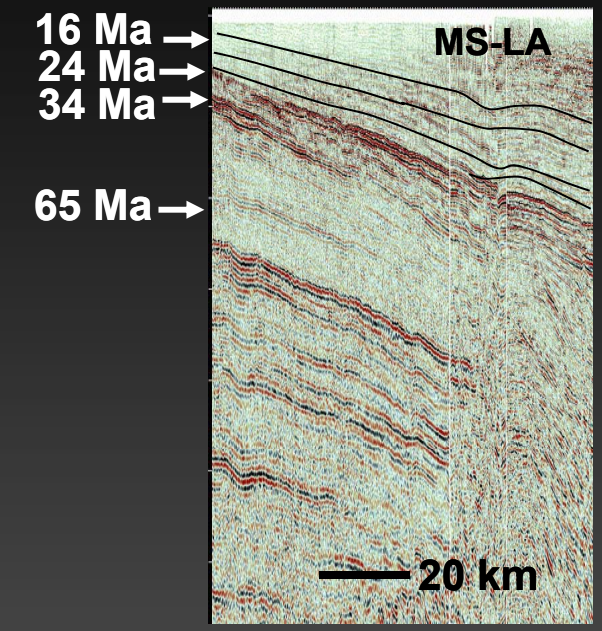


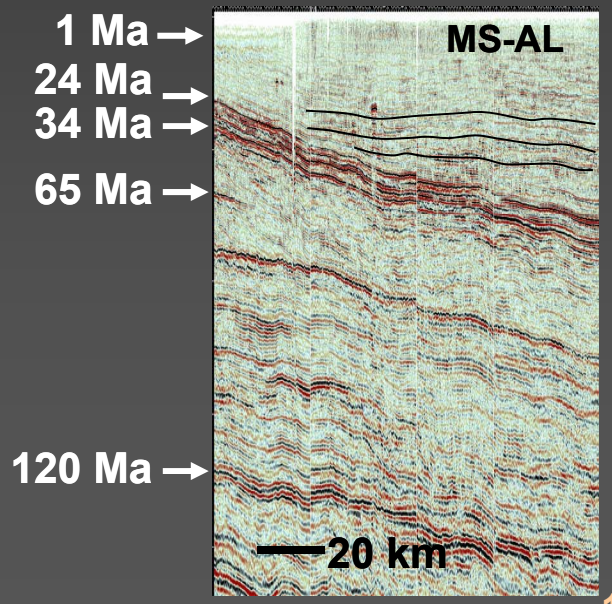
Seismic data and interpretation from GulfSpan Merge

Interior Uplift Accelerated in Miocene

Eastern Gulf Coast, Miocene Onlap

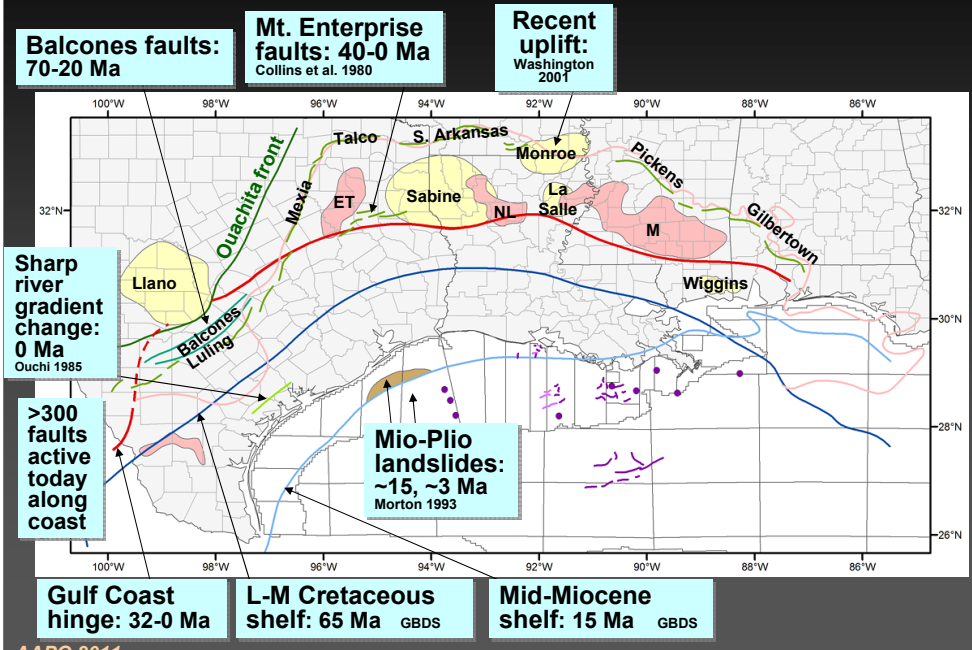
- Gulf Coast interior began rising in Oligocene, but onlaps indicate that rise accelerated in mid-Miocene (~15 Ma).
- Mid-Miocene onlap is weak in most dip lines (upper right) but stronger in strike lines (lower right).





