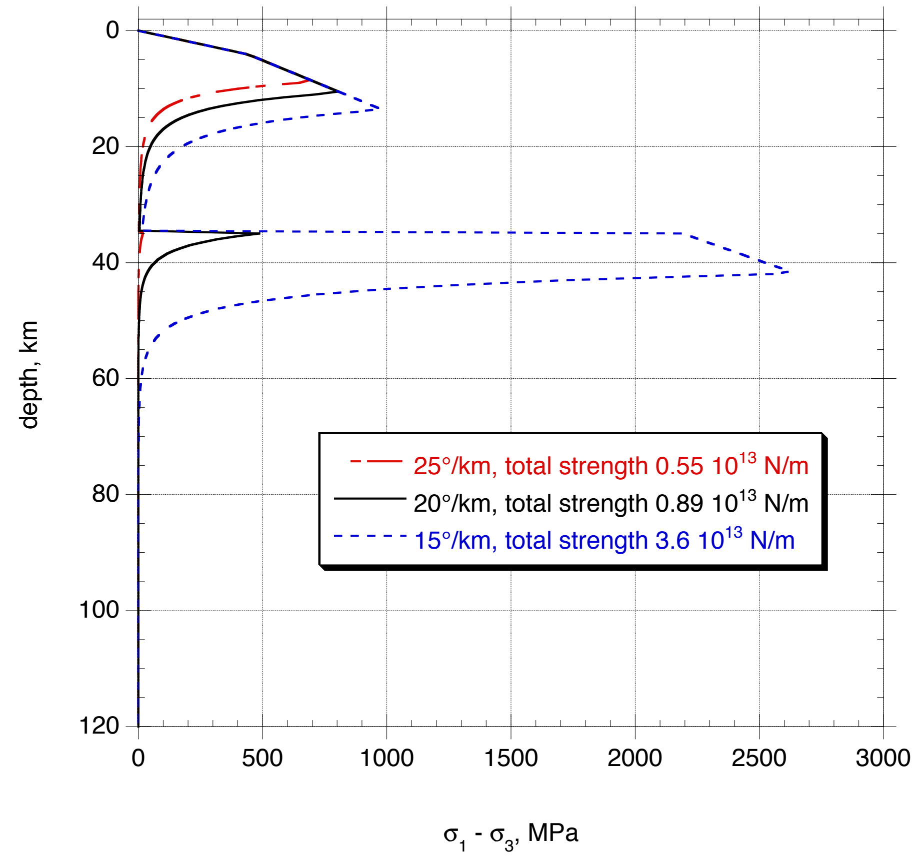
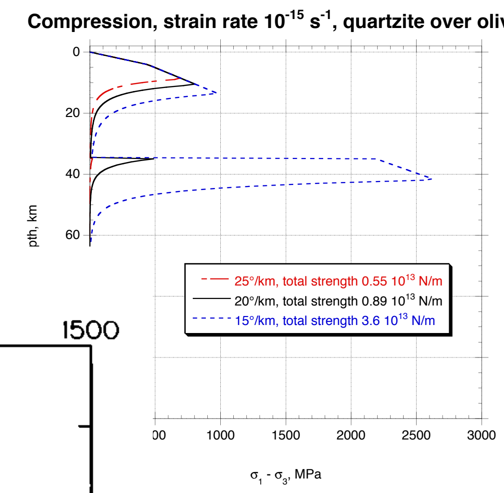
What drives deformation?

Most simply put, it is when stresses overcome strength

So, what is strength? Where do stresses come from?

Compression, strain rate 10^{-15} s^{-1}, quartzite over olivene





Overall strength much lower in extension

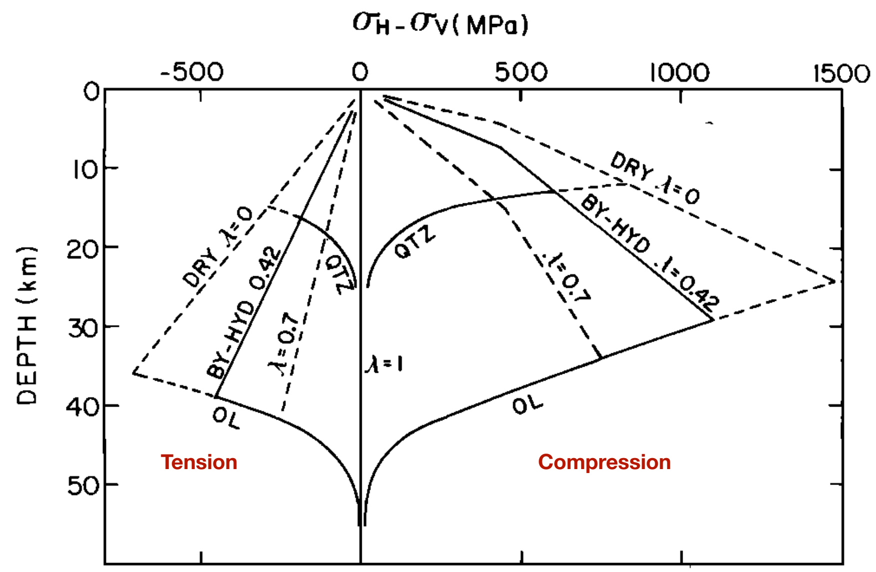
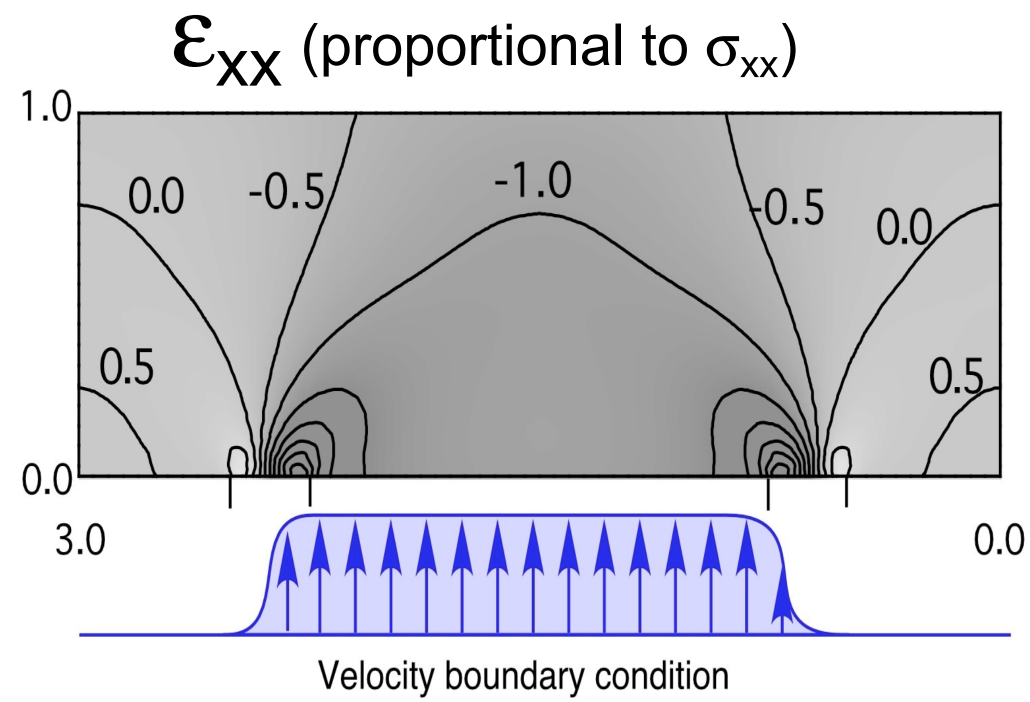


Fig. 5. Difference between maximum or minimum horizontal stress and the vertical stress as a function of depth. Values of λ give pore pressure level. See also Figure 4.

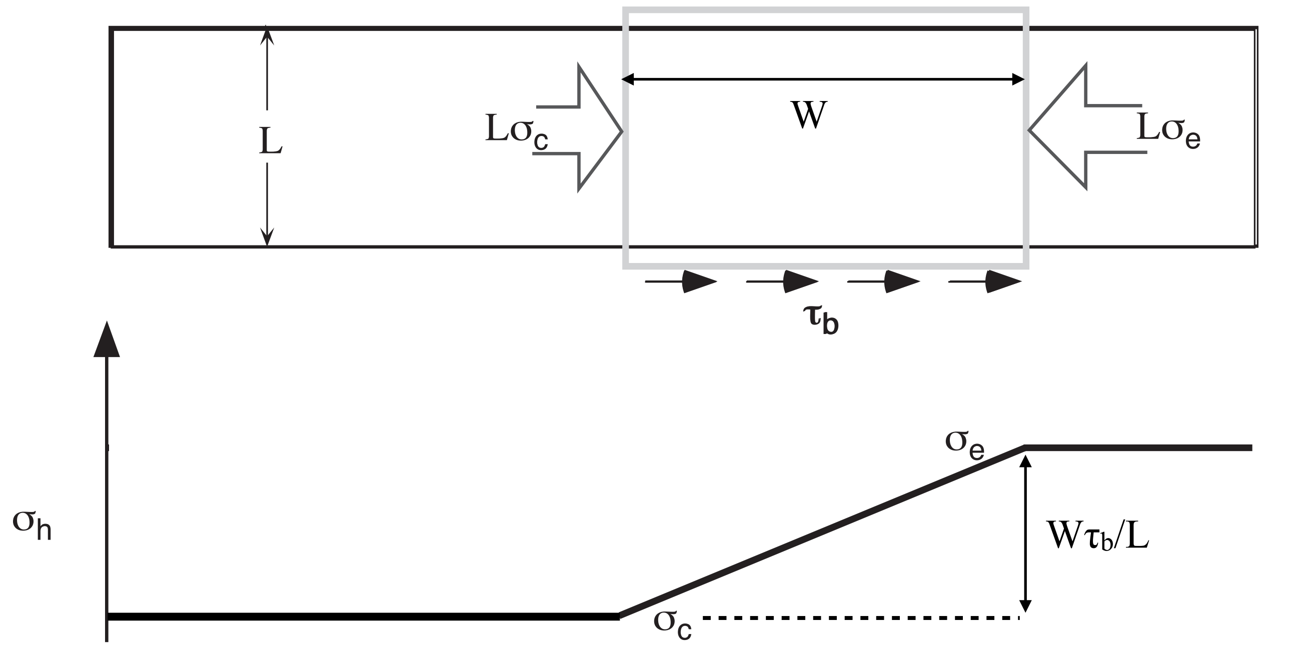
What of stresses?

