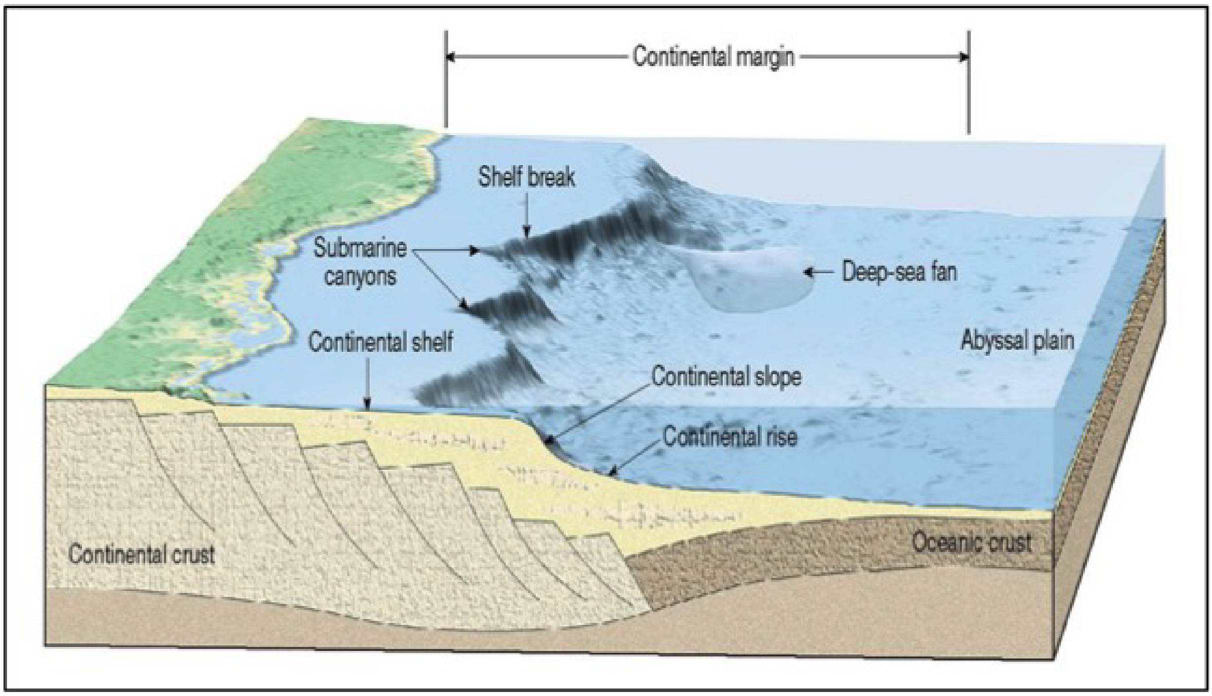
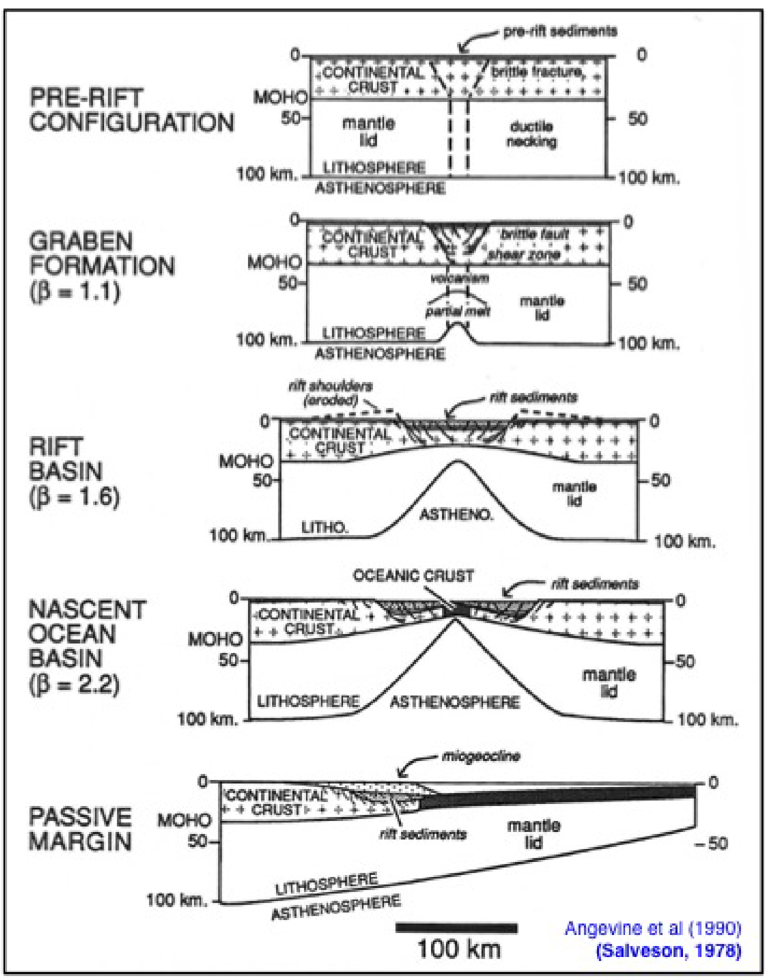
## Subsidence at Rifted Continental Margins

