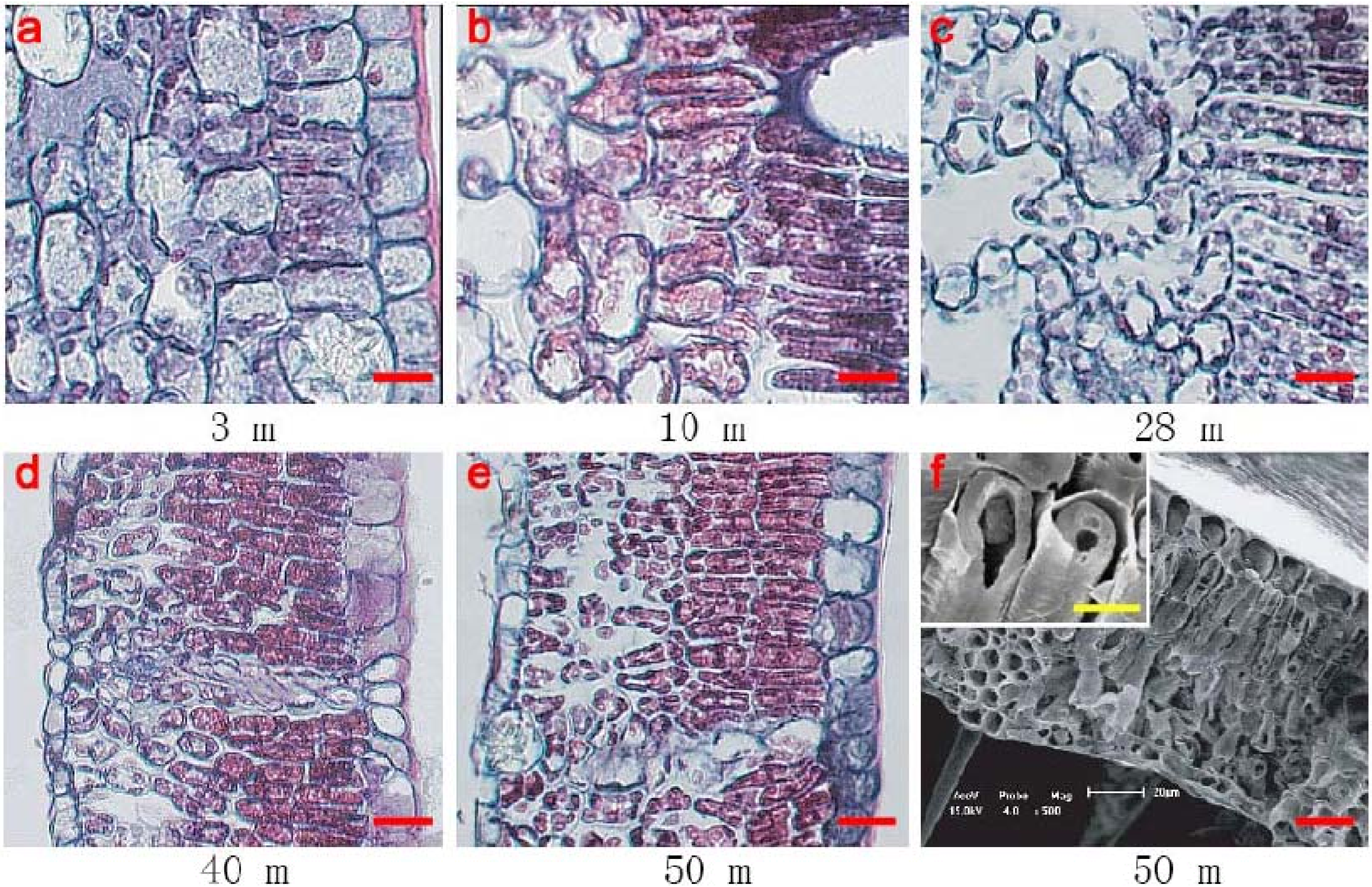
Why the mesophyll cell sizes decrease with tree height?

