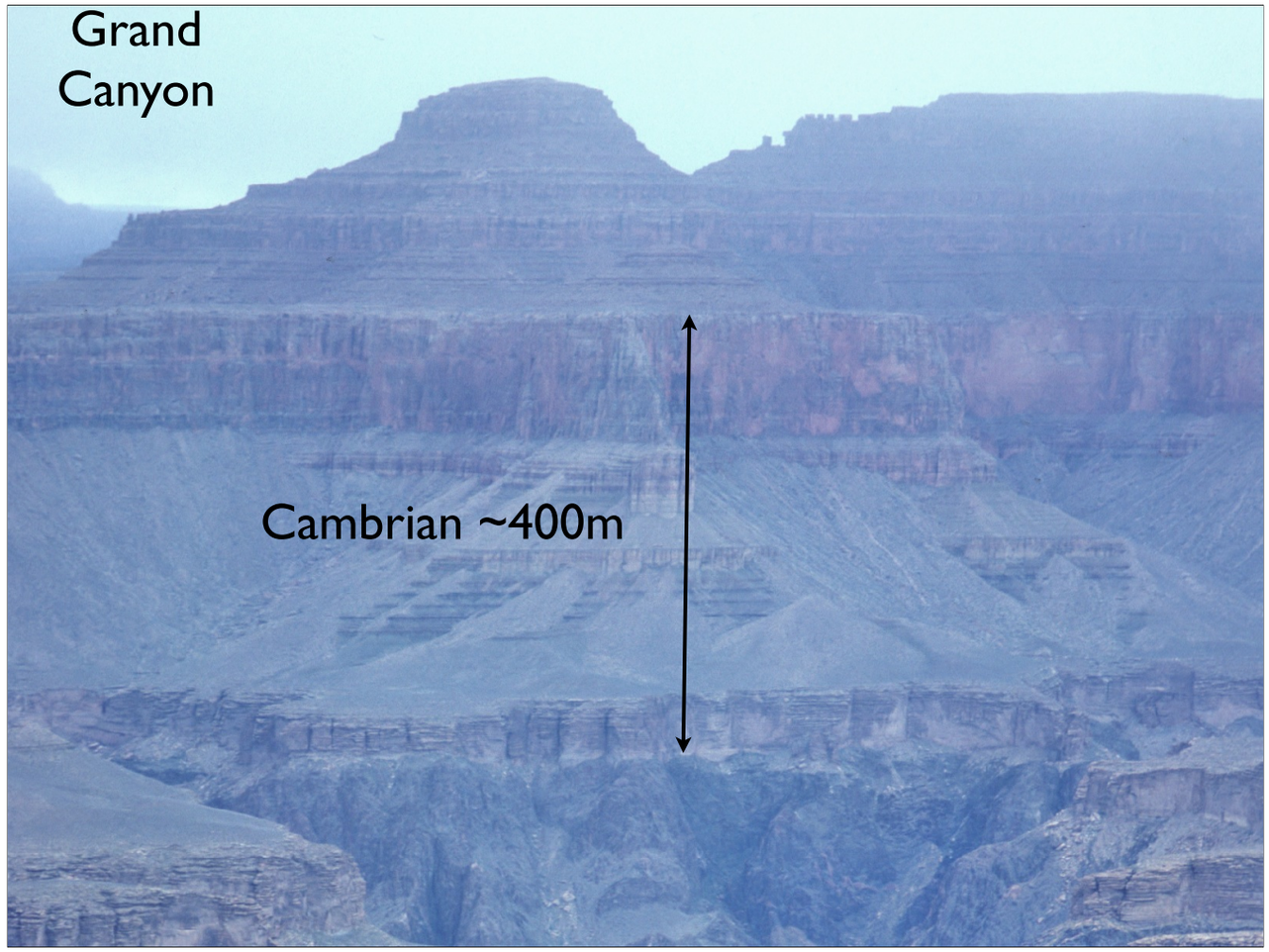
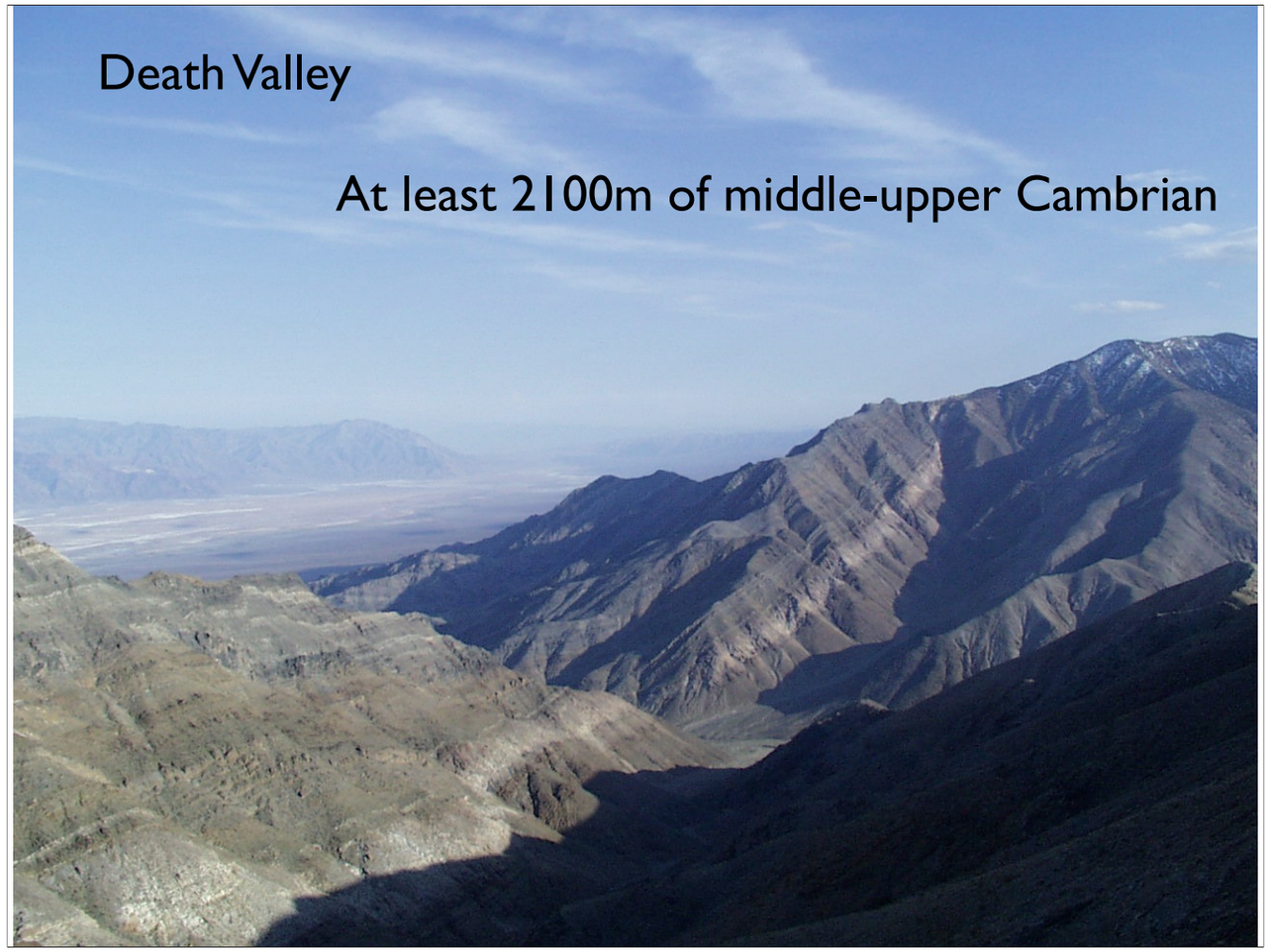