- **How does a passive margin acquire this overall shape ?**
- **What processes control the evolution of passive margins ?**



## Two-Stage Evolution of Rifted Continental Margins

**(1) Rift Stage =** Initial (isostatic) subsidence: due to thinning of the crust

**(2) Drift Stage =** Thermal Subsidence: due to *post-rift* cooling of lithosphere

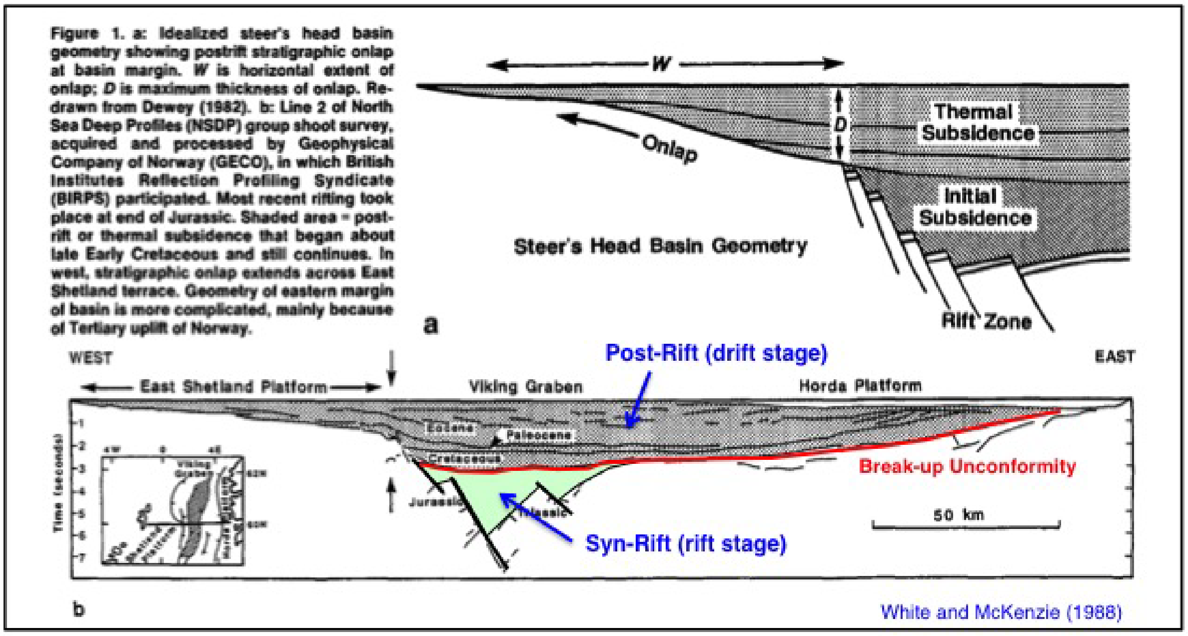
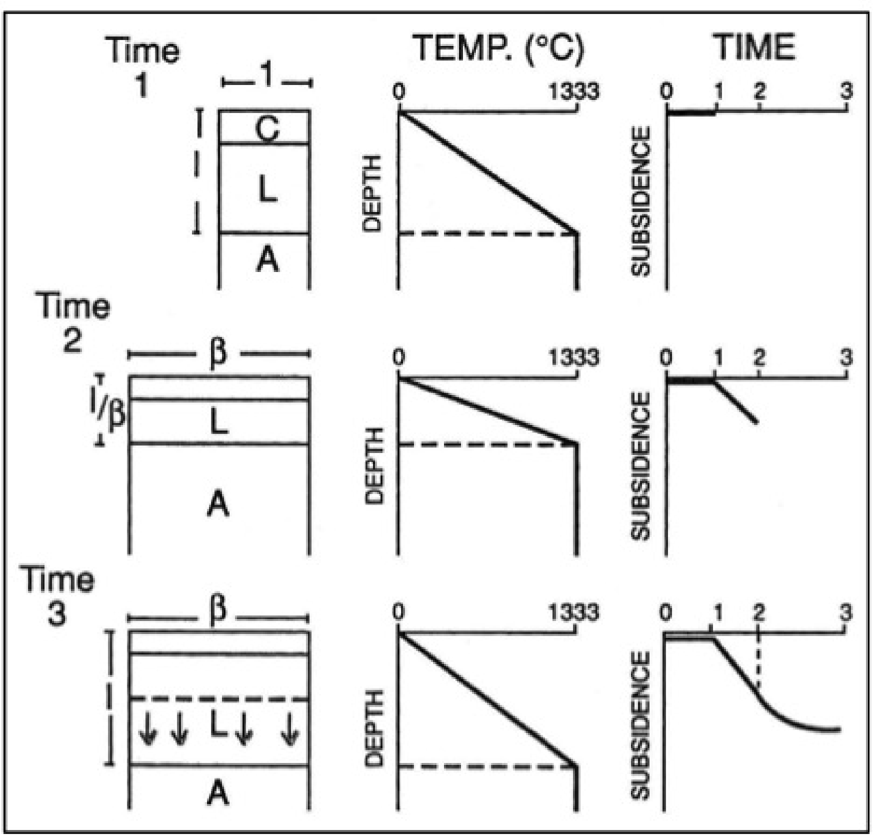



Figure 1. a: Idealized steer's head basin geometry showing postrift stratigraphic onlap at basin margin. *W* is horizontal extent of onlap; *D* is maximum thickness of onlap. Redrawn from Dewey (1982). b: Line 2 of North Sea Deep Profiles (NSDP) group shoot survey, acquired and processed by Geophysical Company of Norway (GECO), in which British Institutes Reflection Profiling Syndicate (BIRPS) participated. Most recent rifting took place at end of Jurassic. Shaded area = post-rift or thermal subsidence that began about late Early Cretaceous and still continues. In west, stratigraphic onlap extends across East Shetland terrace. Geometry of eastern margin of basin is more complicated, mainly because of Tertiary uplift of Norway.