---A mechanical view

Ming GUO

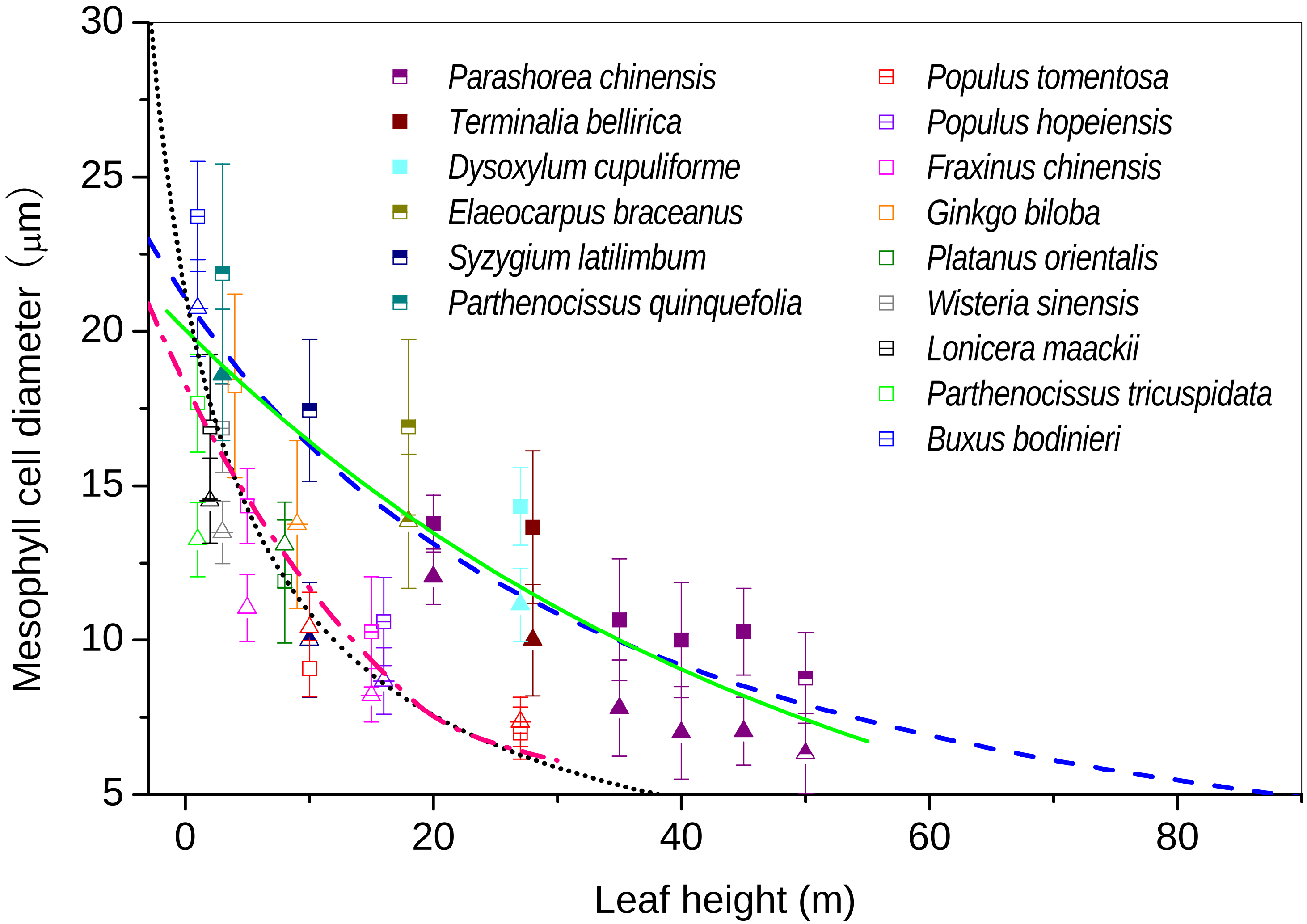
01/11/2008

Mesophyll cell sizes versus heights



Red Scale Bar = 20 μm

Mesophyll cell sizes versus heights



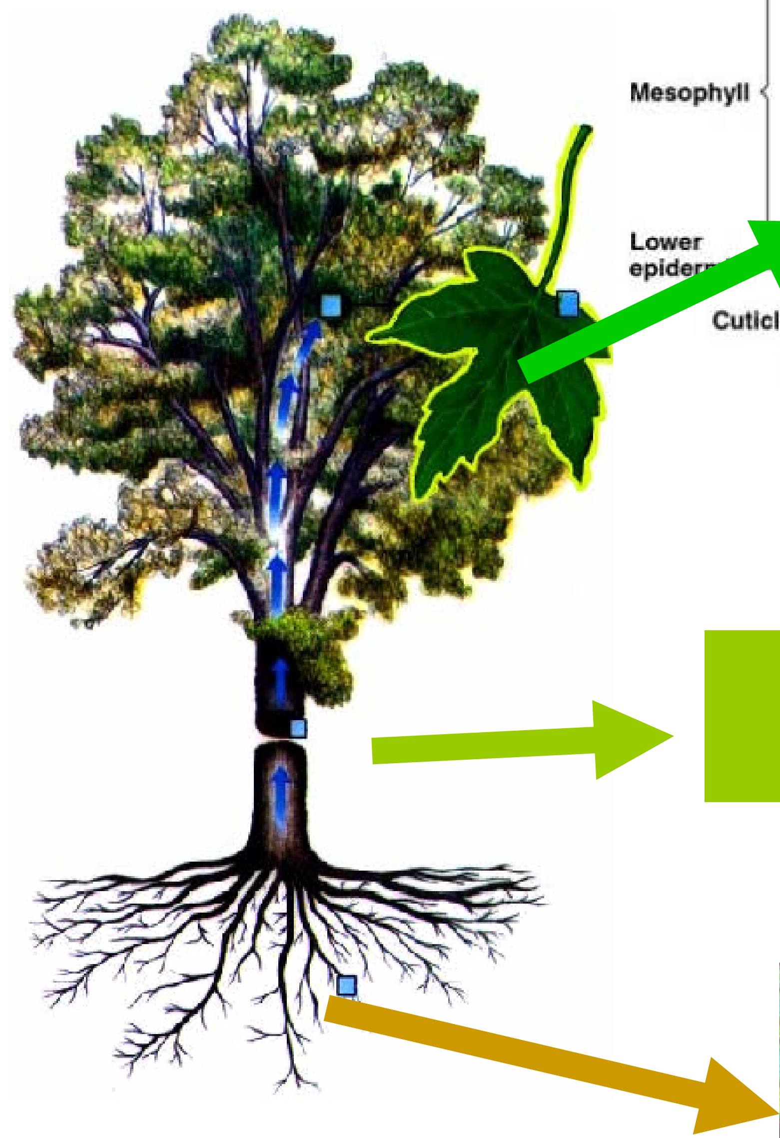
Summary on observations

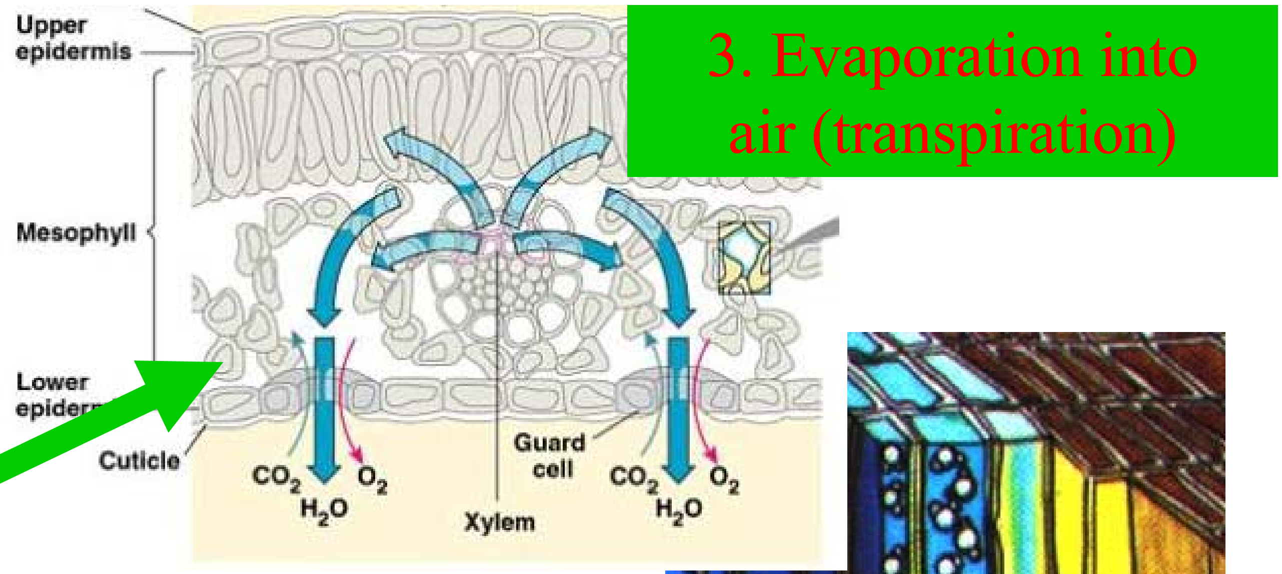
- Our microscopic observations of mesophyll cells reveal that the cell sizes are remarkably reduced with increasing heights of the leaves.