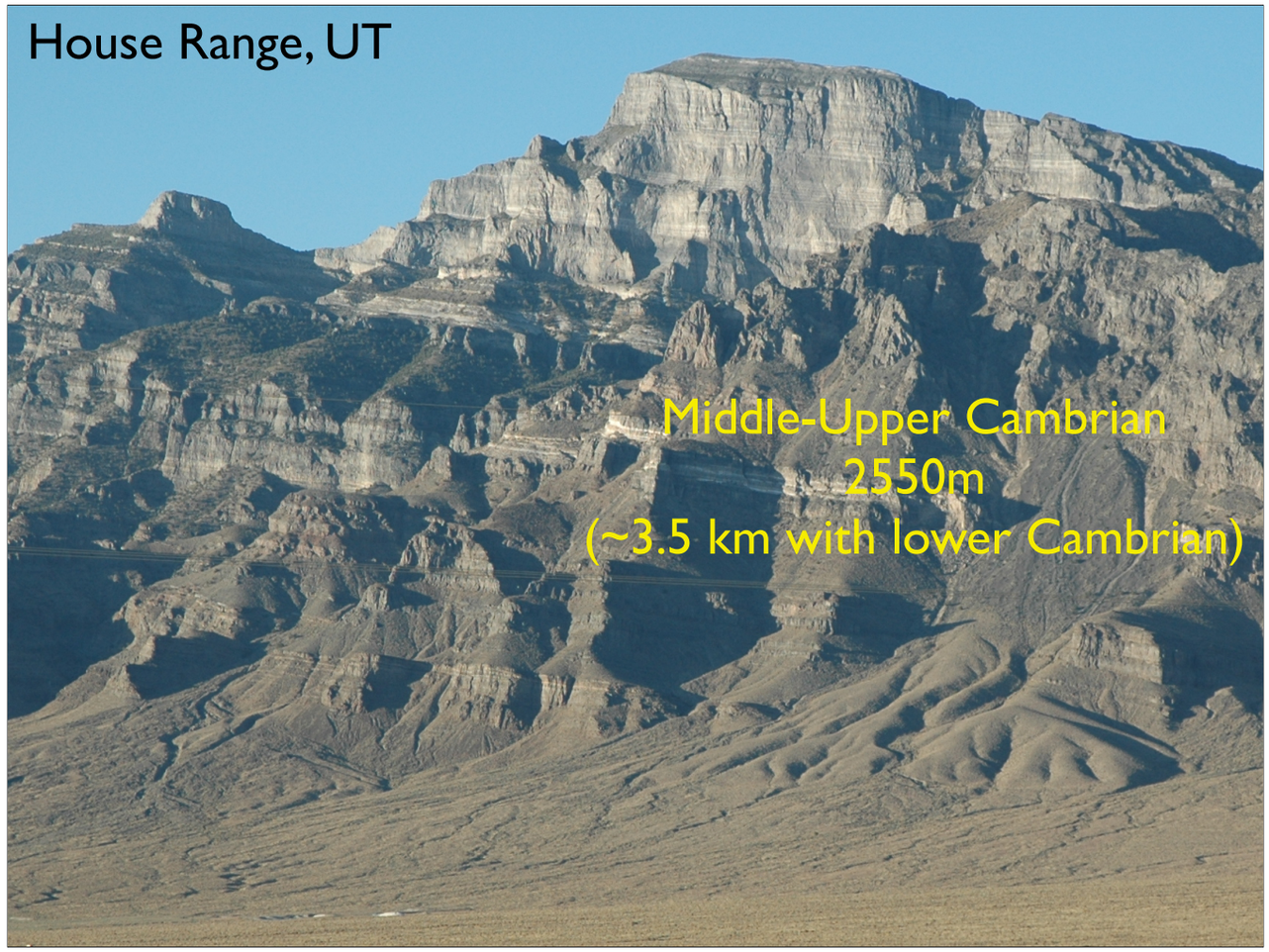
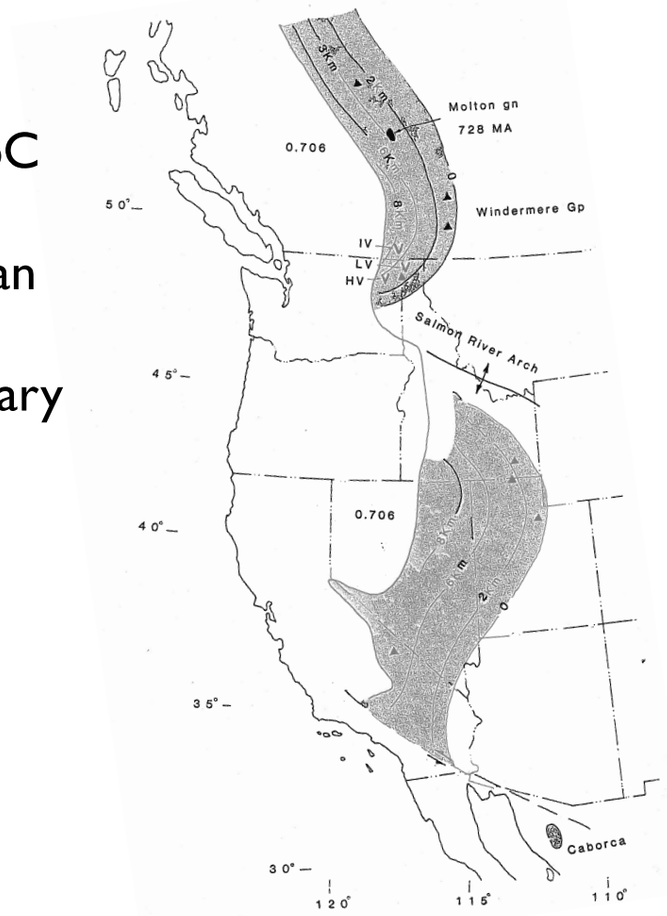