For edge forces, deformation should decrease with distance from edge…



Modified from Sonder and Jones (1999)

Basal shear stress

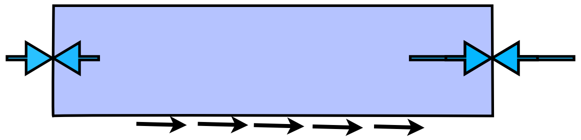


…great way to get higher horizontal stresses far inland
(produces shortening to the right)

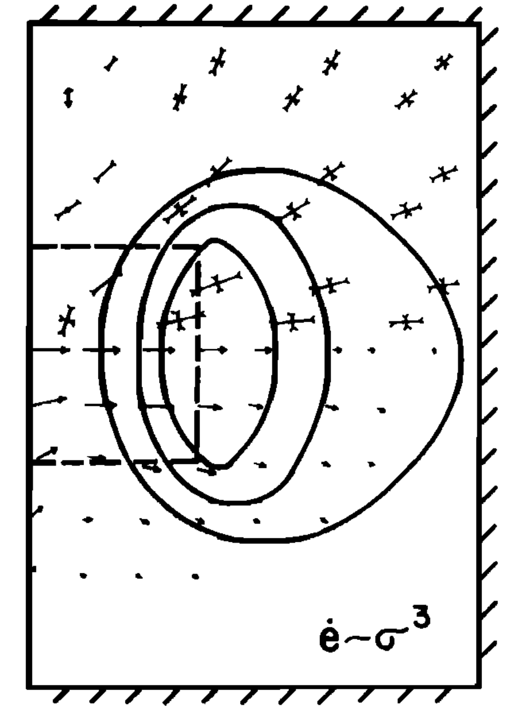
But for normal faulting, can we get lower stresses?

This is the classic flat slab model for the Laramide; note it requires that basal shear to be pretty high.

Basal shear



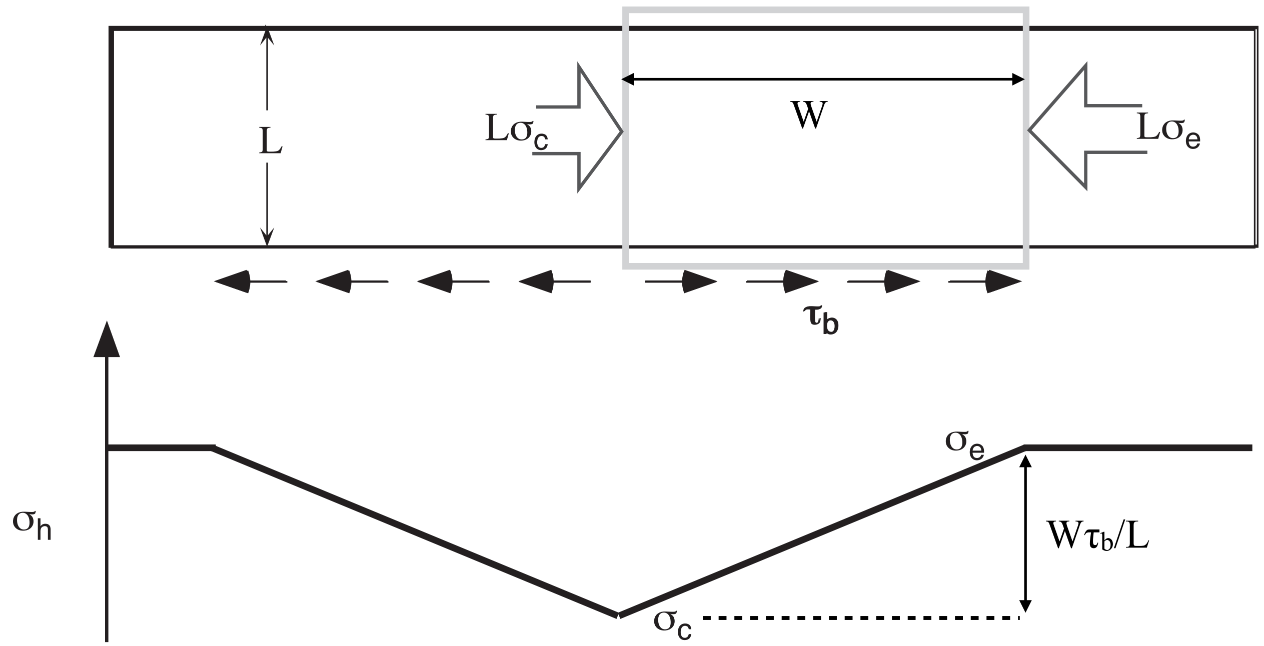
Basal shear increases horizontal normal stresses in direction of shear



Bird, *Tectonics*, 1984

Contours are rate of crustal thickening (not relevant here), stresses in top, velocities at bottom.