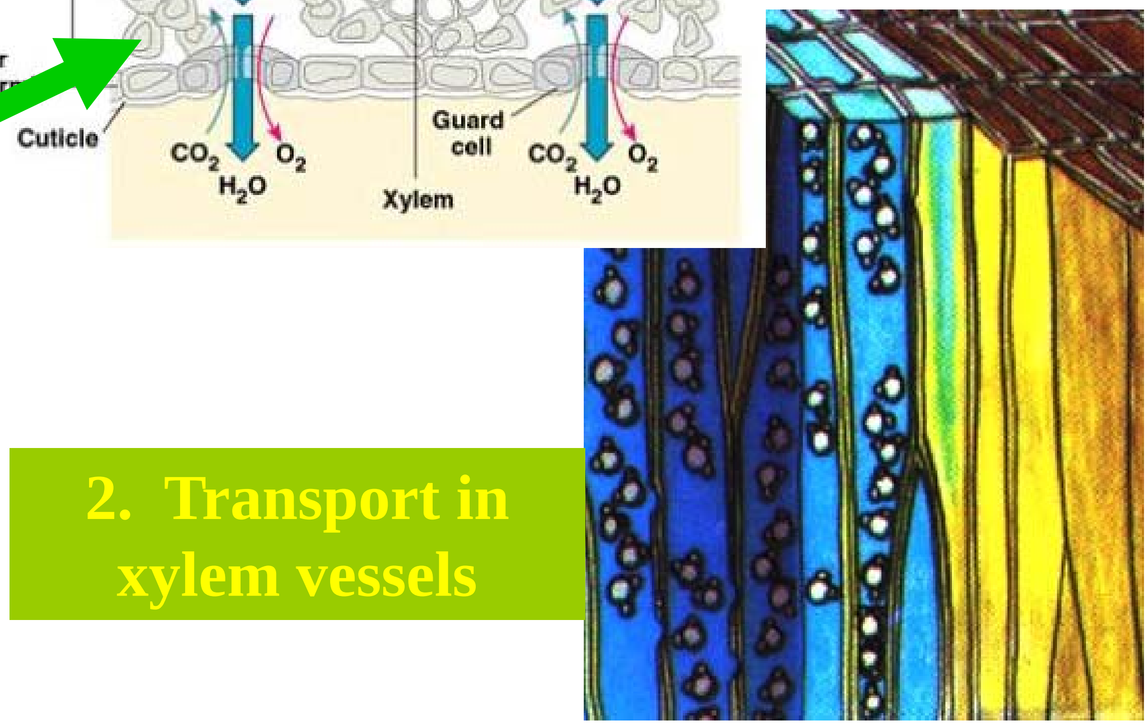
- The reduction rates depend strongly upon the growth regions.

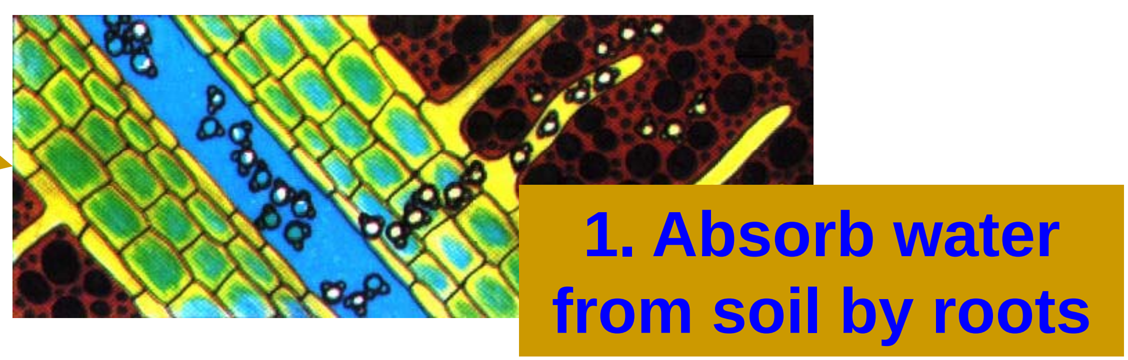
- My previous explanation was based on a famous plant growth model.

Why the mesophyll cell sizes decrease with tree height, from the view of mechanics?



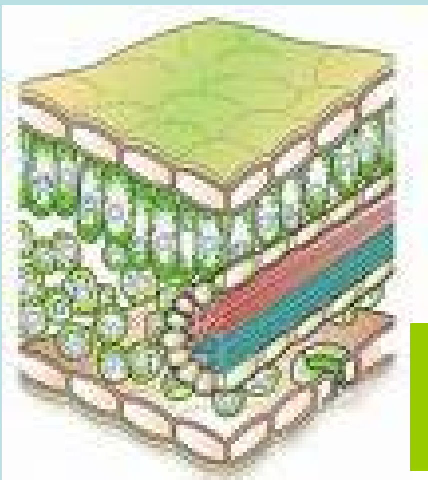


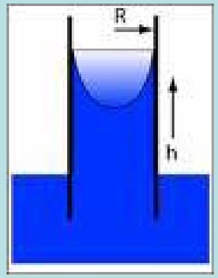




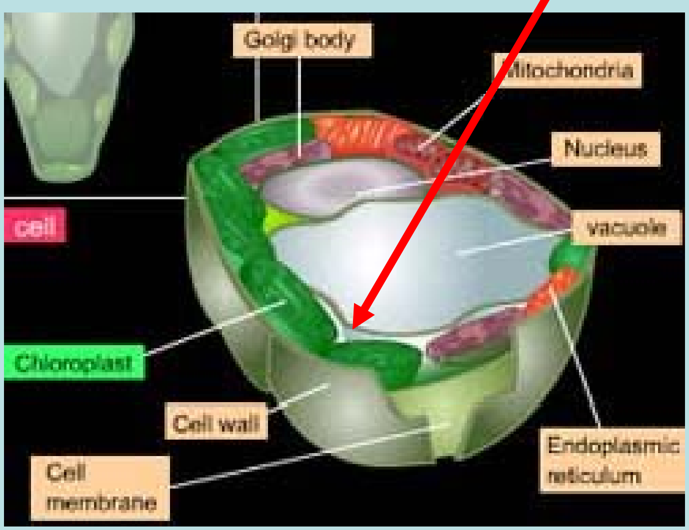
Plant Physiology, 3rd ed. (2005)