Grand
Canyon
Cambrian ~400m


Death Valley
At least 2100m of middle-upper Cambrian

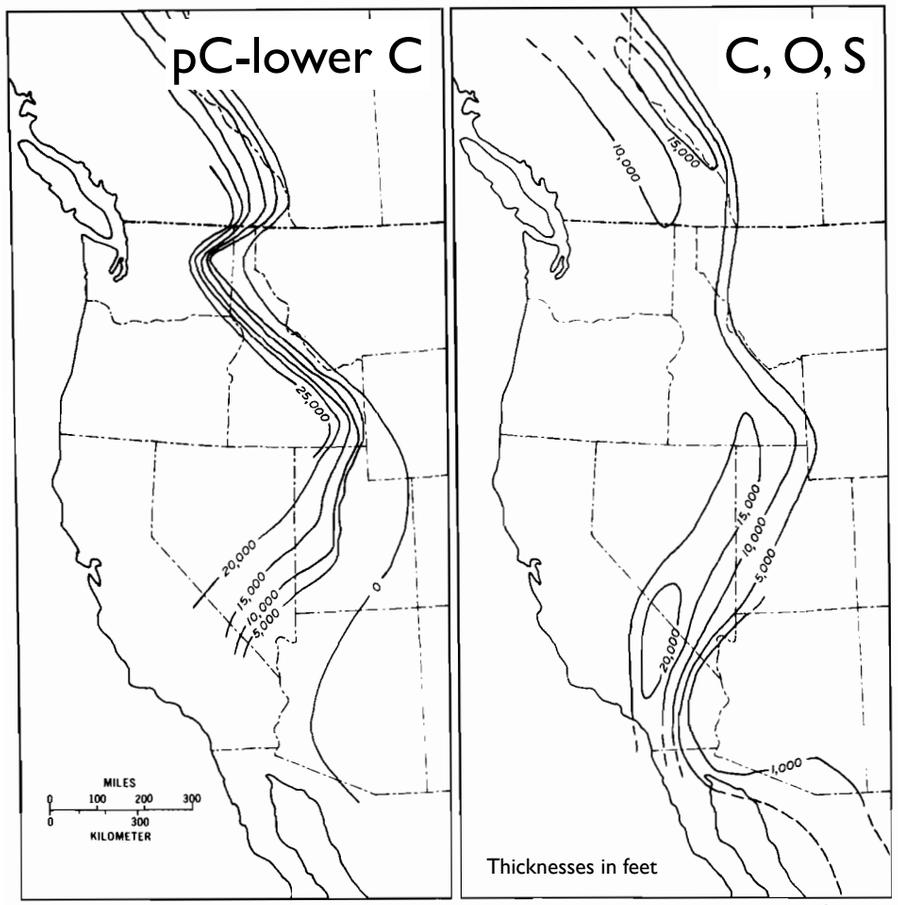

House Range, UT
Middle-Upper Cambrian
2550m
(~3.5 km with lower Cambrian)

this is what my slides notes said but I need to check and see what this really was

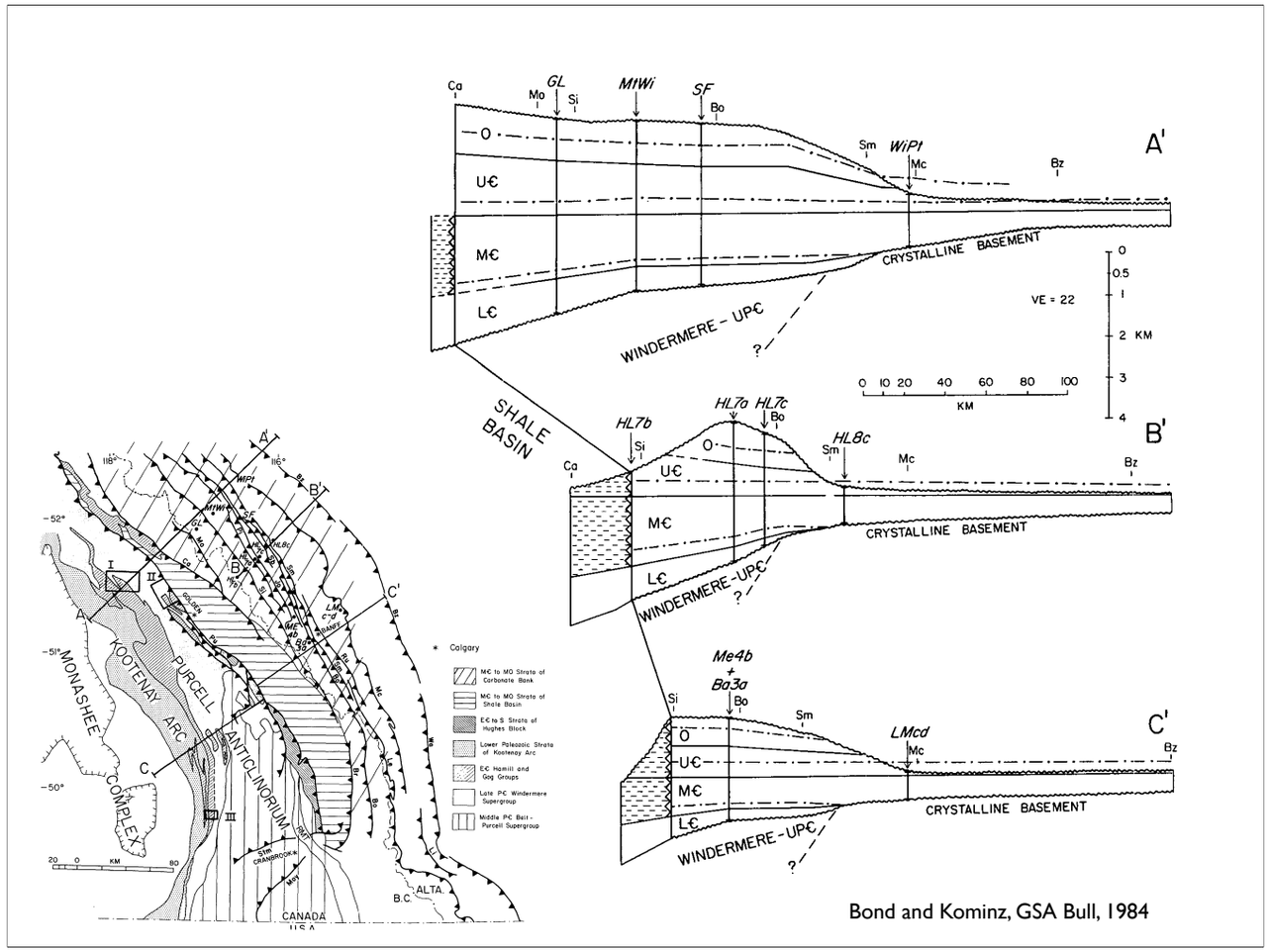
Upper pC lower Cambrian silicic sedimentary rocks