Seismic data from GulfSpan Merge

Gulf Coast Structures Active in Neogene

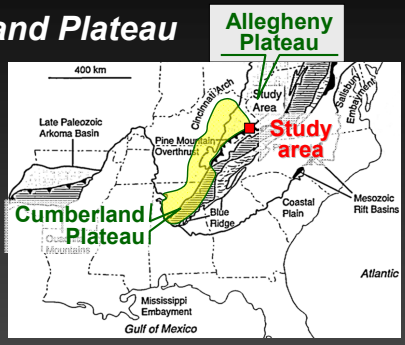


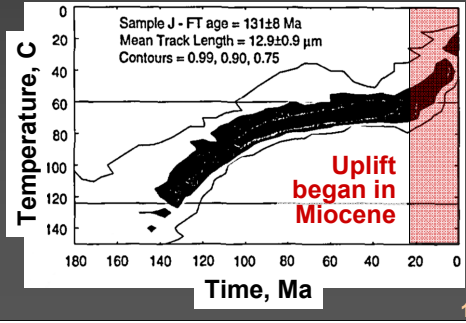
Presenter's notes: Uplift of interior indicated by: Age of faults, age of onlaps on tilted margin, volume balancing of erosion and sediments, fission-track analysis, neotectonic geomorphology and earthquakes.

Interior Uplift in Miocene

Miocene Uplift of Cumberland Plateau

- Since mid-Miocene, most sediments entering northern GoM came from the N and NE.
- Apatite fission-track analysis indicates uplift of Cumberland Plateau since ~22 Ma, which shed sediments into GoM.
- 40ºC cooling is equivalent to 1.6 km uplift (assuming geotherm of 25ºC/km).

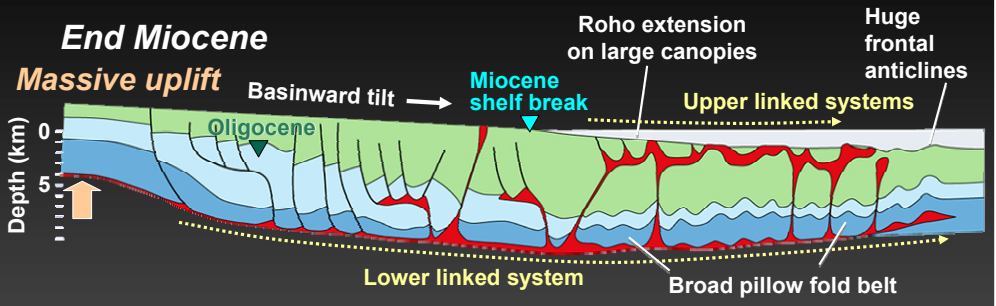




Boettcher & Milliken (1994)

Presenter's notes: Cordilleran sediment source has declined since mid-Miocene (Hay et al., 1989) because arid climate slowed sediment transport, and Rio Grande rift opened and diverted sediment.