White and McKenzie (1988)

## Two-Stage Evolution of Rifted Continental Margins




Angevine et al (1990)

**McKenzie (1978) model**

**Pre-Rift**

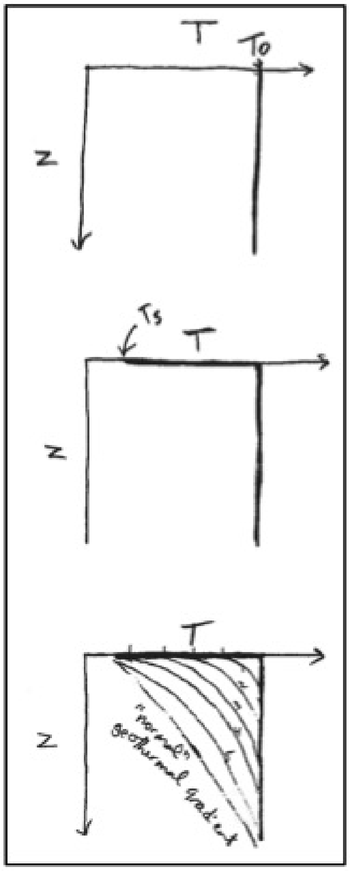
**(1) Rift Stage:**

- Isostatic Subsidence
- Rapid (1-5 mm/yr)
- "instantaneous"
- assume Airy Isostasy

**(2) Drift Stage:**

- Thermal Subsidence
- Rate slows thru time
- Exponential decay
- 10's of Myr

## Thermal Subsidence: conductive cooling ...




"At the crest of an ocean ridge, hot mantle rock injected in dykes and extruded as lava flows is suddenly subjected to a cold surface temperature ... and then continues to lose heat to the cold seawater as the seafloor spreads away from the ridge. The initial cooling can be treated as instantaneous.

We know from the 1D conduction equation where A (radiogenic heat production) = 0 that:

**Because:**

$$\partial T/\partial t = \partial q/\partial z \qquad (1)$$

*and*

$$q = -K\, \partial T/\partial z \qquad (2)$$

(Fourier's Law)

**Therefore:**

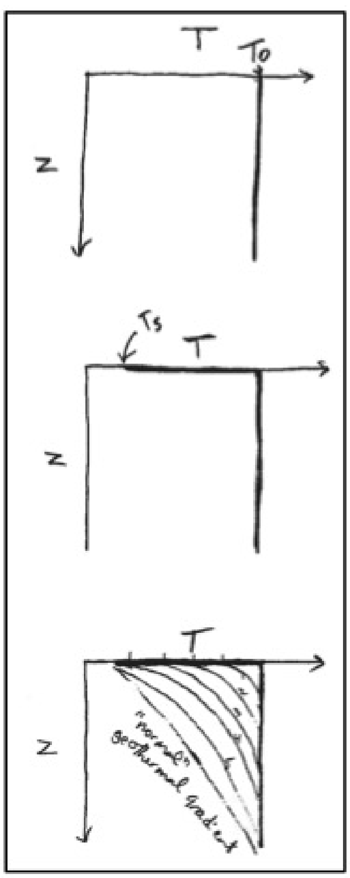
$$\frac{\partial T}{\partial t} = \kappa \frac{\partial T^2}{\partial z^2} \qquad (3)$$

T = temperature
z = depth
t = time
q = rate of heat transfer
K = constant: "thermal conductivity"

**Basic Diffusion Equation**

Allen and Allen (2013)

## Thermal Subsidence: conductive cooling ...




② Drift-Stage = Thermal Subsidence.
Cooling of lithosphere, thickness of mantle lith increasing, entire column becoming progressively denser, causing subsidence.

Historically, two models have been used for thermal subs:

1. Half-space model, curve follows $\sqrt{t}$ ($t^{1/2}$).
   see handout (Turcotte + Schubert, 1982; Parsons + Sclater, 1977).
   Note misfit between $t^{1/2}$ theoretical curve and ocean data.

2. Plate model, curve follows exponential decay.
   see handout (Parsons + Sclater, 1977),
   Angevine et al (1990) EQN 4.8

* both models assume conductive heat loss (diffusion)

Theoretical subsidence curves using the plate model have been shown to fit real ocean data better than the half-space model. See also Angevine et al. Figs. 4.2 - 4.5.