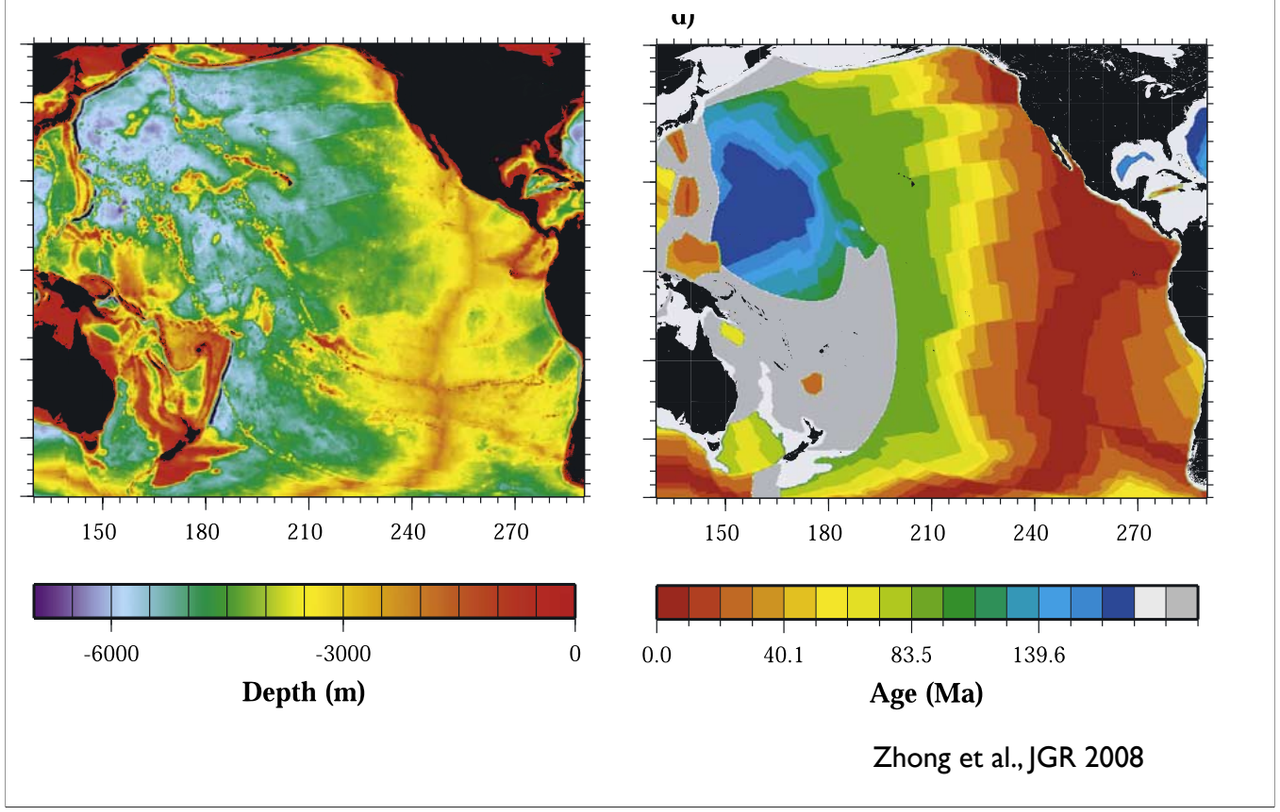
Burchfiel et al., DNAG



Stewart, GSA Bull, 1972



Bond and Kominz, GSA Bull, 1984



Zhong et al., JGR 2008

Heat in the Earth

Heat moves from hot to cold. The rate at which moves—the **heat flow**—is proportional to the gradient in temperature and a constant, the thermal conductivity (k, about 2-3 W m^{-1} °C^{-1} for crustal rocks). With z positive down and temperature only varying with depth, we get

$$q = -k\frac{dT}{dz}$$

Heat in the Earth

$$q = -k\frac{dT}{dz}$$

A change in temperature requires either that heat be created in the rock or that the heat flow in differs from the heat flow out.
The total heat in a body is ρCT where
ρ is density
C is heat capacity (J kg^{-1} °C^{-1})
T is temperature (K)
If radioactive heat production is A (J m^{-3}) then

$$\frac{dq}{dz} = A - \frac{d}{dt}\left(\rho CT\right)$$

Heat in the Earth

$$q = -k\frac{dT}{dz}$$

$$\frac{dq}{dz} = A - \frac{d}{dt}\left(\rho C T\right)$$

We can combine these two equations, removing q, to get:

$$k\frac{d^2T}{dz^2} = \rho C\frac{dT}{dt}$$

$$\frac{dT}{dt} = \kappa\frac{d^2T}{dz^2}$$

Where κ is thermal diffusivity ($m^2\ s^{-1}$). An approximate value for some rocks, easy to remember, is 1 mm^2/s

Heat in the Earth

$$k\frac{d^2T}{dz^2} = \rho C\frac{dT}{dt}$$

$$\frac{dT}{dt} = \kappa\frac{d^2T}{dz^2}$$

A key to solving this for the earth is to recognize that $\sqrt{\kappa t}$ is dimensionally a length and so provides a natural length scale.

We are initially interested in a simple problem: the cooling of a half space of asthenosphere. We assume that the temperature is T_a in the asthenosphere and T_0 at the top. We then solve for $T(t,z)$…

Heat in the Earth

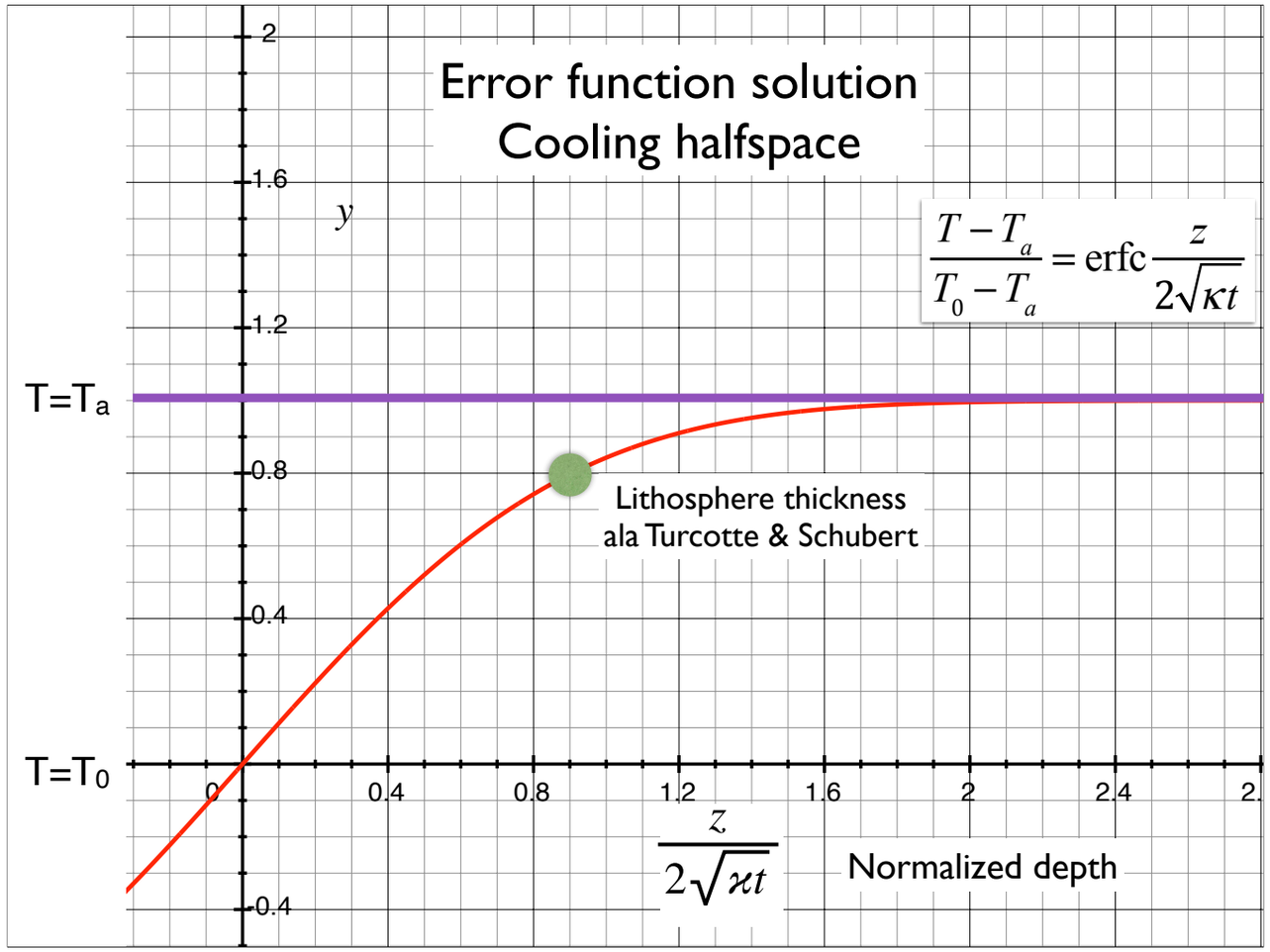
A key to solving this for the earth is to recognize that $\sqrt{\kappa t}$ is dimensionally a length and so provides a natural length scale.