Mesophyll cells – The Engines





Symplasm water



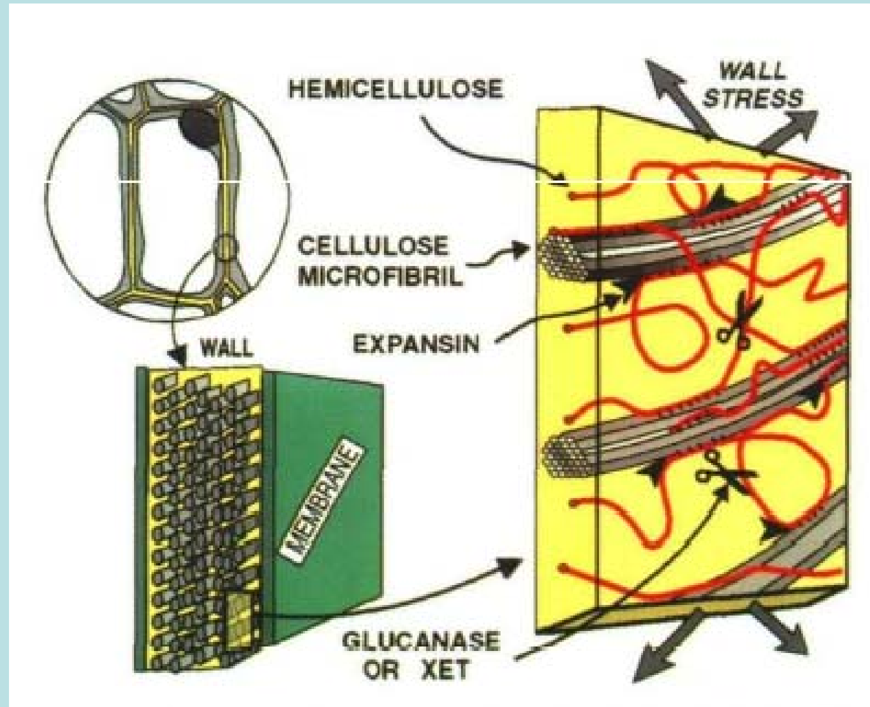
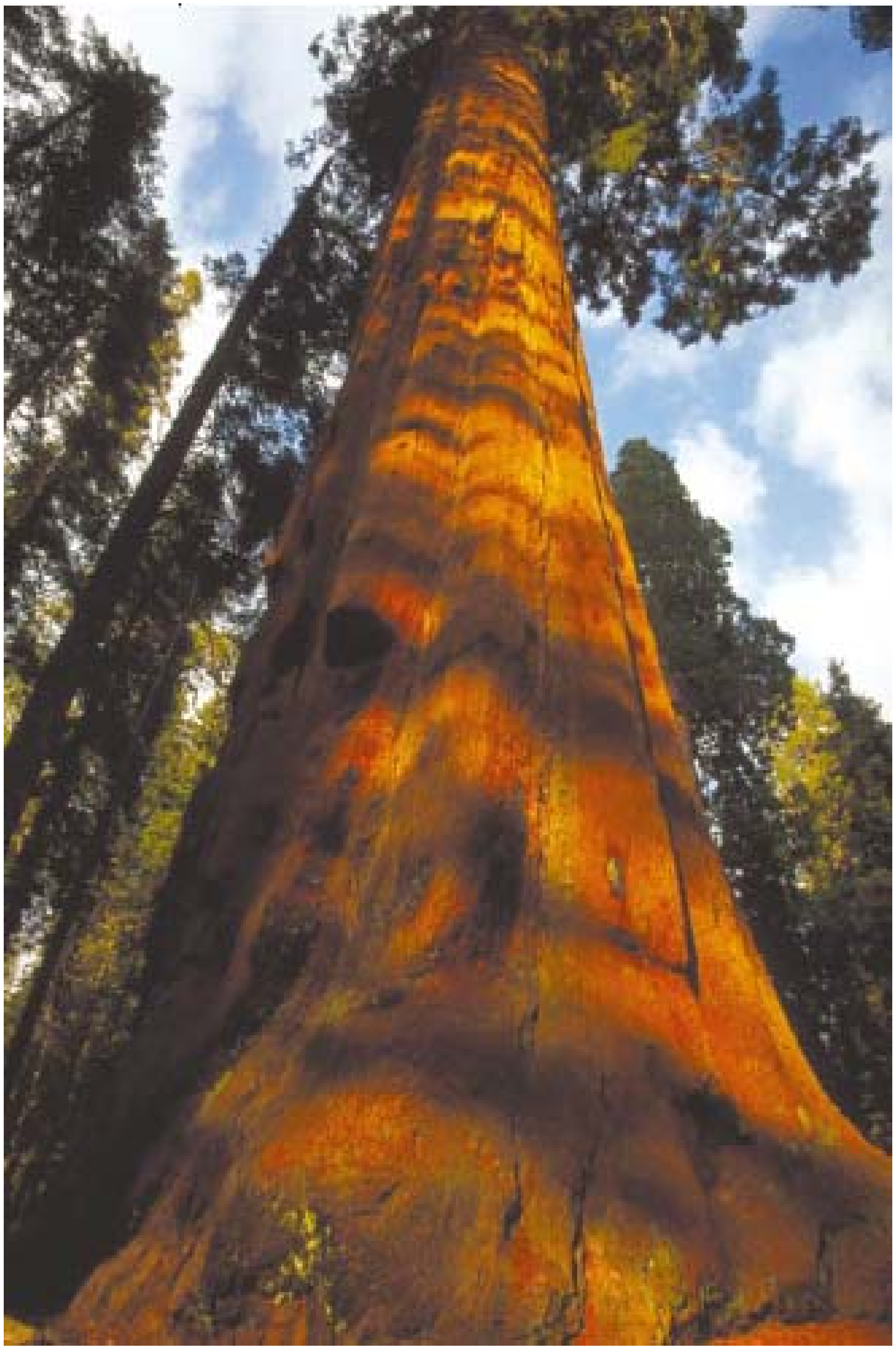
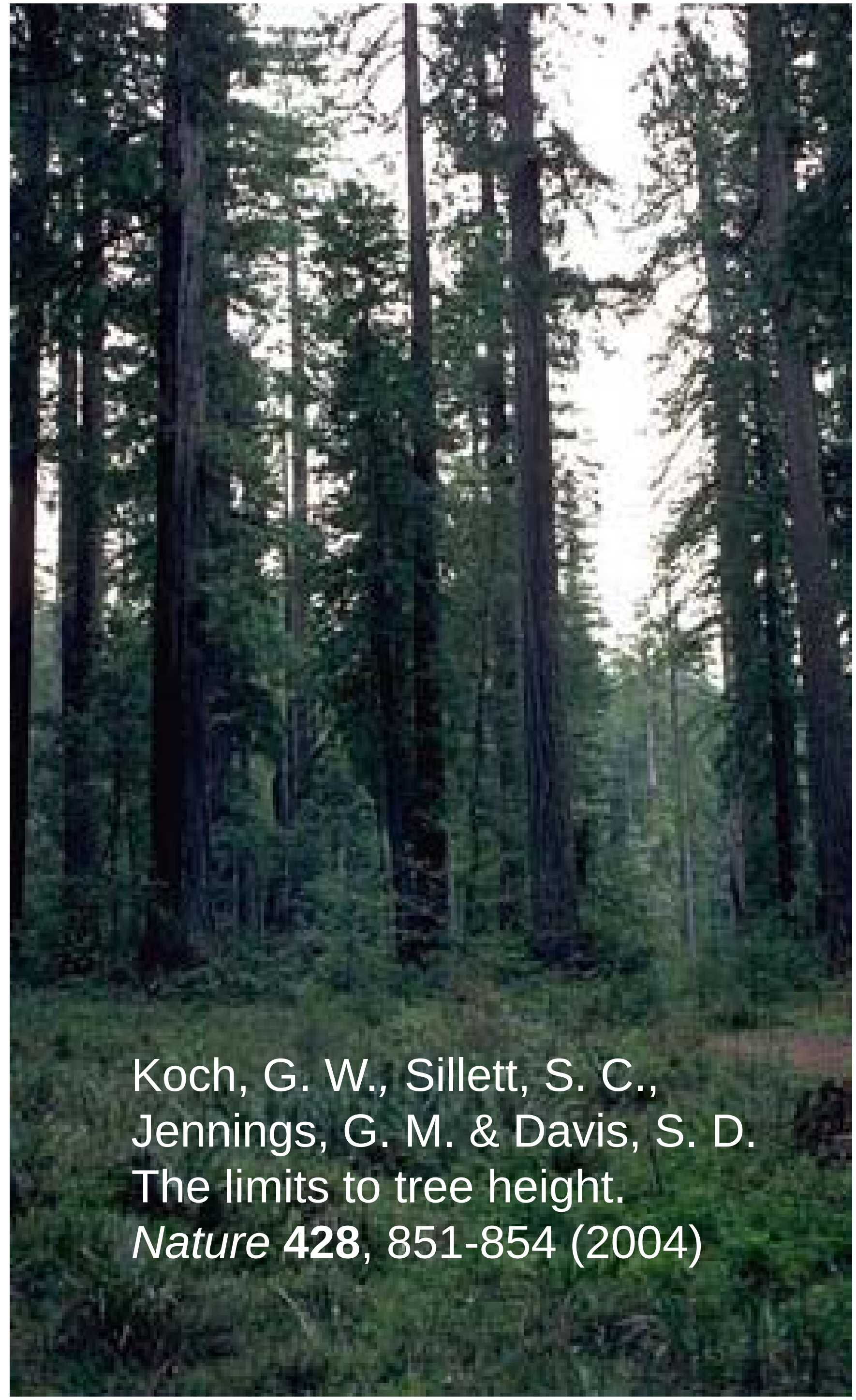


Figure 2. Primary Wall Architecture and Potential Mechanisms for Stress Relaxation and Creep of Cell Walls.