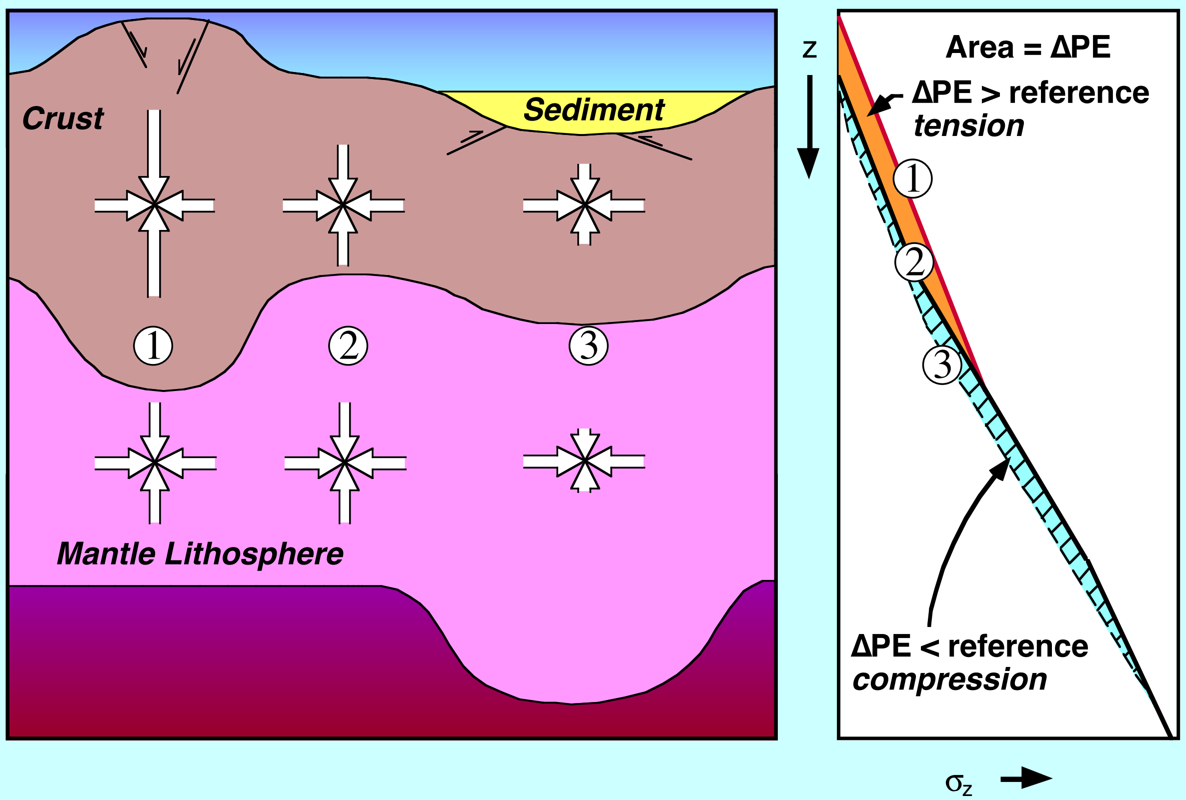
Basal shear stress



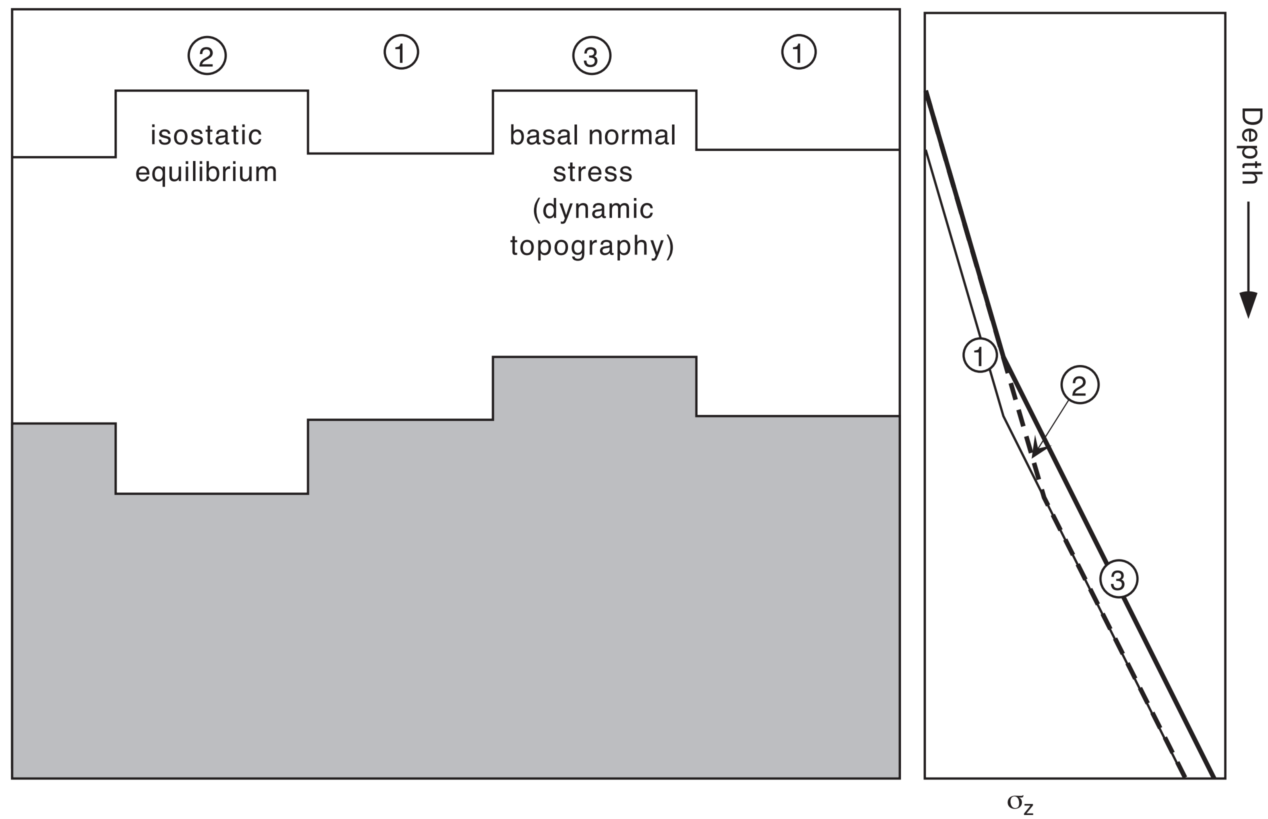
Diverging basal shears can produce low horizontal stress but tends to be tightly focused

This might not be such a terrible model for some back-arc situations, but not so wonderful for extension in continents in general.

Gravitational Potential Energy and stresses



Body forces



Column 1 is an isotropic stress state (no deformation no matter how weak it is).

$$\mathrm{GPE} = \int_0^{z_c+\varepsilon} \rho(z') g z' \, dz'$$

$$= -\int_{z_c}^{-\varepsilon} \rho(z) g (z_c - z) \, dz$$

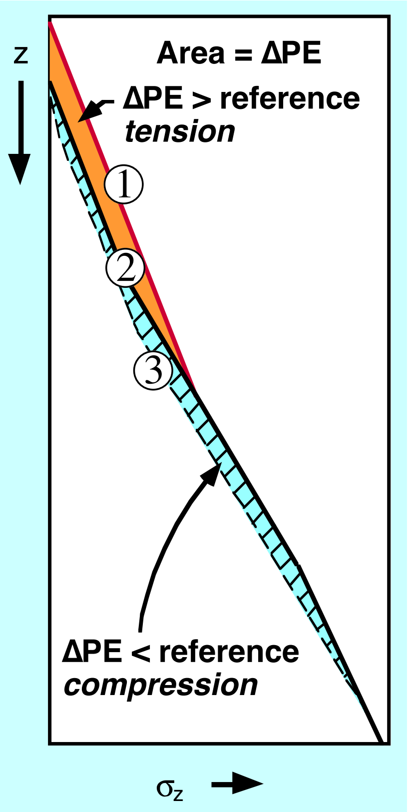
$$= g z_c \int_{-\varepsilon}^{z_c} \rho(z) dz - \int_{-\varepsilon}^{z_c} \rho(z) g z dz$$

Isostasy

$$\mathrm{GPE} = g z_c \int_{-\varepsilon}^{z_c} \rho(z)\,dz - \int_{-\varepsilon}^{z_c} \rho(z) g z\,dz$$

$$\Delta\mathrm{GPE} = \int_{H_0}^{z_c} \rho_a g z\,dz - \int_{-\varepsilon}^{z_c} \rho(z) g z\,dz$$

Asthenosphere



Could make point that GPE is proportional to strain rate for Newtonian viscosity

$$\int_{-\varepsilon}^{z_c} \sigma_z(z)\,dz = \int_{-\varepsilon}^{z_c}\int_{-\varepsilon}^{z} g\rho(z')\,dz'\,dz$$

$$= \left[zg\int \rho\, dz' \right]_{-\varepsilon}^{z_c} - \int_{-\varepsilon}^{z_c} gz\rho(z)\,dz$$

$$= \left[z\sigma_z \right]_{-\varepsilon}^{z_c} - \int_{-\varepsilon}^{z_c} gz\rho(z)\,dz$$

$$= z_c \int_{-\varepsilon}^{z_c} g\rho(z)\,dz - \int_{-\varepsilon}^{z_c} gz\rho(z)\,dz = GPE$$

$$\frac{\partial \overline{\tau}_{ij}}{\partial x_j} + \frac{\partial \overline{\tau}_{zz}}{\partial x_i} = \frac{1}{L}\frac{\partial (PE)}{\partial x_i}$$

Can make stresses by changing structure of the lithosphere

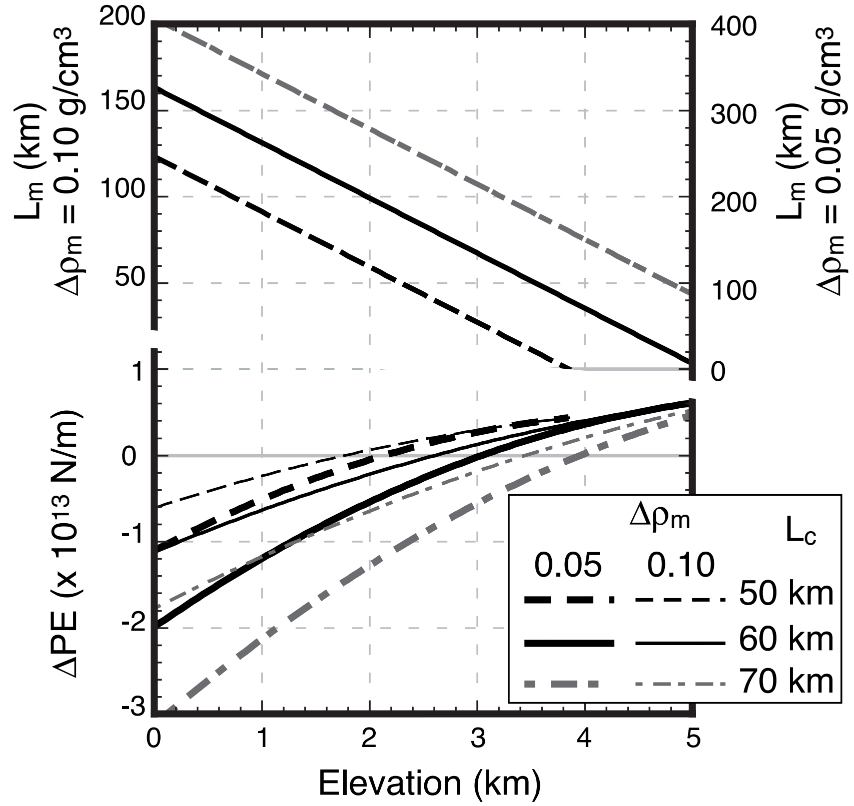
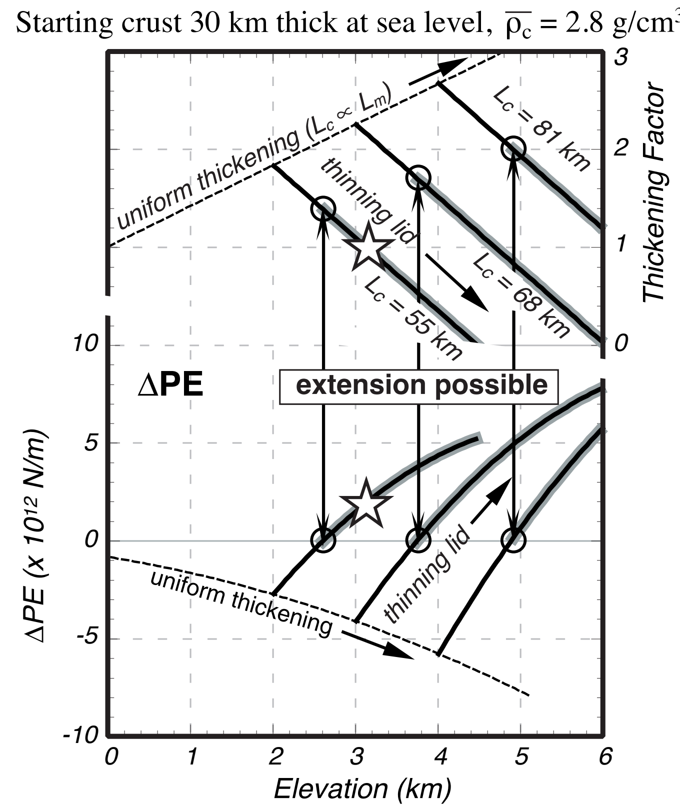


Figure 3. ΔPE for lithospheric columns with different crustal thicknesses (L_c) as a function of elevation. Two mean density contrasts ($\Delta\rho_m$) between mantle lithosphere and asthenosphere are illustrated. Note that low elevations with 50–70-km-thick crust likely for the early Tertiary Great Basin would require very thick or exceptionally dense mantle lithosphere and imply very negative values of ΔPE.