We are initially interested in a simple problem: the cooling of a half space of asthenosphere. We assume that the temperature is T_a in the asthenosphere and T_0 at the top. We then solve for $T(t,z)$…

$$\frac{T - T_a}{T_0 - T_a} = \mathrm{erfc}\,\frac{z}{2\sqrt{\kappa t}}$$

The erfc is the complementary of the error function which, if you care, is defined as

$$\mathrm{erfc}(\eta) = 1 - \frac{2}{\sqrt{\pi}} \int_0^{\eta} e^{-\eta'^2}\, d\eta'$$



So from this when depth is 4 times sqrt(kappa*t), you are pretty unaffected from surface cooling.
Lithospheric thickness then doubles when time quadruples (so thickness proportional to sqrt (t))

Curve is vs depth for a specified time (can flip it over to see temperature change over time at a specified depth)

Topography from cooling in the Earth

$$\frac{T - T_a}{T_0 - T_a} = \operatorname{erfc} \frac{z}{2\sqrt{\kappa t}}$$

While temperature can be interesting, we want topography. We have to appeal to isostasy and relate temperature to density.

First up, isostasy, which says that the pressure (P_c) at some depth of compensation (z_c) is the same everywhere. For terrain under the oceans, this can be expanded

$$P_c = \int_0^{z_c} \rho g \, dz = dg\rho_w + \int_d^{z_c} \rho g \, dz$$

Where d is the depth of the ocean at this point

Topography from cooling in the Earth

$$\frac{T - T_a}{T_0 - T_a} = \operatorname{erfc} \frac{z}{2\sqrt{\kappa t}}$$

$$P_c = \int_0^{z_c} \rho g \, dz = dg\rho_w + \int_d^{z_c} \rho g \, dz$$

We set the pressure under a mid-ocean ridge (ignoring the crust) against that of some older piece of seafloor:

$$\cancel{d_{ridge} g \rho_w} + \int_d^{z_c} \rho \cancel{g} \, dz = \left(\cancel{d_{ridge}} + w\right) \cancel{g} \rho_w + \int_{d_{ridge}+w}^{z_c} \rho \cancel{g} \, dz$$

Topography from cooling in the Earth

$$\frac{T - T_a}{T_0 - T_a} = \operatorname{erfc} \frac{z}{2\sqrt{\kappa t}}$$

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$$\int_{d_{ridge}}^{d_{ridge}+w} \rho_a \, dz + \boxed{\int_{d_{ridge}+w}^{z_c} \rho_a \, dz} = \boxed{w\rho_w} + \int_{d_{ridge}+w}^{z_c} \rho(z) \, dz$$

Topography from cooling in the Earth

$$\frac{T - T_a}{T_0 - T_a} = \operatorname{erfc} \frac{z}{2\sqrt{\kappa t}}$$

$$P_c = \int_0^{z_c} \rho g \, dz = dg\rho_w + \int_d^{z_c} \rho g \, dz$$

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$$\cancel{d_{ridge} g \rho_w} + \int_d^{z_c} \rho g \, dz = \left(\cancel{d_{ridge}} + w\right) g \rho_w + \int_{d_{ridge}+w}^{z_c} \rho g \, dz$$

$$\int_{d_{ridge}}^{d_{ridge}+w} \rho_a \, dz + \boxed{\int_{d_{ridge}+w}^{z_c} \rho_a \, dz} = \boxed{w\rho_w} + \int_{d_{ridge}+w}^{z_c} \rho(z) \, dz$$

$$w(\rho_a - \rho_w) = \int_{d_{ridge}+w}^{z_c} \left(\rho(z) - \rho_a\right) dz$$

Now we need to relate density to temperature…

Topography from cooling in the Earth

$$\frac{T - T_a}{T_0 - T_a} = \operatorname{erfc}\frac{z}{2\sqrt{\kappa t}}$$

$$w\left(\rho_a - \rho_w\right) = \int_{d_{ridge}+w}^{z_c}\left(\rho\left(z\right) - \rho_a\right)dz$$

Now we need to relate density to temperature…

$$\rho\left(z\right) - \rho_a = -\rho_a\alpha\left(T\left(z\right) - T_a\right)$$

Where α is the coefficient of thermal expansion. Now we combine these and integrate from seafloor down to get…

$$w\left(\rho_a - \rho_w\right) = \int_0^{z_c'} -\rho_a\alpha\left(T_0 - T_a\right)\operatorname{erfc}\frac{z'}{2\sqrt{\kappa t}}dz'$$

$$= \rho_a\alpha\left(T_a - T_0\right)\int_0^{\infty}\operatorname{erfc}\frac{z'}{2\sqrt{\kappa t}}dz'$$