"At the crest of an ocean ridge, hot mantle rock injected in dykes and extruded as lava flows is suddenly subjected to a cold surface temperature ... and then continues to lose heat to the cold seawater as the seafloor spreads away from the ridge. The initial cooling can be treated as instantaneous ..."

Allen and Allen (2013)

## Model Validated: ocean depth vs. age

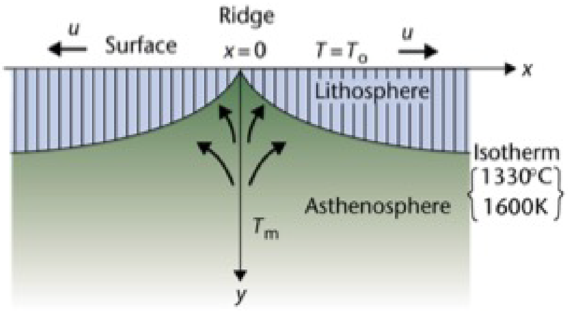



Fig. 2.27 Schematic diagram of the cooling oceanic lithosphere at a mid-ocean ridge. The oceanic plate moves away from the ridge at a velocity u. Its age is therefore determined by x/u, where x is the horizontal distance from the ridge crest. After Turcotte & Schubert (2002). © Cambridge University Press, 2002.

Allen and Allen (2013)

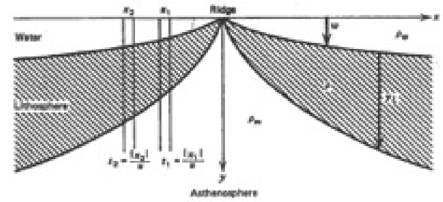
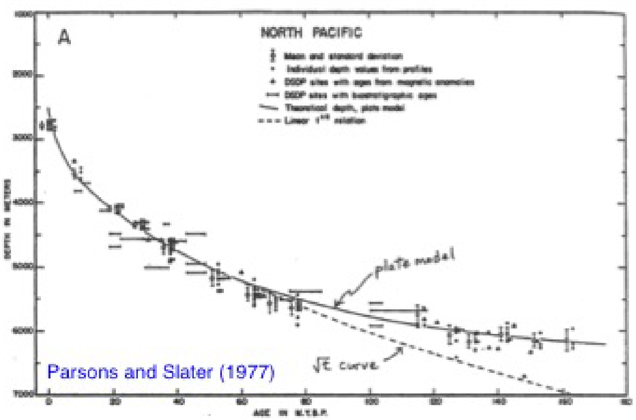



**Figure 4-44** The principle of isostasy requires the ocean to deepen with age to offset the thermal contraction in the lithosphere.

Turcotte & Schubert (1982)

$$w = \frac{2\rho_m \alpha_v (T_m - T_0)}{(\rho_m - \rho_w)} \left( \frac{\kappa x}{\pi u_0} \right)^{1/2} \quad (4\text{-}202)$$

Equation (4-202) predicts that the depth of the ocean increases with the square root of the distance from the ridge or the square root of the age of the ocean floor. This theoretical result is in excellent agreement with observations, as shown in Figure 4-45. The figure shows the theoretical prediction, Equation (4-202), for $\rho_m = 3300$ kg m$^{-3}$, $\rho_w = 1000$ kg m$^{-3}$, $\kappa = 1$ mm$^2$ s$^{-1}$, $T_m - T_0 = 1300$ °K, and $\alpha_v = 3 \times 10^{-5}$ °K$^{-1}$ together with mea-




Parsons and Slater (1977)