Jones et al., *Geology*, 1998

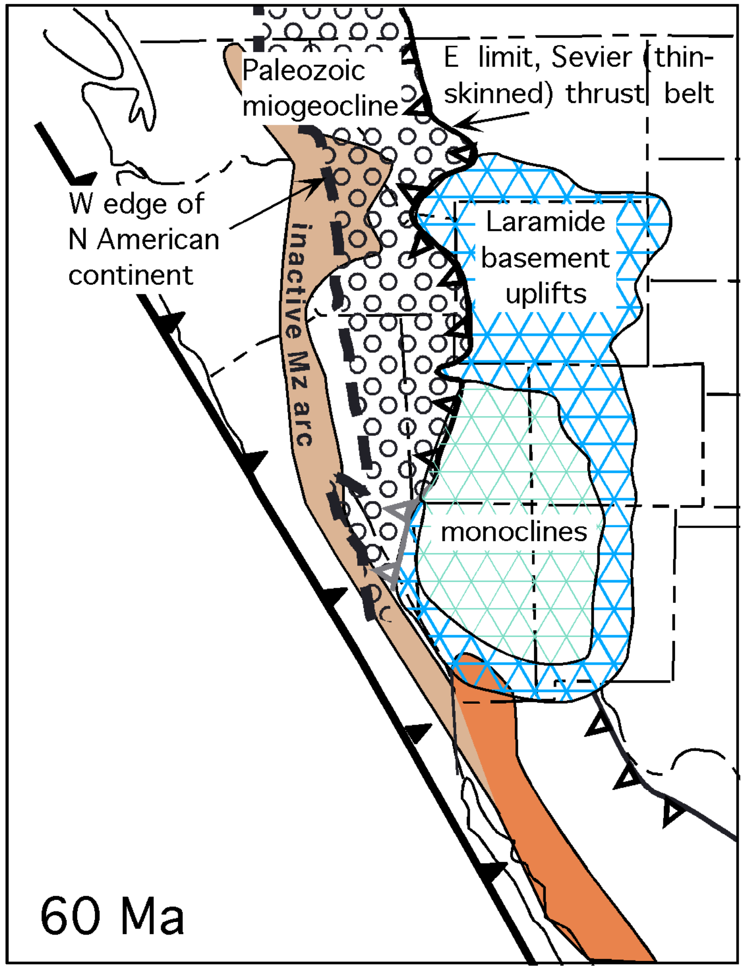
Relation of crustal thickness, elevation, and GPE.

Figure 2. Evolution of orogen with initial phase of uniform lithospheric thickening (dashed lines) followed by thinning of mantle lithosphere once the orogen reaches elevations of 2, 3, or 4 km (solid lines). Note that elevation always increases, but ΔPE reverses once mantle lithosphere begins to be removed. Gray lines indicate conditions under which extension is possible. Crustal thickness L_c = 30 km at outset; L_m = 86 km; ρ_c = 2.8 g/cm^3. An equivalent path in Figure 1 would proceed toward the right from thickening factor = 1 on the solid line, then up toward the dashed curve once thinning of the mantle lithosphere begins.



Jones et al., *Geology*, 1998

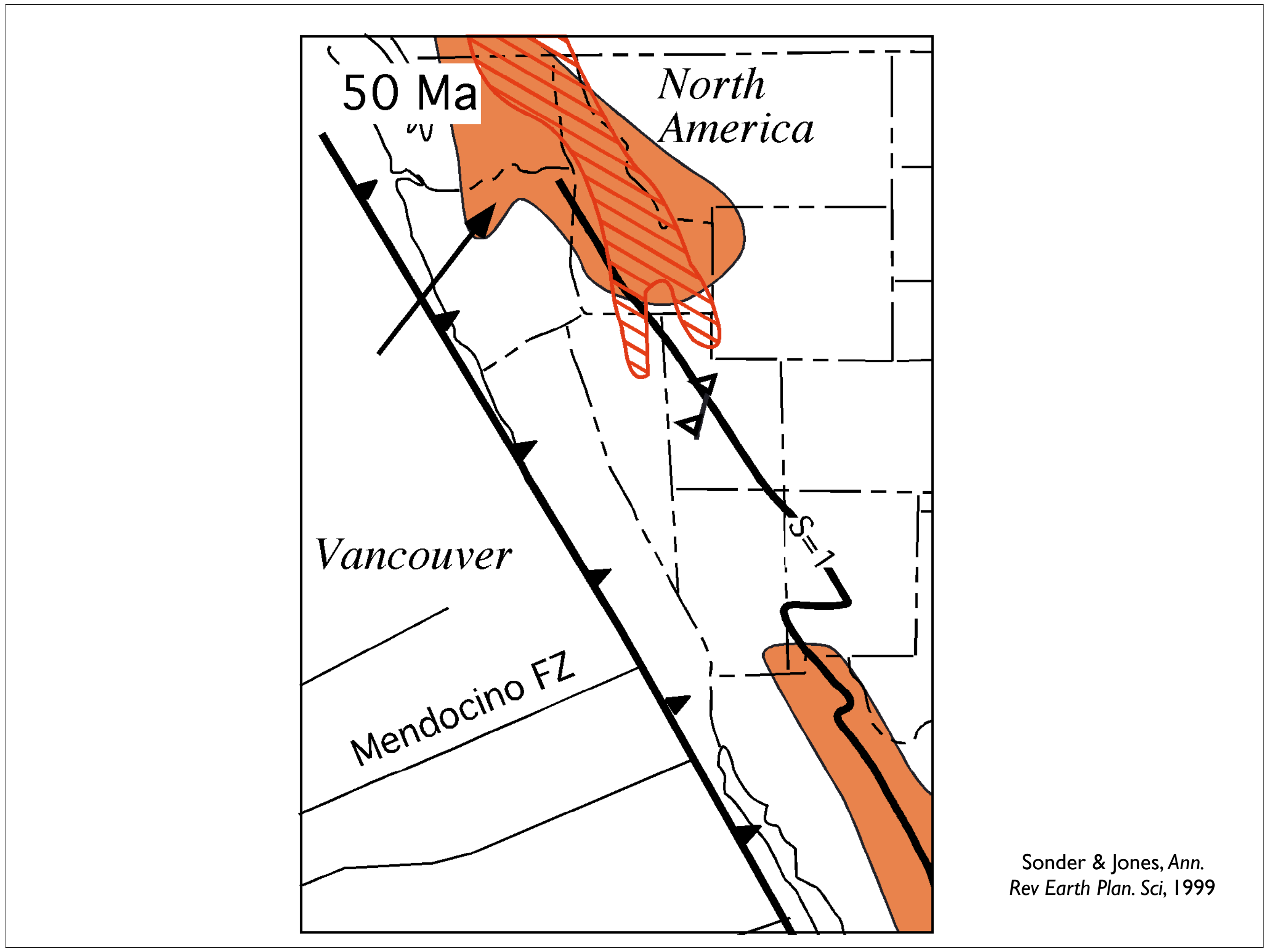
This is set up to move into paleoelevation studies.



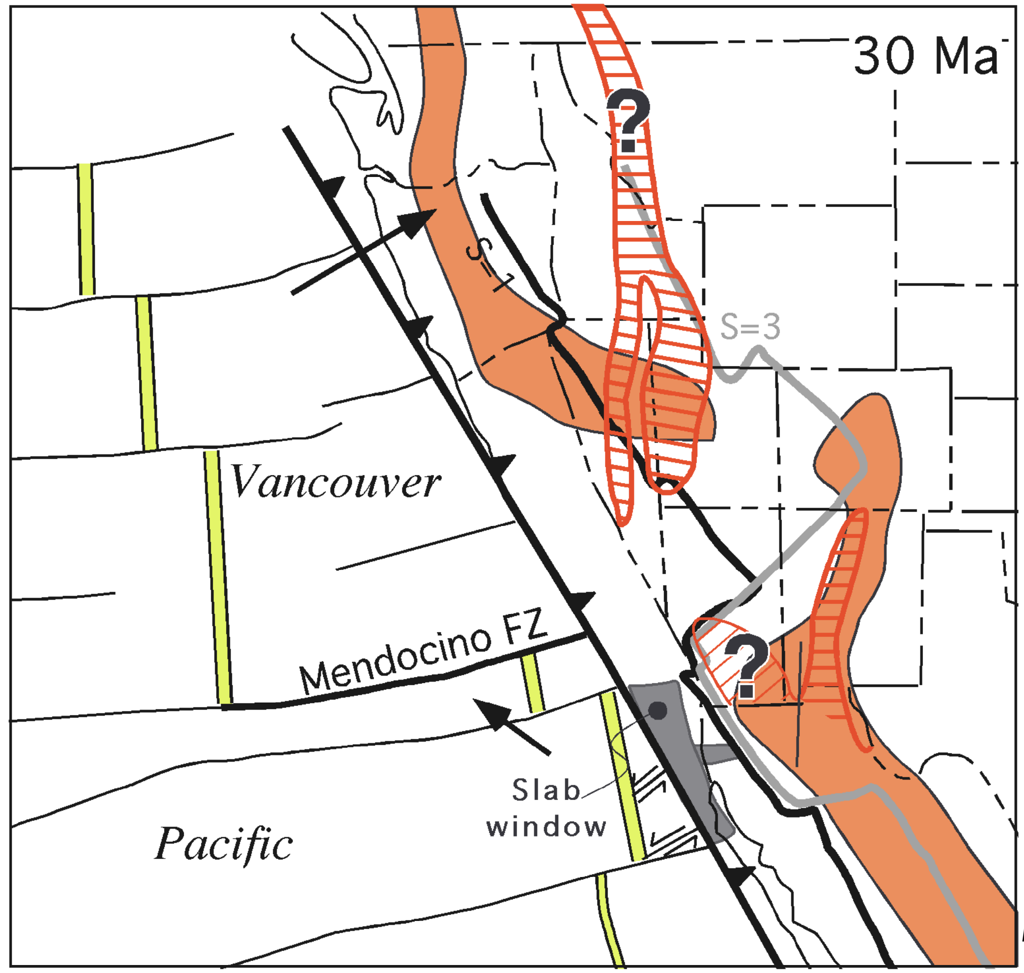
Sonder & Jones, *Ann. Rev Earth Plan. Sci*, 1999

When we look at this at the broadest scales, do we see the causes of extension? Is it strength? Is it stress?