Topography from cooling in the Earth

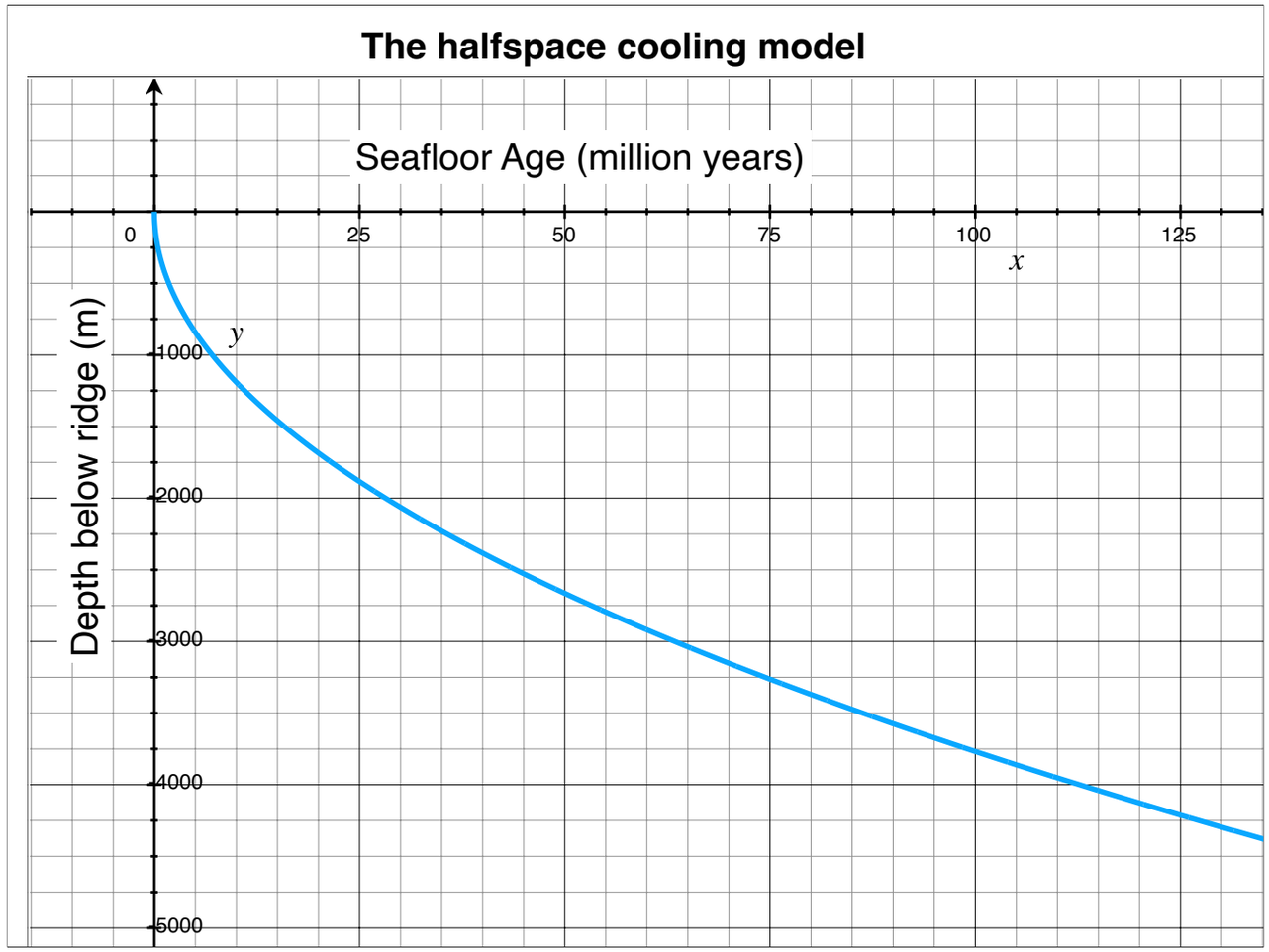
$$w\left(\rho_a - \rho_w\right) = \int_0^{z_c'} -\rho_a \alpha \left(T_0 - T_a\right) \operatorname{erfc} \frac{z'}{2\sqrt{\kappa t}} dz'$$

$$= \rho_a \alpha \left(T_a - T_0\right) \int_0^{\infty} \operatorname{erfc} \frac{z'}{2\sqrt{\kappa t}} dz'$$

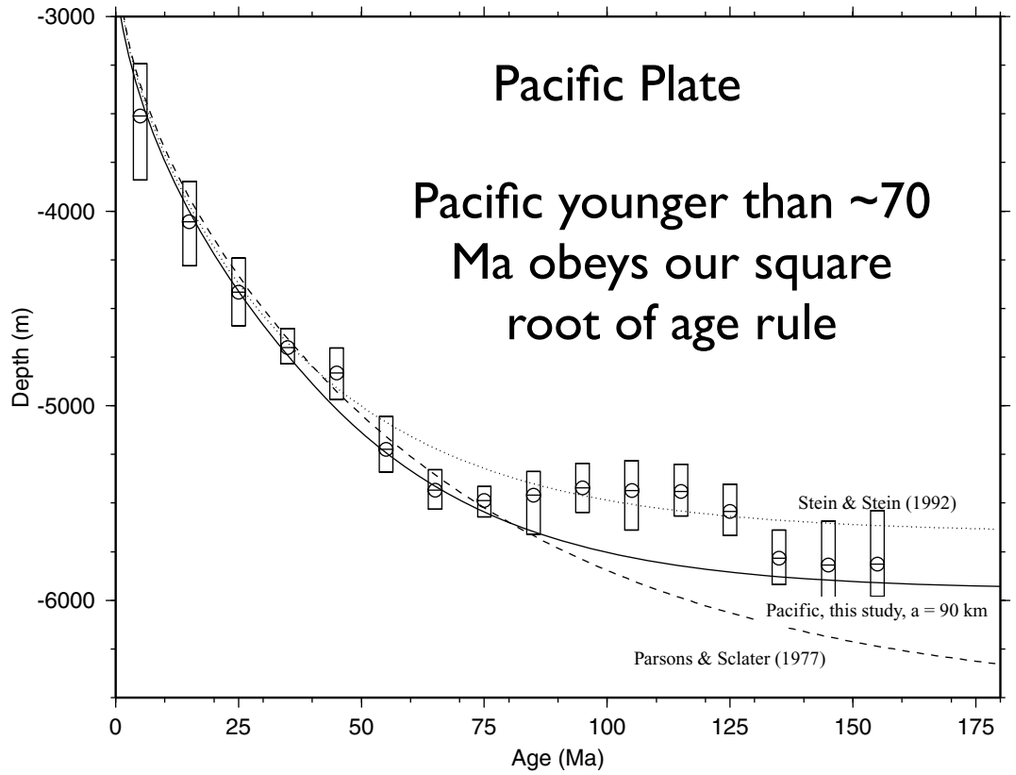
Notice we integrated all the way to infinity because temperatures converged. We can then use a solution to the integral of the erfc to get:

$$w = \frac{2\rho_a \alpha \left(T_a - T_0\right)}{\rho_a - \rho_w} \sqrt{\frac{\kappa t}{\pi}}$$

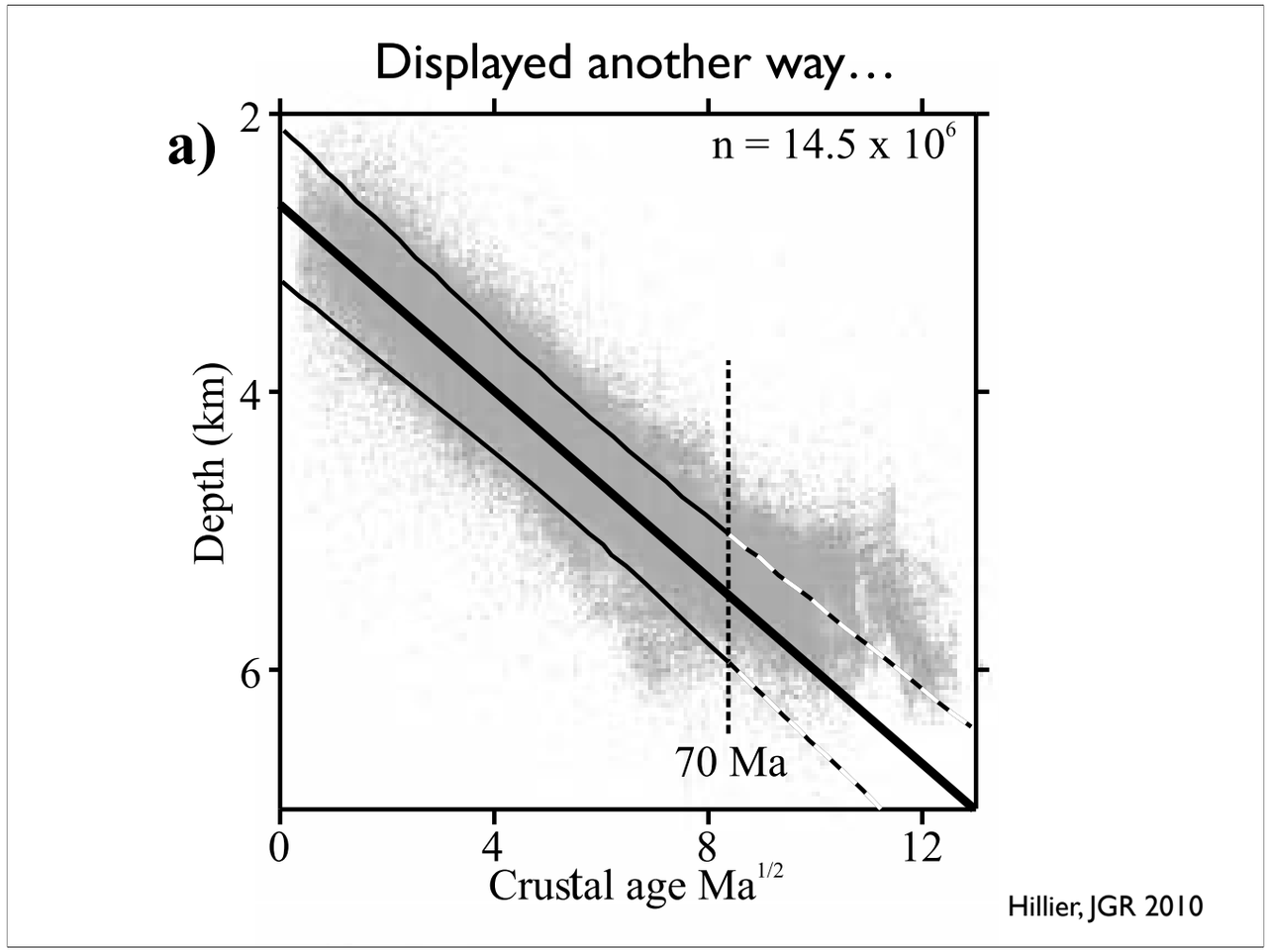
The important thing is that subsidence is a function of the square root of age (so long as the assumption of a cooling half space is valid)