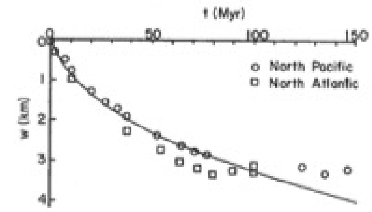
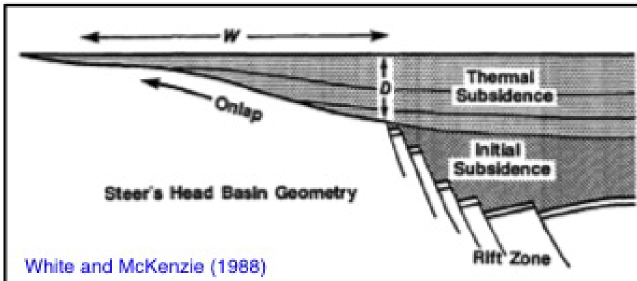



**Figure 4-45** Ocean depth relative to the depth of the ridge crest as a function of age of the seafloor. Data from B. Parsons and J. G. Sclater. An analysis of the variation of ocean floor bathymetry with age, *J. Geophys. Res.* **82**, 803–827, 1977.




White and McKenzie (1988)

## "Steer's Head" Geometry – Why?

- Sea-level rise?
- Flexure due to sedim. loading?
- Or .... ??

**Two-layer stretching: mantle lithosphere is stretched over region wider than crust**

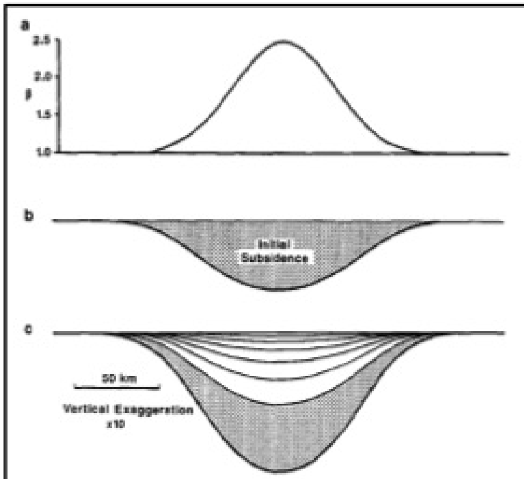



**Figure 2. a:** $\beta$, stretching factor in crust and upper mantle, is plotted as function of distance using equations 1 and 2 (see text); $\sigma_m = \sigma_c = 30$, so stretching in crust and upper mantle is identical. In center of basin, $\beta_c = \beta_m = 2.5$. **b:** Initial subsidence immediately after stretching. Basin has been loaded with sediment having density of 2.0. Other parameters have same values as in McKenzie (1978). **c:** Total subsidence 150 m.y. after rifting. Thermal subsidence is represented by time lines drawn every 25 m.y. Thermal subsidence dies out at same position as initial subsidence.

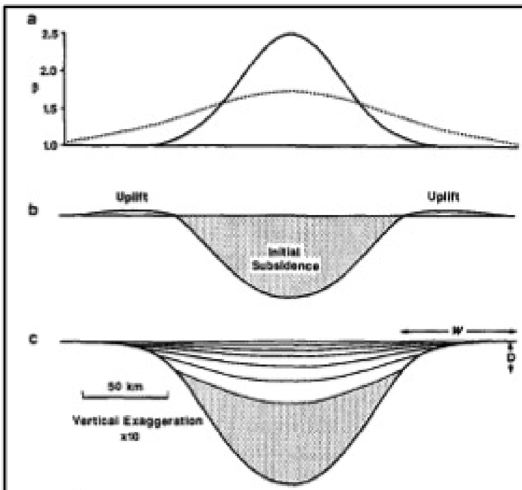



**Figure 3. a:** $\beta_c$, stretching factor in crust (solid line), and $\beta_m$, stretching factor in upper mantle (dotted line) are plotted as function of distance using equations 1 and 2 (see text); $\sigma_m = 60$ and $\sigma_c = 30$, as in Figure 2. In center of basin, $\beta_c = 2.5$ as before, but now $\beta_m = 1.75$. All other parameters are identical to those used in Figure 2. **b:** Initial subsidence immediately after stretching. Note localized uplift along flanks of basin. **c:** Total subsidence 150 m.y. after rifting. Thermal subsidence is represented by lines drawn every 25 m.y. Onlap produced by thermal subsidence at basin margin results in steer's head geometry. *W* is horizontal extent of