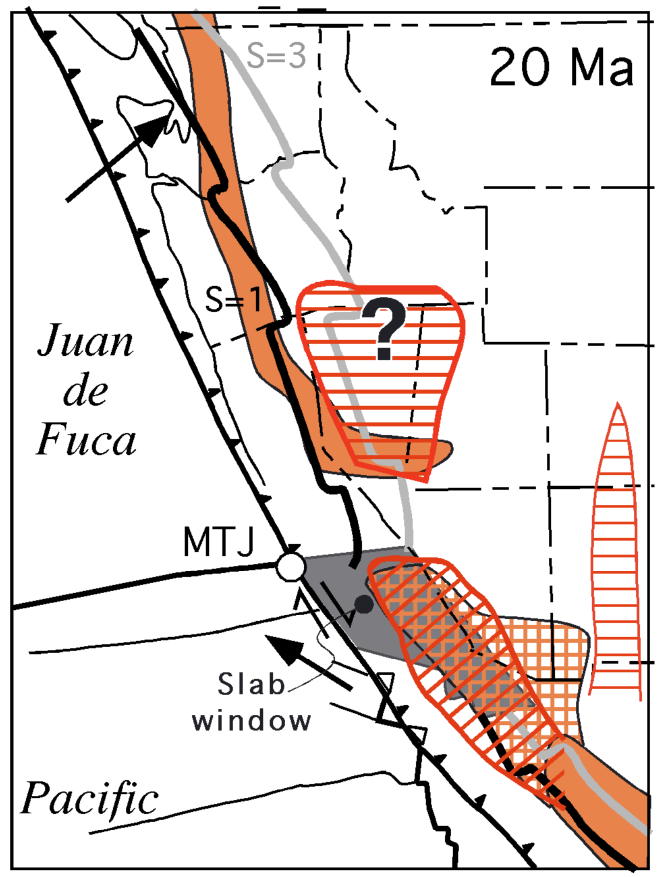
Dark orange is calc-alkaline volcanic areas (some interpret as arc)



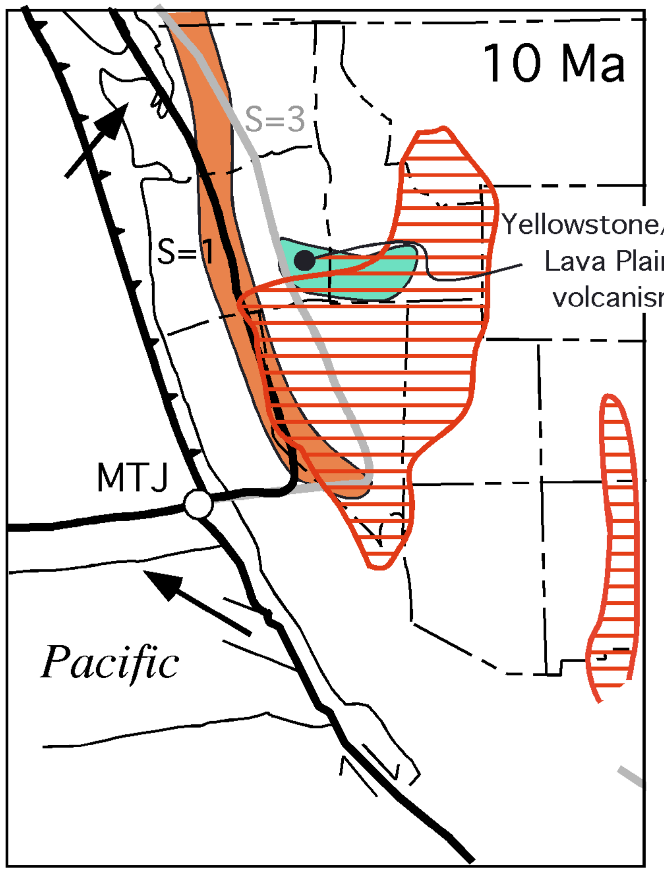
Big arrow is relative plate motion. Large heavy line (S=1) indicates position along which slab has fairly constant thermal state. “At each point on the slab, S equals the time since subduction divided by one-tenth of the age of that point at the time it was subducted.”
S=1 is approximately maximum depth of seismic slab. S = 10T/(A-T-C) where T is time since subduction, A age of magnetic anomaly and C is time of map construction (so A-C is age of slab at subduction.



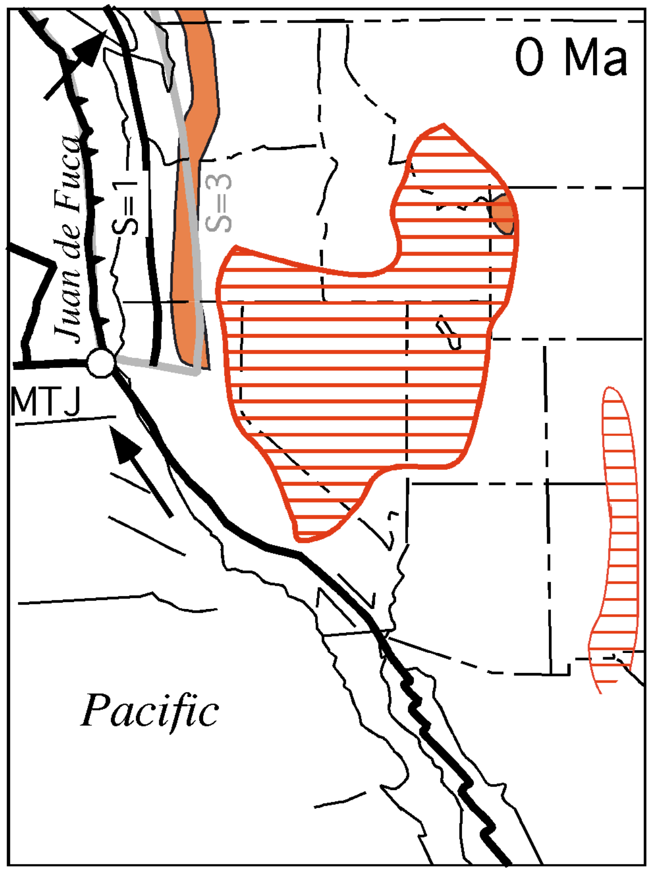
Sonder & Jones, *Ann. Rev Earth Plan. Sci*, 1999