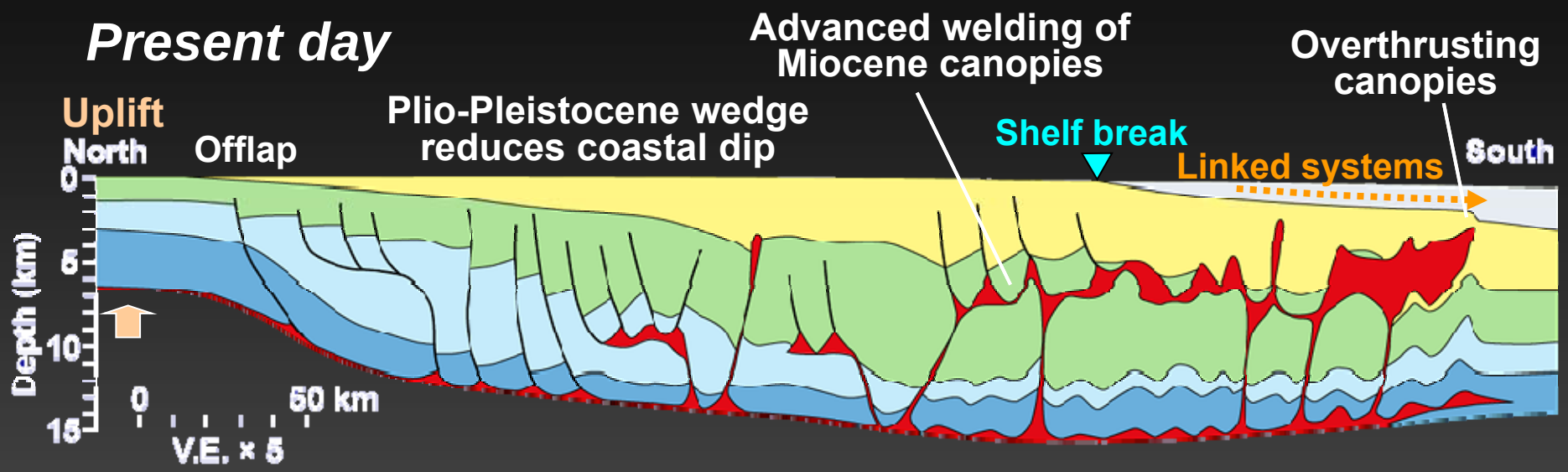
Major Uplift of Interior



- Interior uplift by several km. Tilted margin created a long basinward slope far inland from Miocene shelf break.
- Coastal uplift drove a lower linked system on autochthonous salt → widespread shortening independent of shelf break.
- Upper linked systems detached on Miocene canopies: extension on upper slope as salt canopies spread seaward.
- Two offset linked systems allowed extension above canopy roughly coeval with shortening below canopy.

Presenter's notes: Cross section is ~430 km long. Sketch combines features from 3 GulfSpan Merge seismic lines across eastern Gulf Coast to show simplified structural styles. The restorations that follow are qualitative.

Current Result of Interior Uplift



- Continental interior continues rising (Balcones, Mt. Enterprise faults) at unknown rate.
- Plio-Pleistocene sediment wedge (yellow) infills continental margin and reduces basinward tilt of topography.
- Shelf break once again controls gravity spreading.
- Linked system now mainly above Plio-Pleistocene canopy, which overthrusts at Sigsbee Escarpment.