10~40 nm pores on outer surface

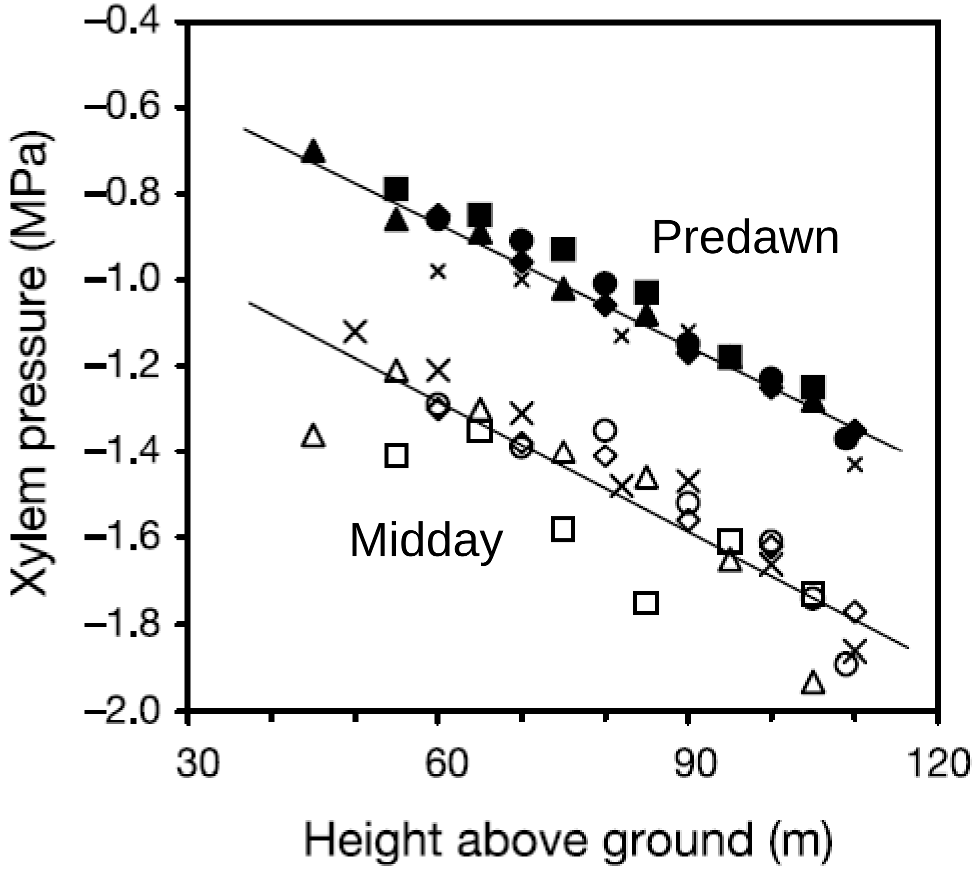
generate large negative pressure ~MPa





Koch, G. W., Sillett, S. C., Jennings, G. M. & Davis, S. D. The limits to tree height. *Nature* **428**, 851-854 (2004)

Relationship Between Xylem Pressure and Tree Height



Hydrostatic gradient before dawn is equal to the gradient due to gravity.

At midday, 2/3 of the xylem pressure due to gravity.

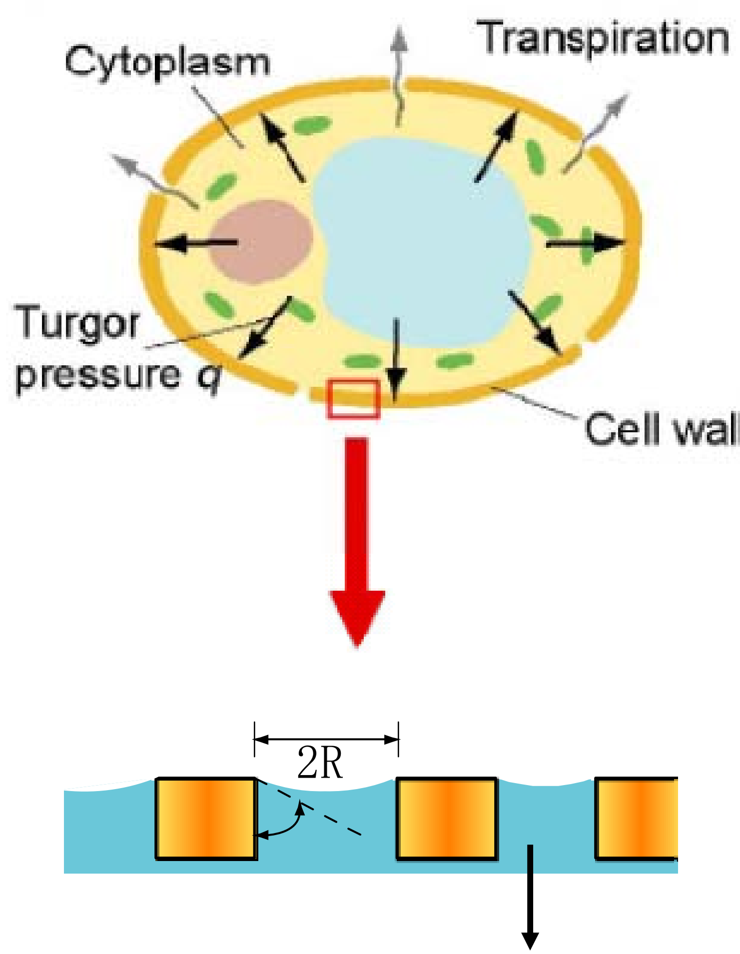
Guess negative water pressure is the reason.

- An important process in tree’s life is the continuous water transport to tree leaves, which is mainly driven by the negative pressure inside the leaf mesophyll cells, generated by transpiration.
- However, <u>the effects of these negative pressures</u> on the mesophyll cells are mostly unknown.

Focus on cells under transpiration!