Sonder & Jones, *Ann. Rev Earth Plan. Sci*, 1999

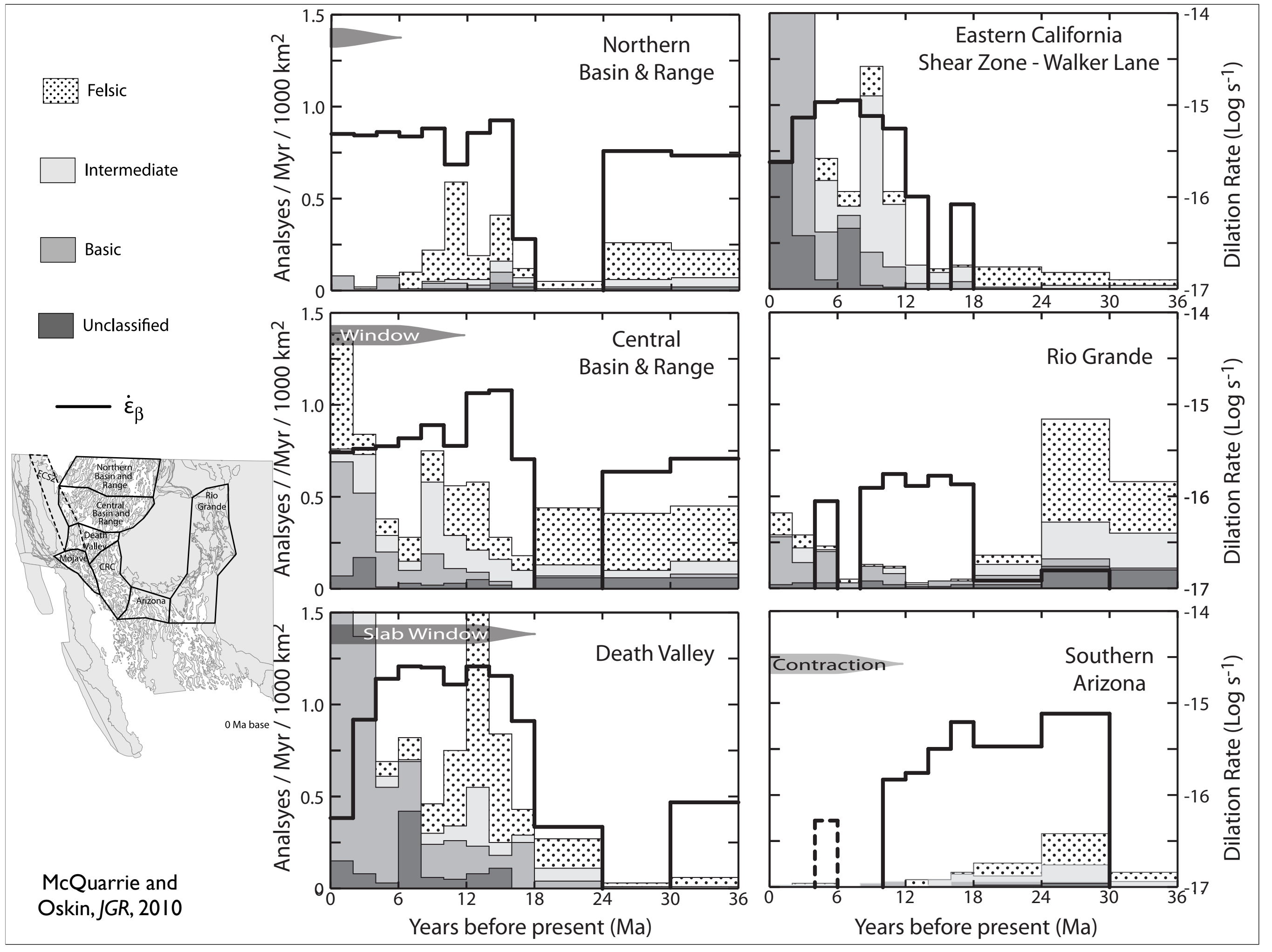


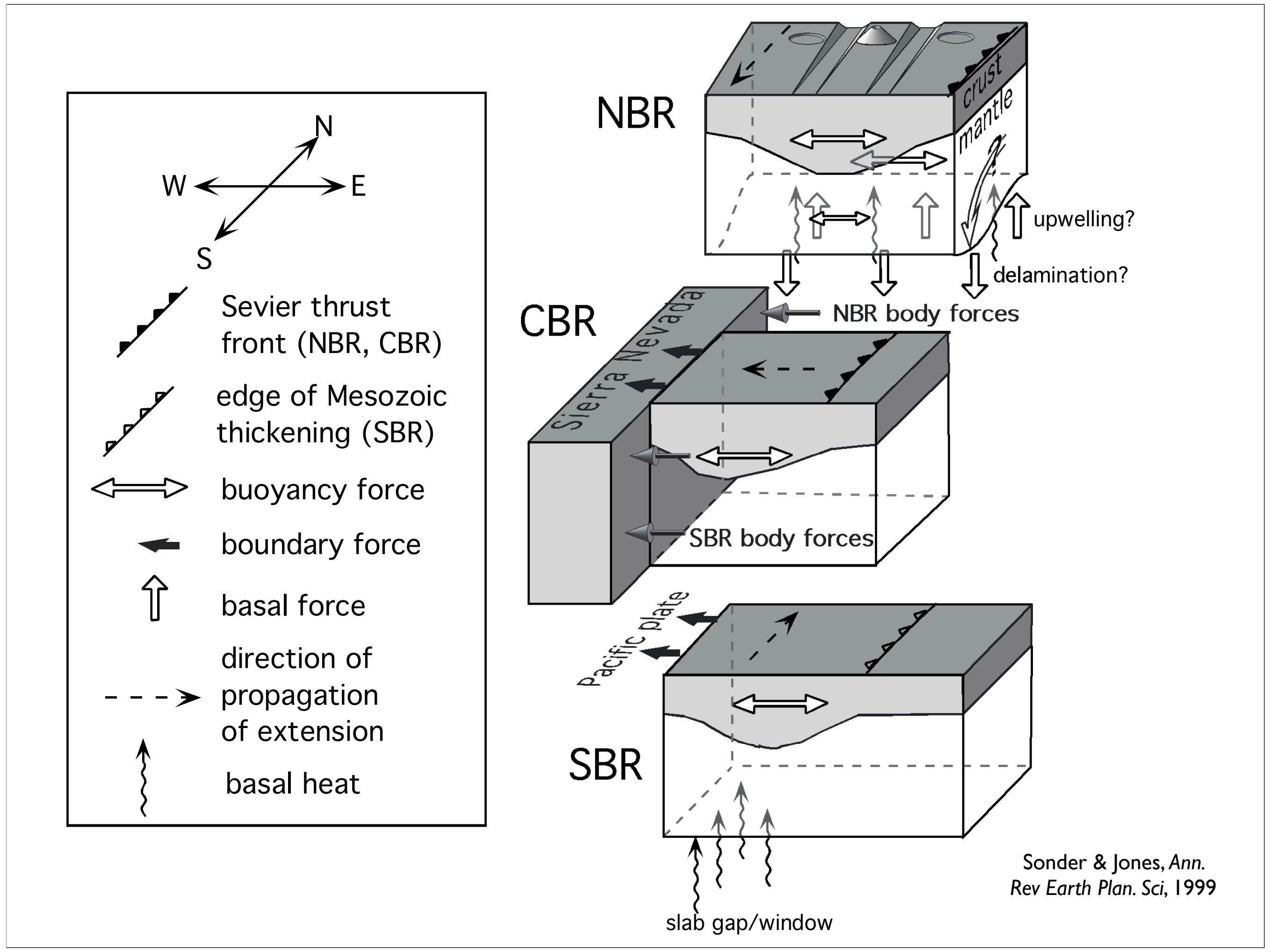
Sonder & Jones, *Ann. Rev Earth Plan. Sci*, 1999

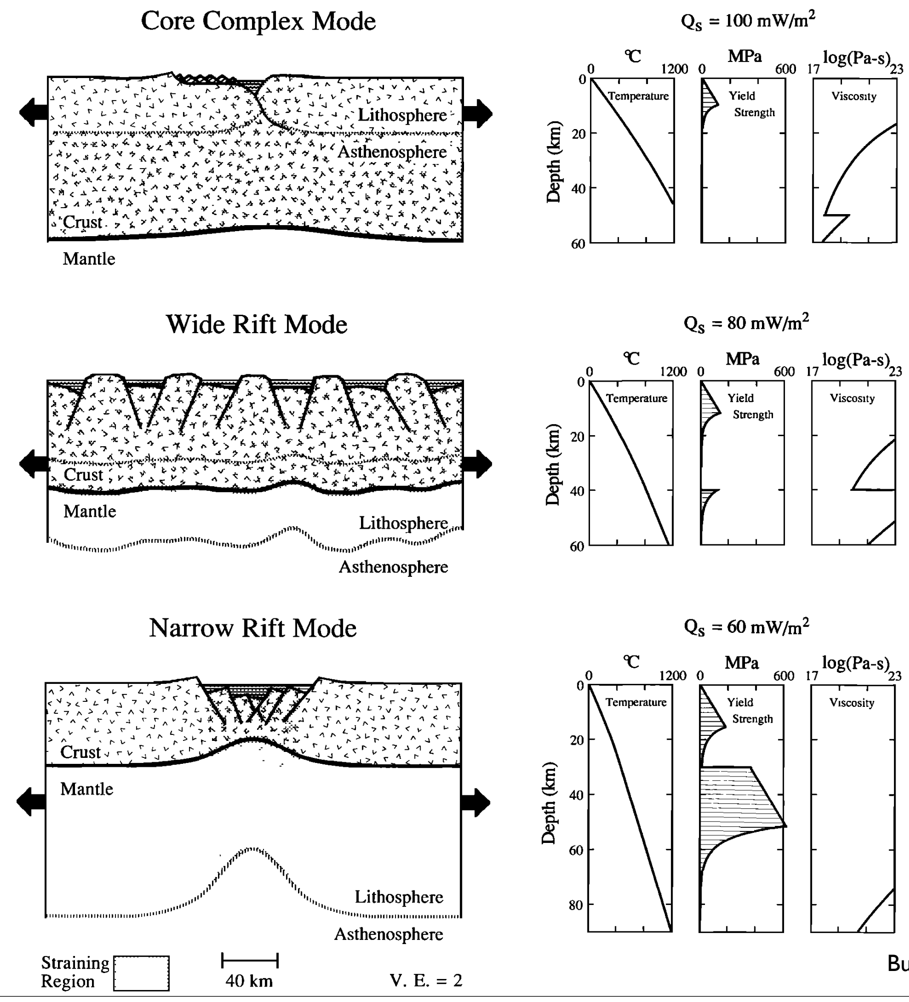


Sonder & Jones, *Ann. Rev Earth Plan. Sci*, 1999

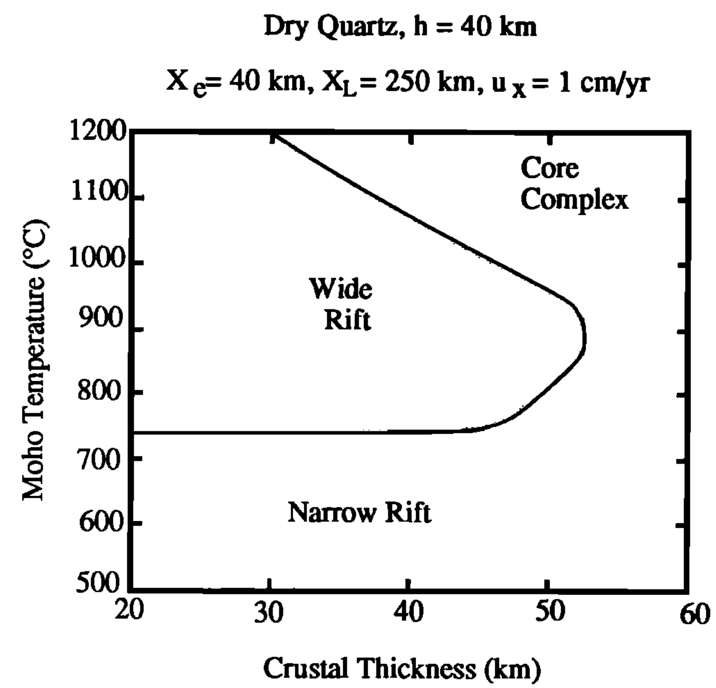
Note that the B&R extent seems unrelated to the triple junction.