This is using some crude numbers (kappa 3.1 x 10^7 m^2/My, alpha3x10^-5 K^-1, rho-a 3300 Ta 1300C, T0 0C

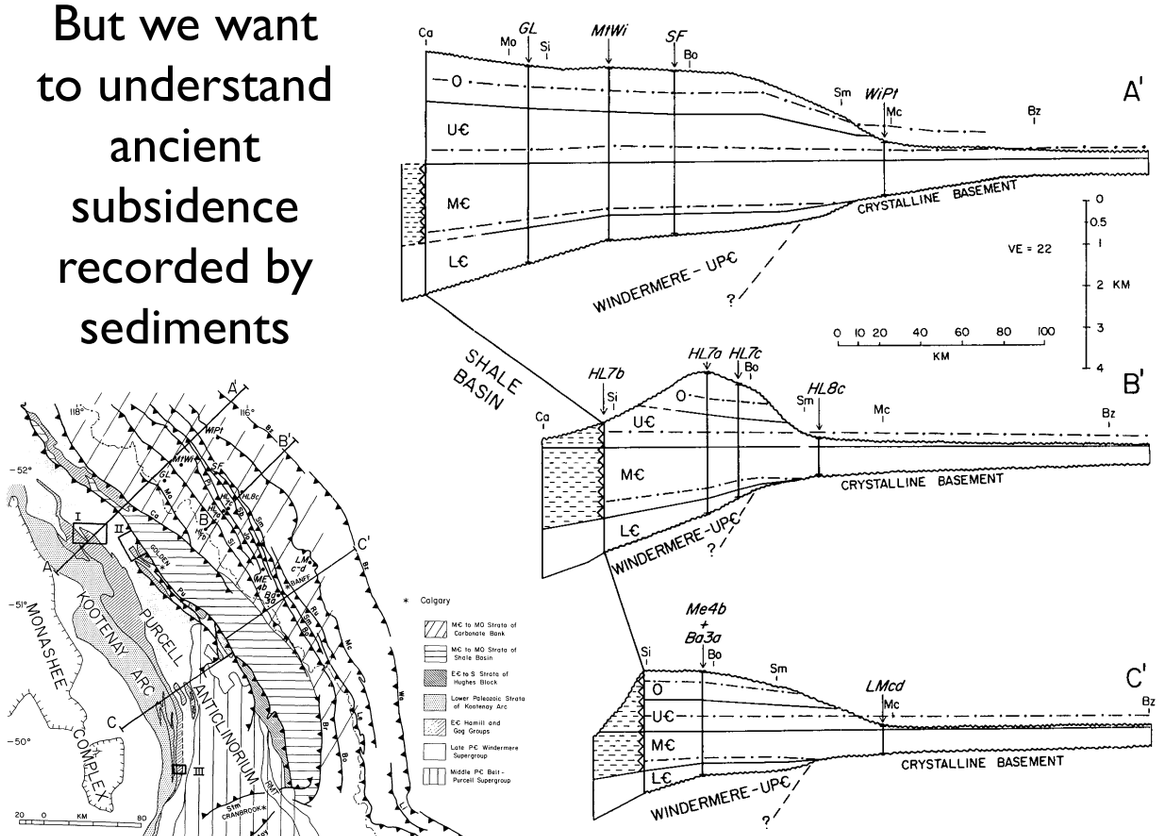


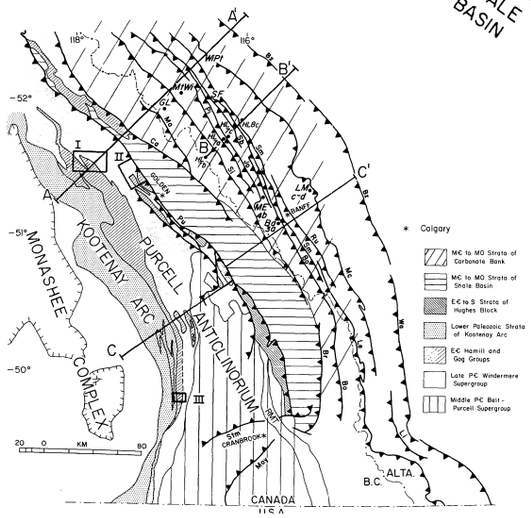
Crosby et al., JGI 2006



Challenging 2008 paper claiming half space works for everything. Raw data points…

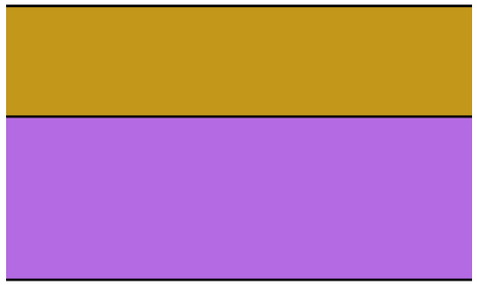
But we want to understand ancient subsidence recorded by sediments