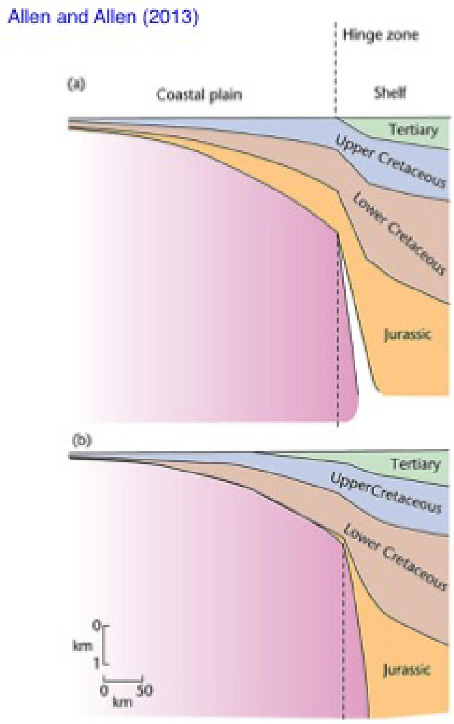



**Fig. 3.30** Synthetic stratigraphy along profiles crossing the coastal plain and shelf off New Jersey, constructed using the flexural loading model of Watts & Thorne (1984). (a) One-layer uniform stretching model. (b) Two-layer model in which the lithosphere and crust are thinned by equal amounts seaward of the hinge zone, but only the mantle lithosphere is thinned landward of the hinge zone. The lithospheric thinning promotes early uplift of the zone landward of the hinge line, and helps to explain the absence of Jurassic strata from this region (after Steckler *et al.* 1988).

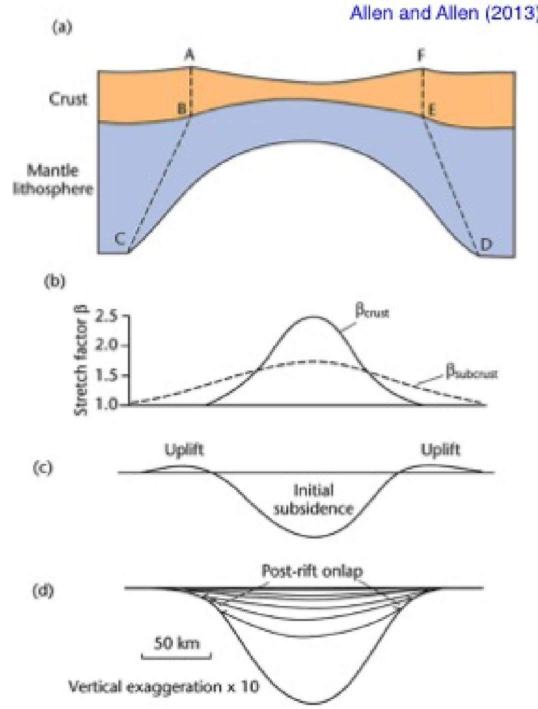



**Fig. 3.31** Basin filling pattern resulting from continuous depth-dependent stretching (Rowley & Sahagian 1986; White & McKenzie 1988). (a) Geometry of a tapering region of extension in the subcrustal lithosphere. (b) Stretch factors in the crust and subcrustal lithosphere as a function of horizontal distance. (c) Initial subsidence and uplift immediately after stretching, showing prominent rift flank uplift. (d) Total subsidence 150 Myr after rifting, showing progressive onlap of the basin margin during the thermal subsidence phase, giving a steer's head geometry.

## Baltimore Canyon Trough – Eastern U.S. Passive Continental Margin