Felsic
Intermediate
Basic
Unclassified
$\dot{\varepsilon}_\beta$
Northern Basin & Range
Eastern California Shear Zone - Walker Lane
Central Basin & Range
Rio Grande
Death Valley
Southern Arizona
Window
Slab Window
Contraction
Analsyes / Myr / 1000 km^2
Dilation Rate (Log s^{-1})
Years before present (Ma)
0 Ma base
McQuarrie and Oskin, *JGR*, 2010

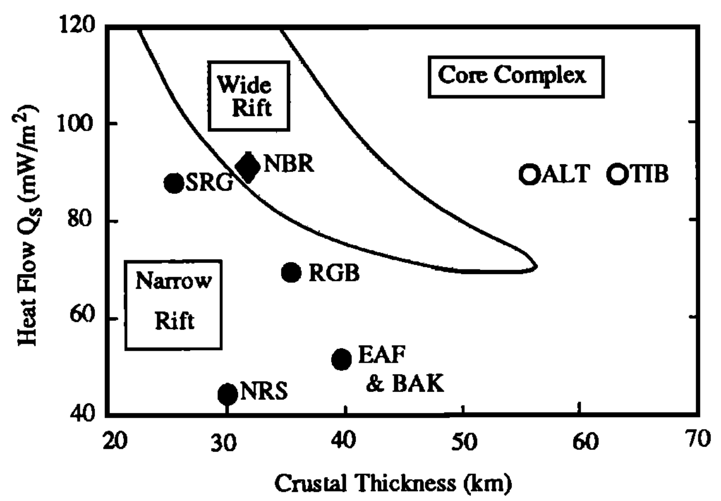

N
W
E
S
Sevier thrust front (NBR, CBR)
edge of Mesozoic thickening (SBR)
buoyancy force
boundary force
basal force
direction of propagation of extension
basal heat
NBR
crust
mantle
upwelling?
delamination?
CBR
NBR body forces
Sierra Nevada
SBR body forces
Pacific plate
SBR
slab gap/window
Sonder & Jones, Ann. Rev Earth Plan. Sci, 1999