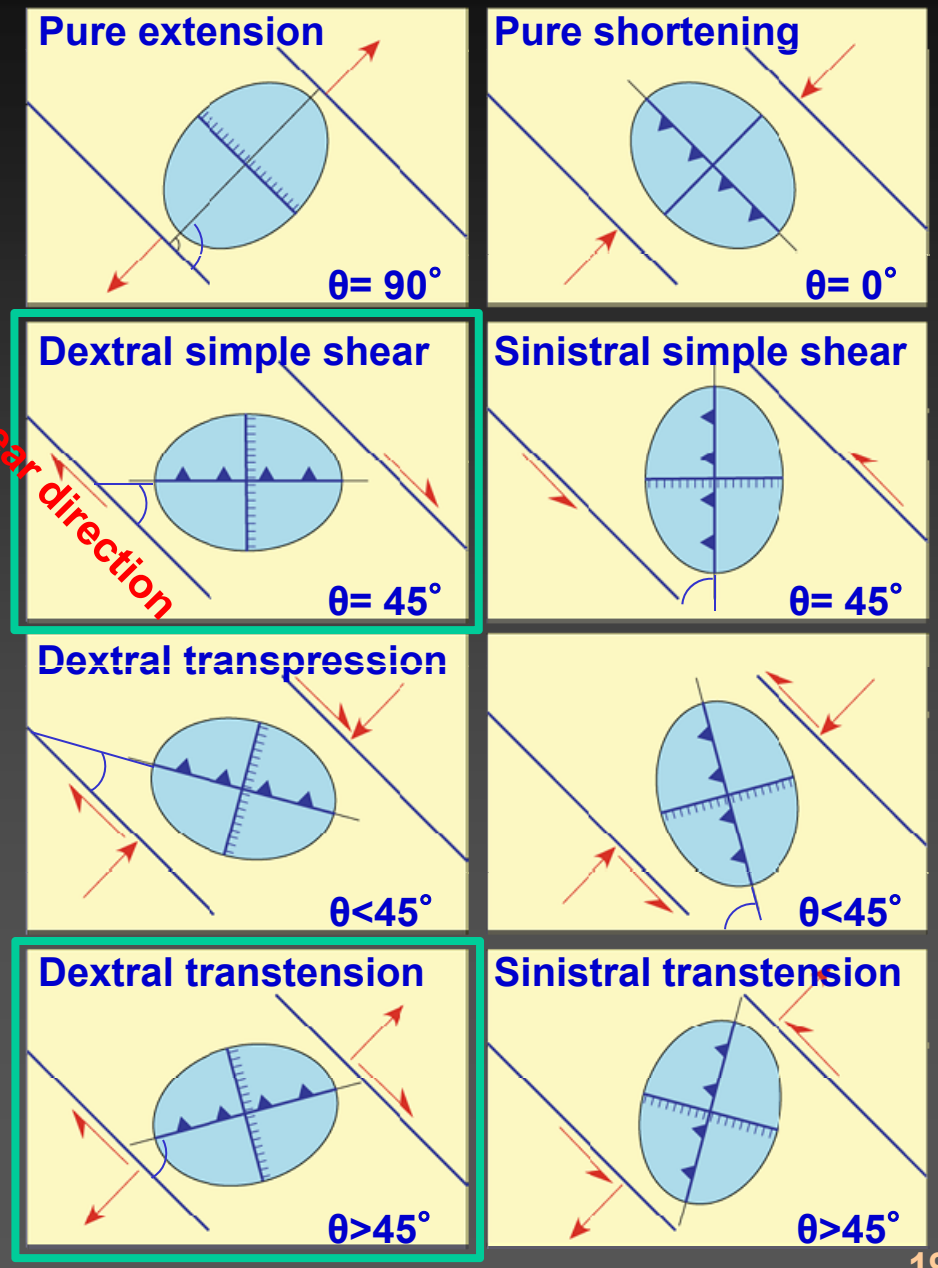
Hypothesis 2

Crustal Shear Shortens Cover

Effects of Crustal Shear on Parallel Faults

Structures Formed by NW-Striking Crustal Faults

- Shear between crustal blocks deforms cover without a topographic slope.
- Crustal transfer faults striking NW could be reactivated in highly variable ways.
- Thus effects are difficult to prove or disprove without knowing more about the deep structure



Conclusions

- Gulf of Mexico has large Oligocene and Miocene pillow fold belts, having a subtle mixture of halokinesis and shortening.
- Timing and distribution of pillow fold belts are highly anomalous in places.
- Anomaly can be explained by two tectonic hypotheses.

(1) Interior uplift and coastal tilting in the Miocene overpowered the influence of the paleoshelf break. Separate detachments allowed subcanopy shortening and supracanopy extension in the same place.

(2) Reactivated shear along crustal transfer faults could have caused widespread shortening, but crustal shear has highly variable effects; so it is difficult to prove or disprove.

Acknowledgments

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