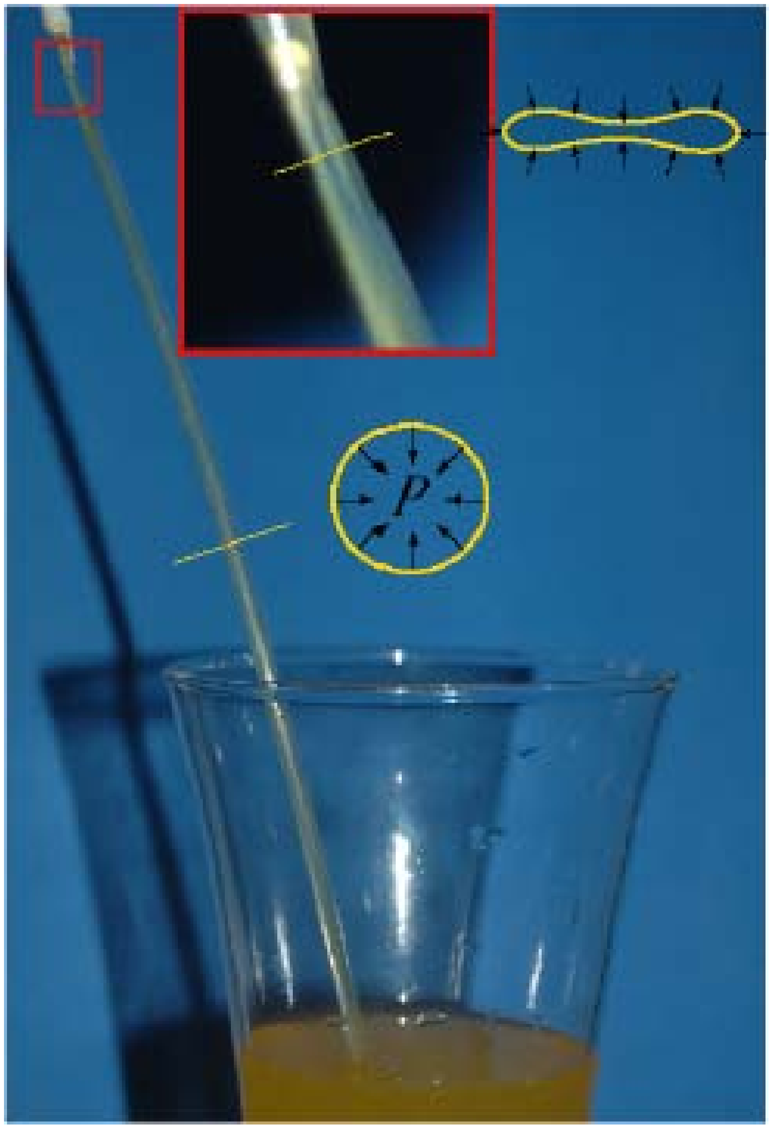
Negative Pressures

- Transpiration on nanoscale wall-pores generate negative pressure in apoplast water.
- Xylem negative pressures become more negative with increasing height.
- What's the effects of negative pressure to the evolution and structure of mesophyll cells？



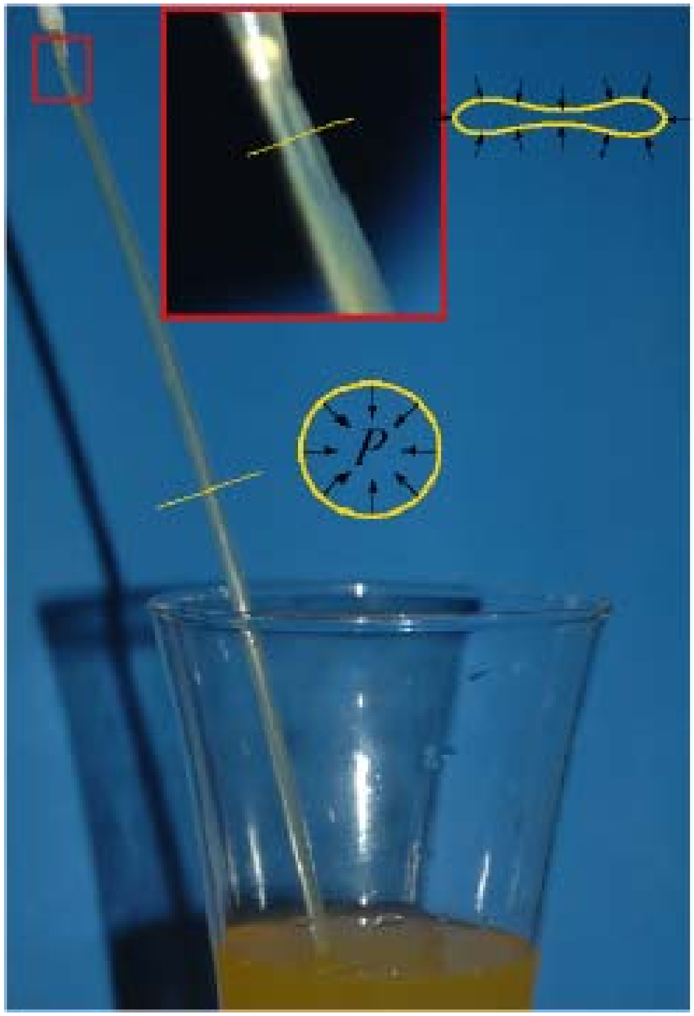
Negative apoplast water pressure

Straw Collapse Analogy



When drinking furiously through a straw, the straw may suddenly collapse into flat, due to the negative pressure inside.

Straw Collapse Analogy



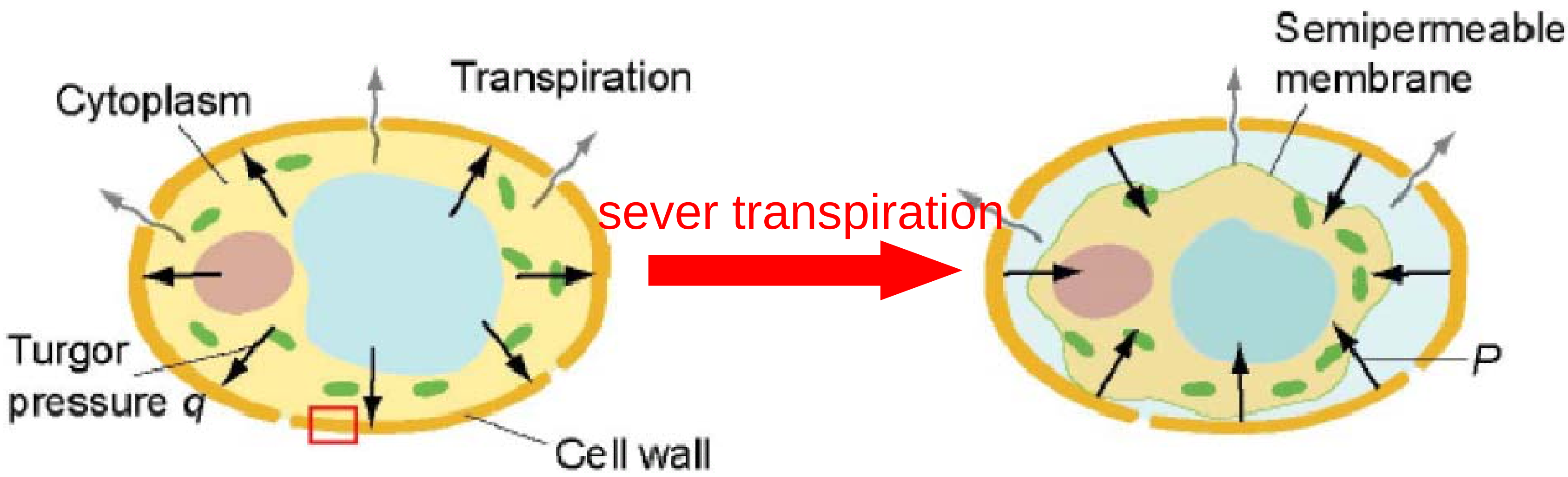
For cylindrical thin shell:

$$P_{cr} = \frac{2Et^3}{D^3\left(1-\nu^2\right)}$$

$$\text{so, } D_{\text{cr}} = \sqrt[3]{\frac{2Et^3}{(1-\nu^2)P}}$$

Timoshenko, Theory of elastic stability

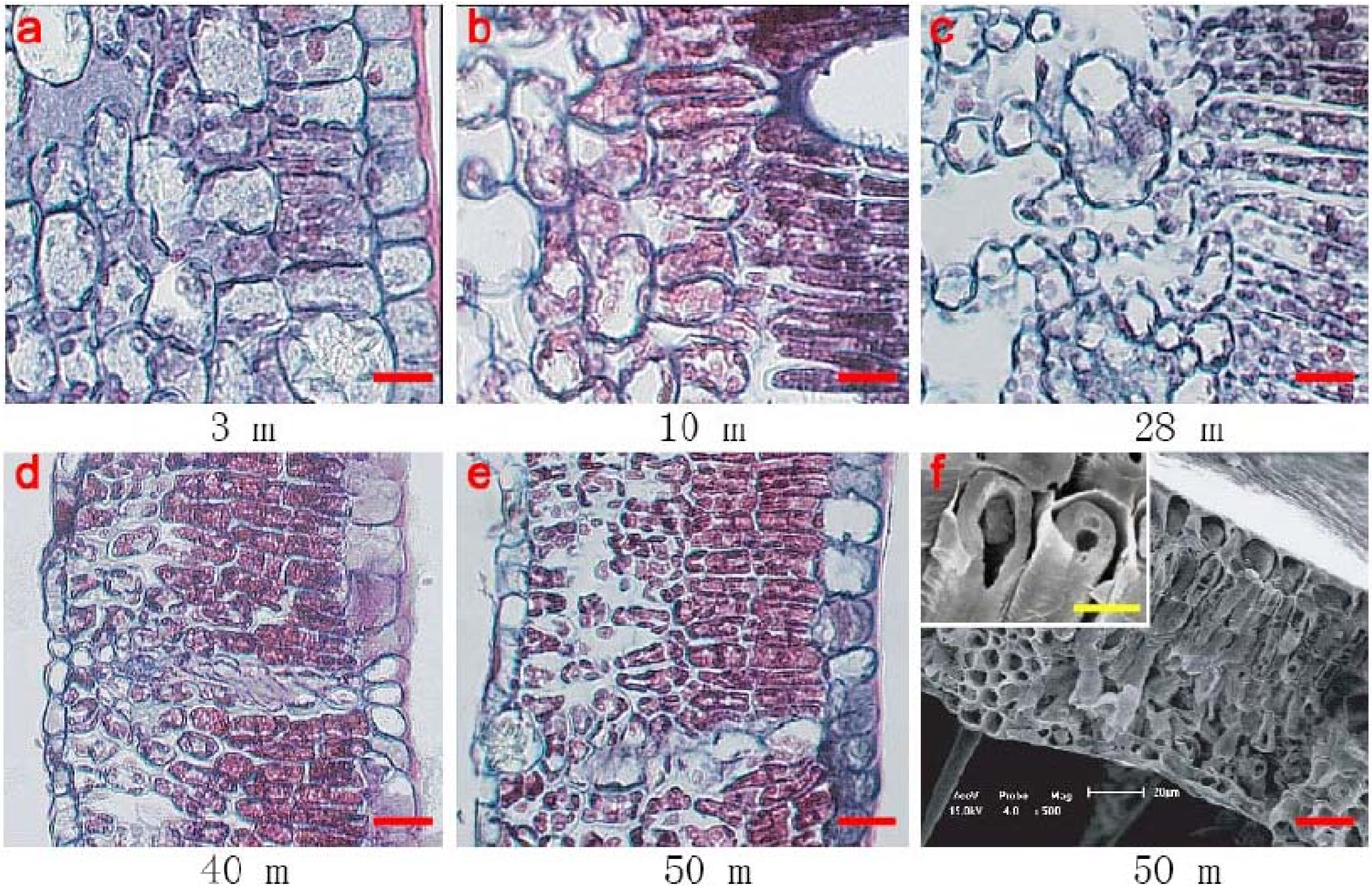
Elastic Instability Mechanism for large cells



cylindrical shell model:

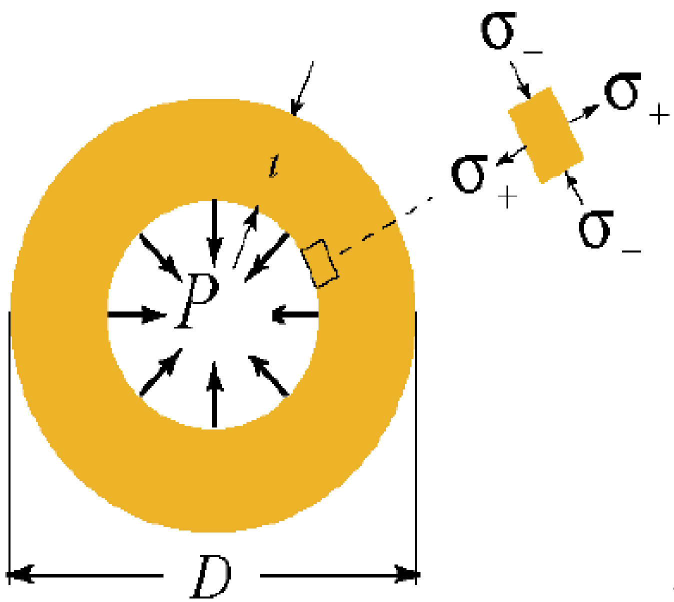
$$D < D_{\mathrm{cr}} = \sqrt[3]{\frac{2Et^3}{(1-\nu^2)P}}$$

Mesophyll cell sizes versus heights



Red Scale Bar = 20 μm

Strength Failure Mechanism for small cells



Assume isotropic elastic material

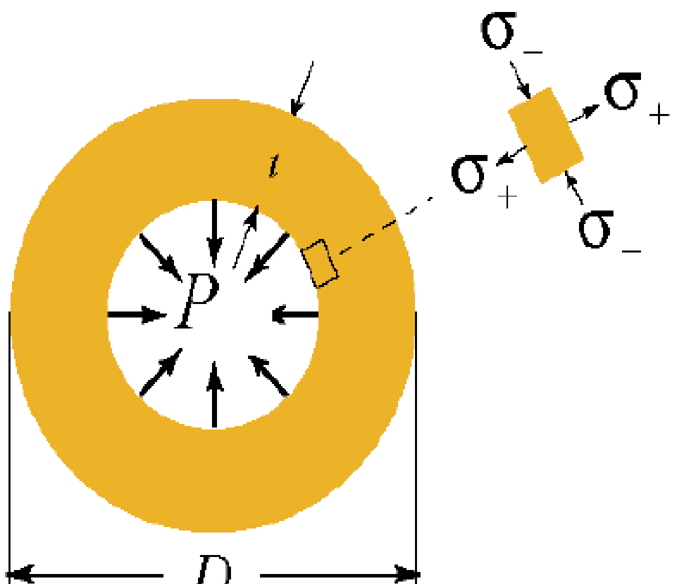
$$\sigma_r \Big|_{r=\frac{D}{2}-t} = P$$

$$\sigma_r \Big|_{r=D/2} = 0$$

$$\sigma_r = -\frac{P(D-2t)^2}{D^2-(D-2t)^2} + \frac{PD^2(D-2t)^2}{4\left(D^2-(D-2t)^2\right)r^2}$$

$$\sigma_\phi = -\frac{P(D-2t)^2}{D^2-(D-2t)^2} - \frac{PD^2(D-2t)^2}{4\left(D^2-(D-2t)^2\right)r^2}$$