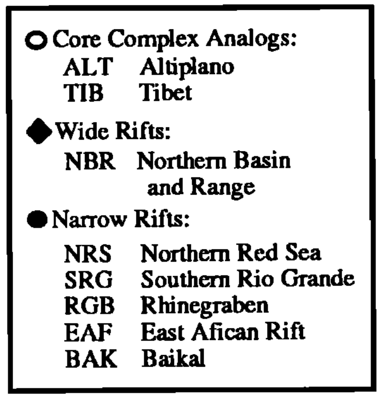


Buck, *JGR*, 1991

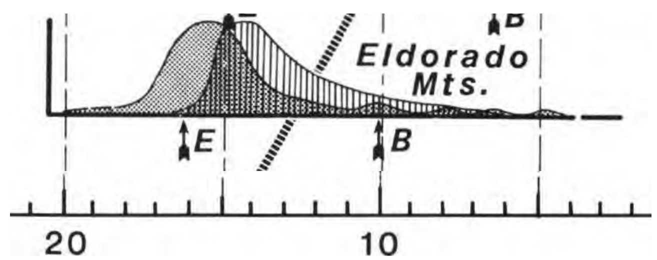


Buck, *JGR*, 1991

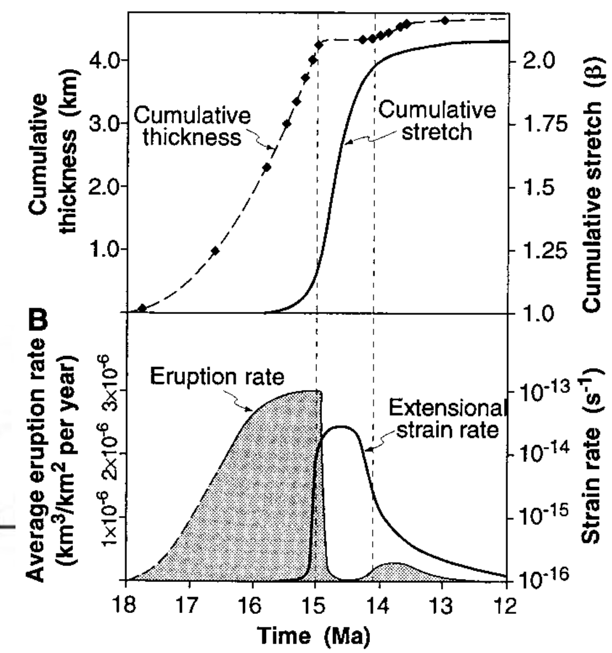




Buck, *JGR*, 1991

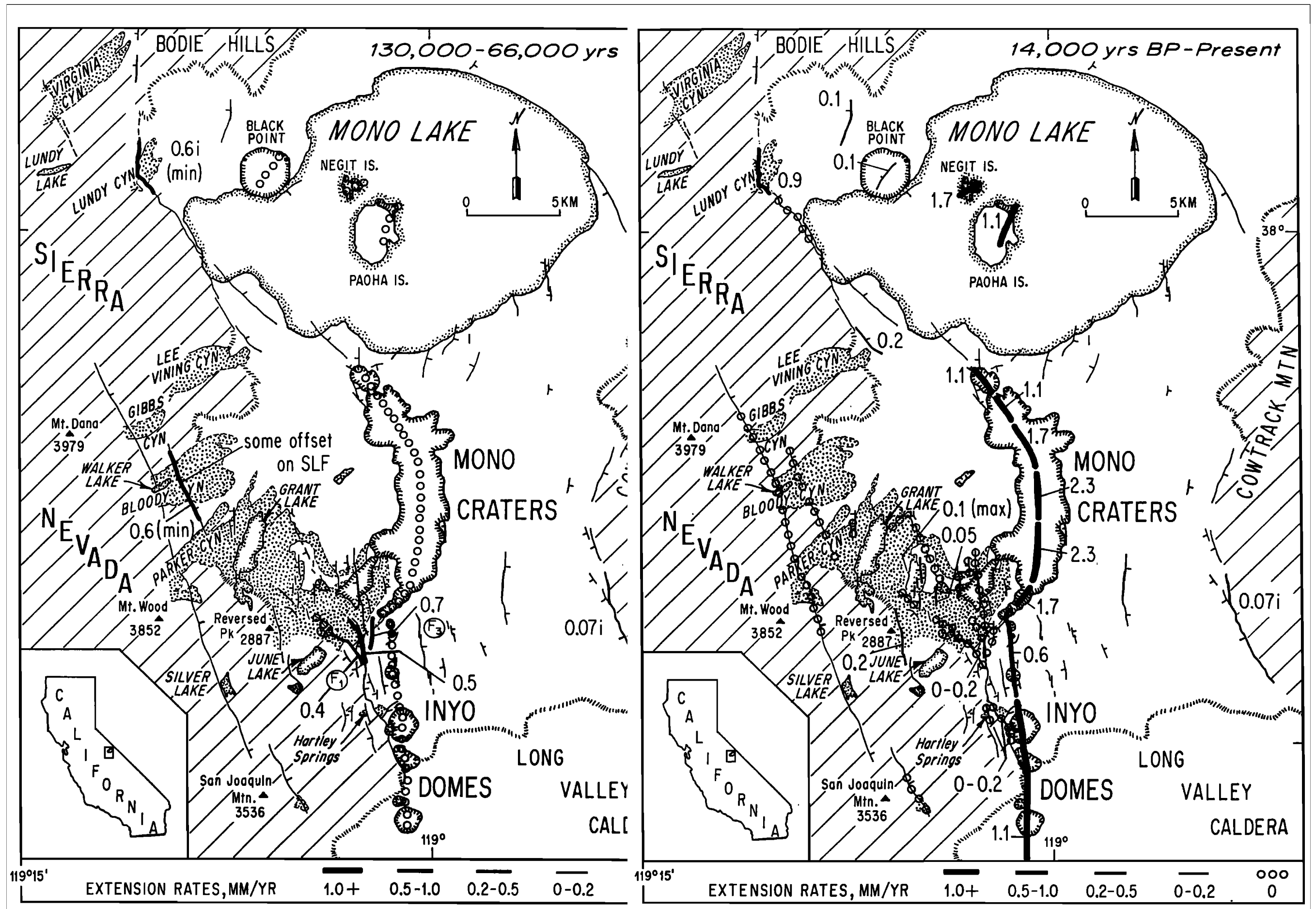


Gans et al., *GSA Spec. Paper*, *233*, 1989



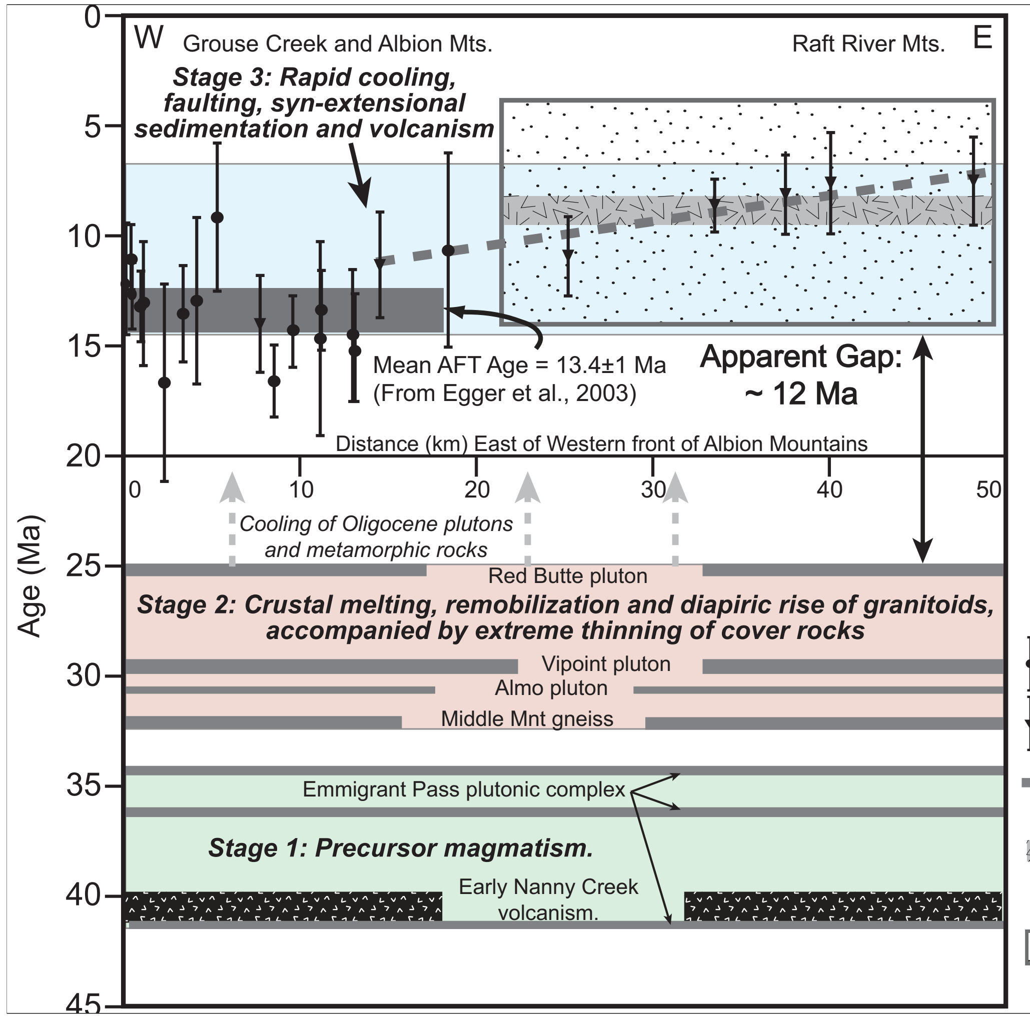
Gans and Bohrson, *Science*, 1997

Closer examination of at least one complex suggests that while tightly related in time, extension and volcanism are not coeval.



Bursik and Sieh, *JGR*, 1989

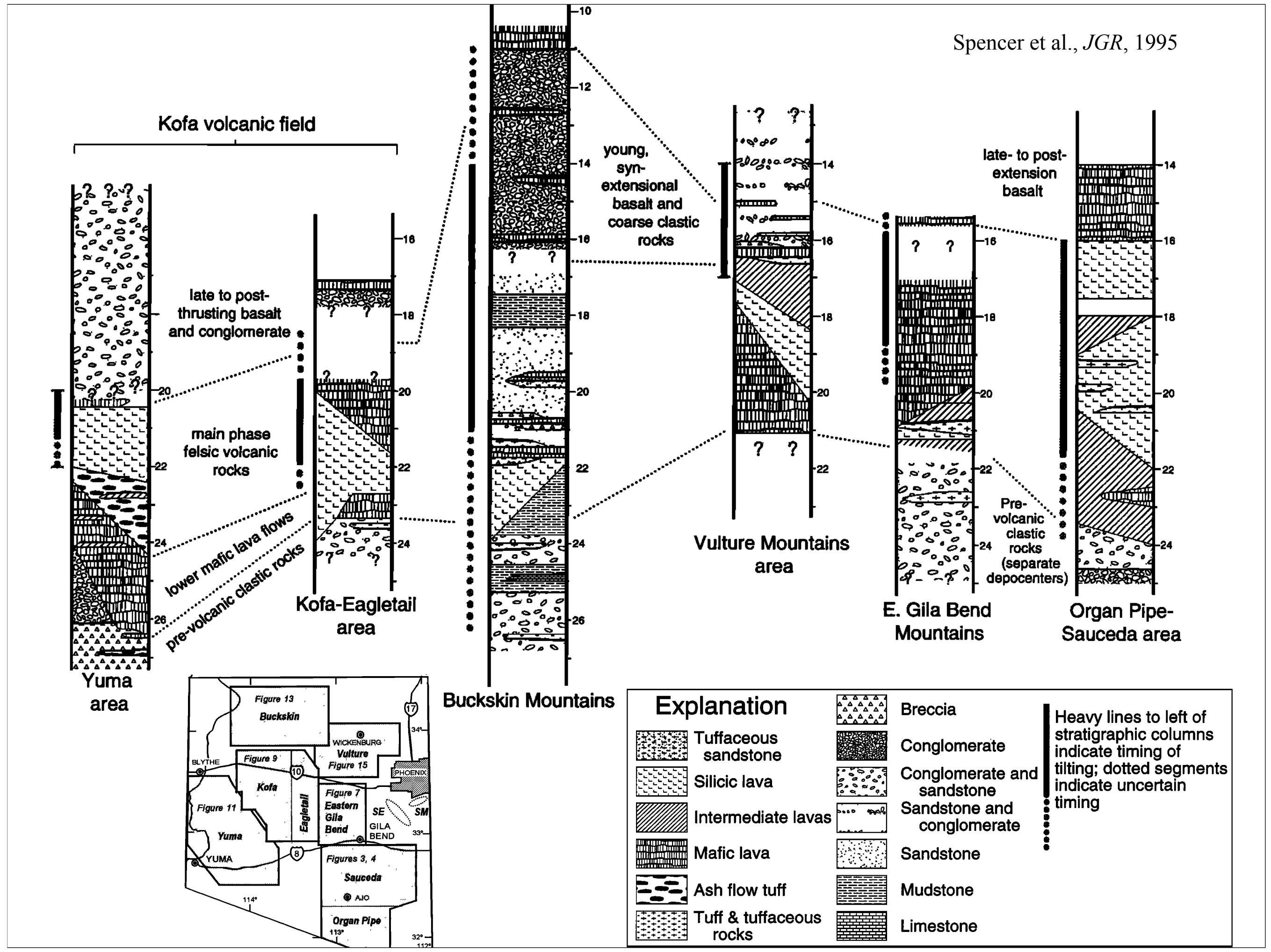
Initiation of volcanism has shifted extension into diking--so volcanism could represent extension.



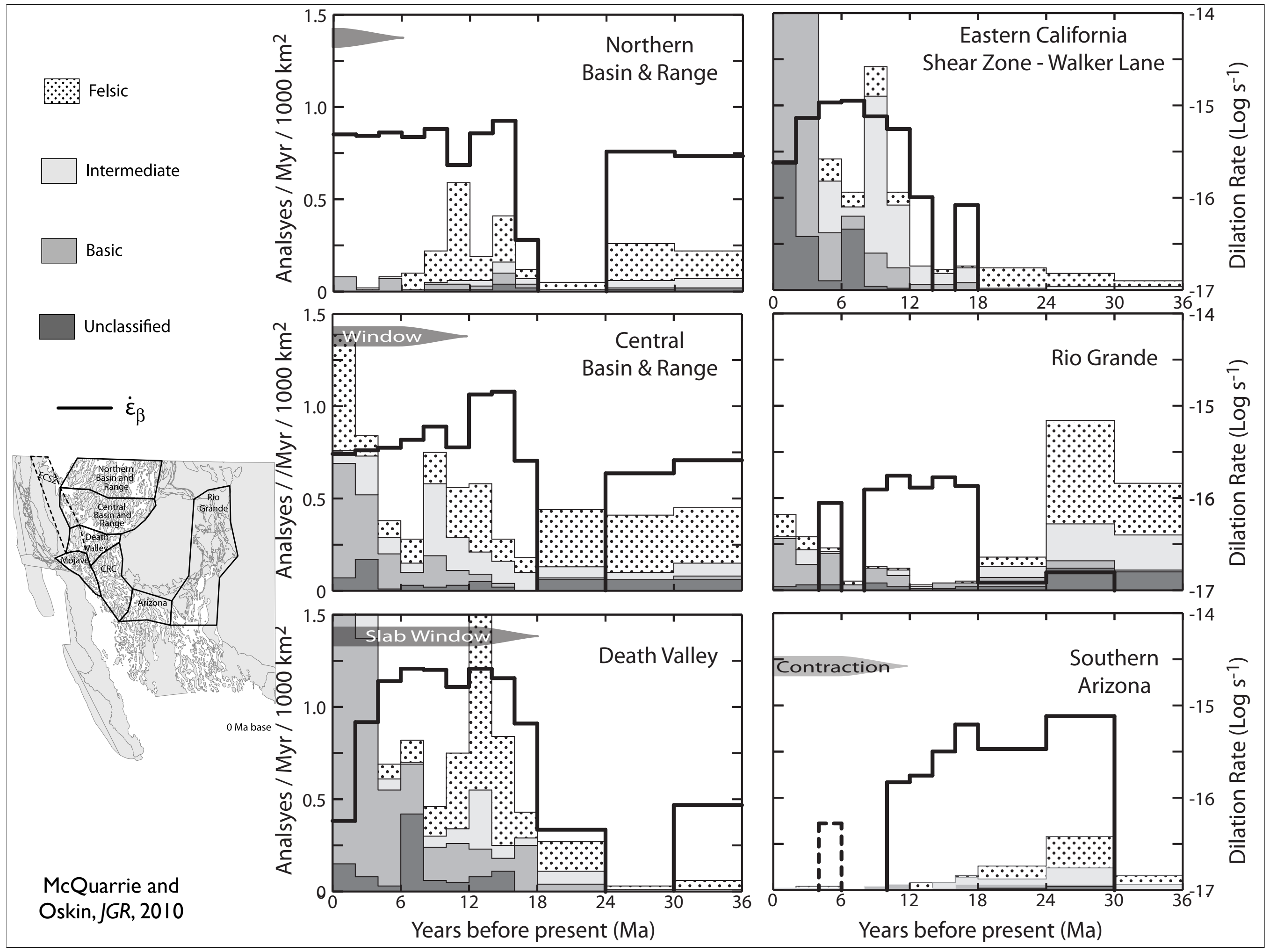
Raft River-Albion Core Complex

Konstantinou et al., *Geosphere*, 2013

Or, maybe, we have grossly overestimated extension in Paleogene.



Arizona relation of tilting to volcanism. Note too some thick clastic sequences preceding volcanism.



Recall these are not volumes….