Strength Failure Mechanism for small cells



Max stresses:

$$\sigma_r \big|_{r=a} = P$$

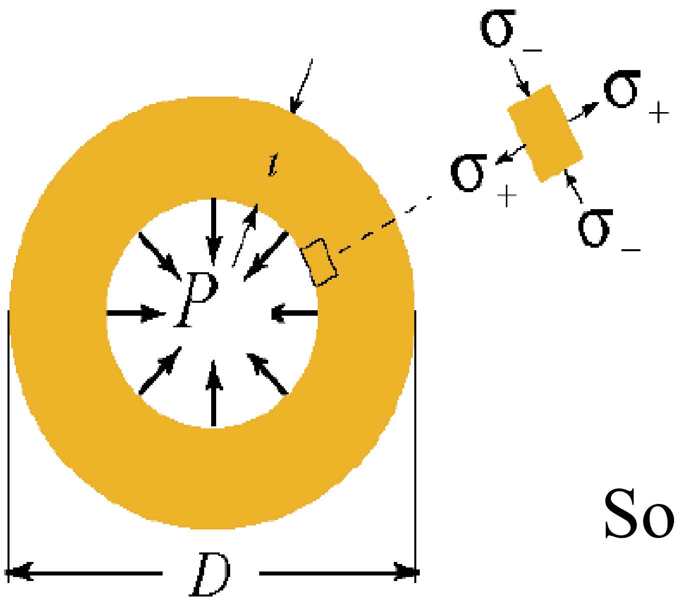
$$\sigma_\phi \big|_{r=a} = -\frac{D^2 + (D-2t)^2}{D^2 - (D-2t)^2} P$$

Strength criteria:

$$|\sigma_{r(r=a)}| = P < \sigma_{s+} \quad (= \text{tensile strength})$$

$$|\sigma_{\phi(r=a)}| = \frac{D^2 + (D-2t)^2}{D^2 - (D-2t)^2} P < \sigma_{s-} \quad (= \text{compressive strength})$$

Strength Failure Mechanism for small cells



So

$$D < D_{cr} \sim \left[1 + \frac{\sigma_{s-}}{P} + \sqrt{\left(\frac{\sigma_{s-}}{P}\right)^2 - 1} \right] t$$

Detailed parameters…

$$P_{low} = P_0 + (n+1)\rho g H$$

extra pressure flow resistance index

$$E = 130 \text{ MPa}; \;\; \upsilon = 0.3; \;\; t = 1.5 \text{ μm}$$

$$\sigma_{s-} = 2.3 \text{ MPa for rainforest trees}$$

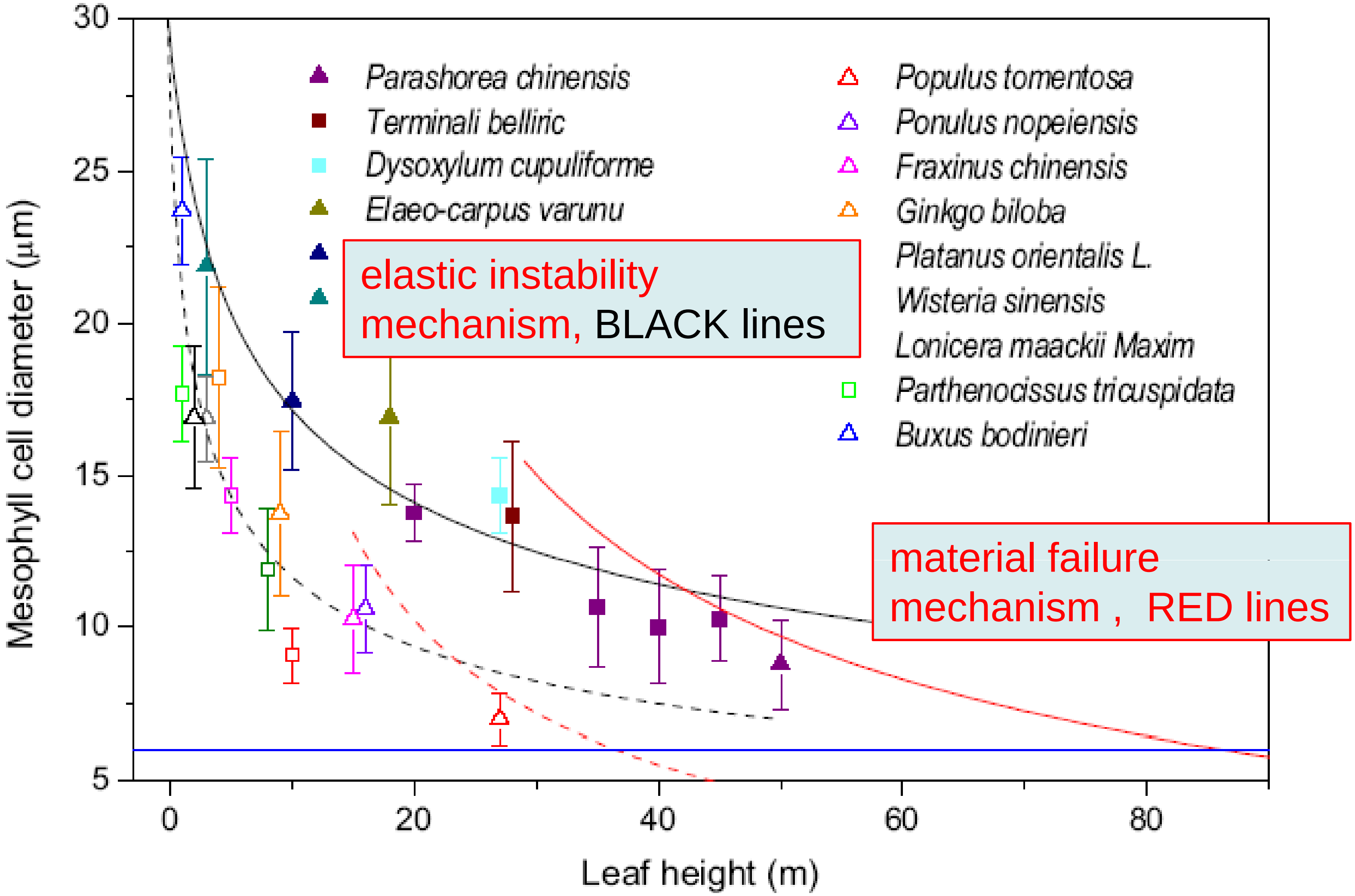
$$\sigma_{s-} = 3.5 \text{ MPa dry-temperate trees}$$

Curve fitting results:

n = 0.5 for rainforest zone trees

n = 4.6 for dry-temperate zone trees

Model Estimates



In both mechanisms, leaf cells should decrease their sizes to prevent structure and material collapse, with increasing height.