Bond and Kominz, GSA Bull, 1984

Assume we start with lithosphere and stretch it…



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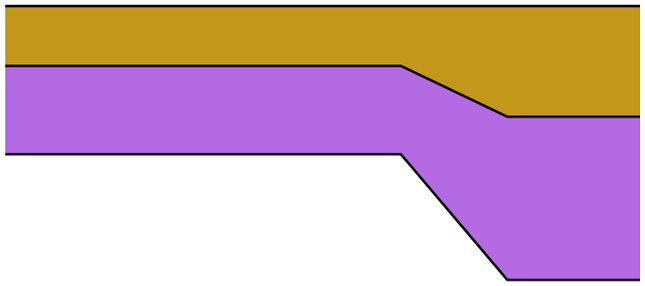
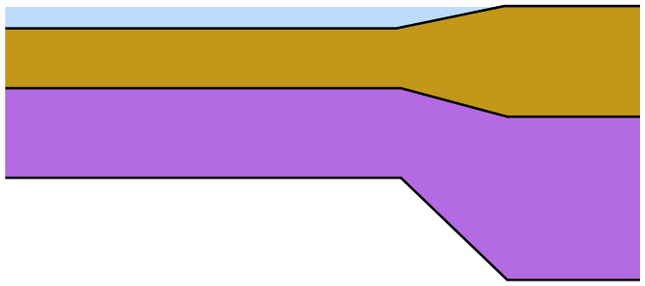


As drawn, this is out of isostatic equilibrium, so the thinned lithosphere must subside (for us, below sea level)

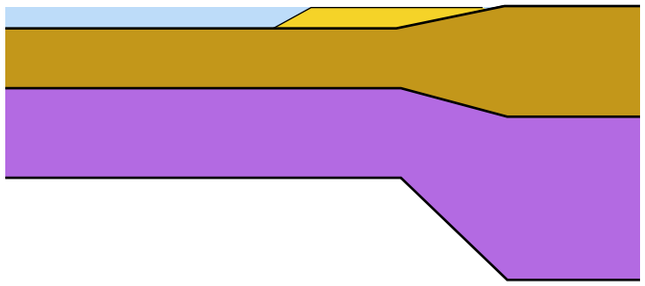
Assume we start with lithosphere and stretch it…



As the lithosphere cools, the top of the crust will get deeper over time. How can we measure this?

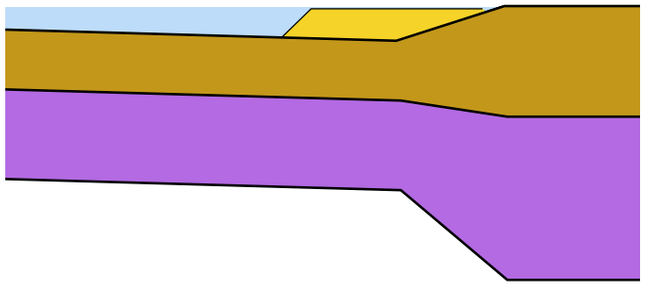
Well, we fill the edge of the ocean with sediment…

Assume we start with lithosphere and stretch it…



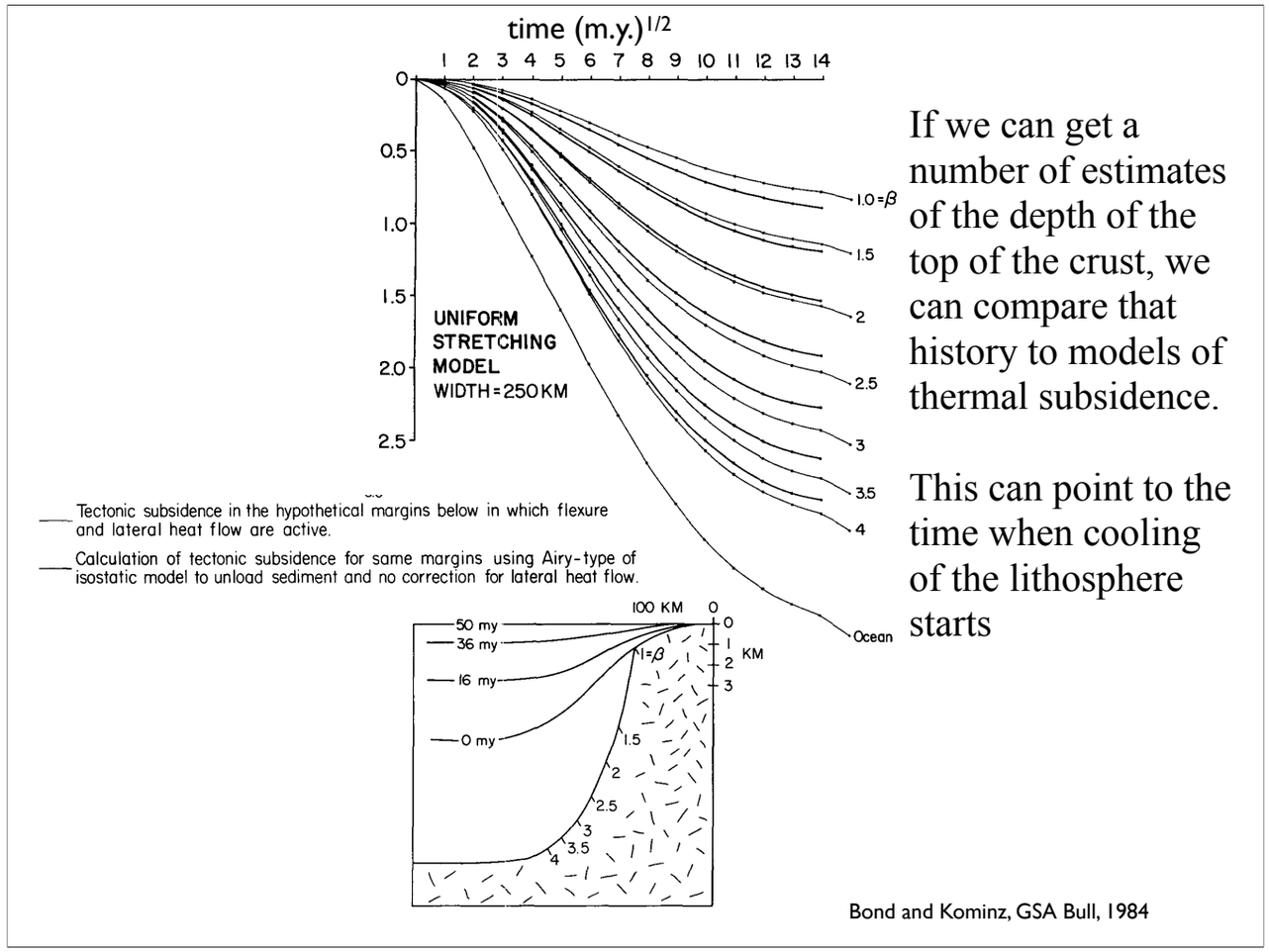
If we know the water depth of the sediments at the top, we know the depth of the top of the crust…
But we are back out of isostatic equilibrium, so the margin sinks

Assume we start with lithosphere and stretch it…



So although the thickening sediment keeps up, it is now thicker than the purely thermal/tectonic subsidence we want.

So we want to estimate the load from these sediments, remove it and allow the lithosphere to rise back up and then we'll know how much the basin floor subsided…
The process of doing this is termed backstripping.



If we can get a number of estimates of the depth of the top of the crust, we can compare that history to models of thermal subsidence.

This can point to the time when cooling of the lithosphere starts

"Uniform" refers to crust and mantle lithosphere strained the same. It is a 2-D sections beta=1 does go down because of adjacent areas. Point in paper was that form of the curve is not sensitive to the 2-D aspect.

Construction of Tectonic Subsidence Curves

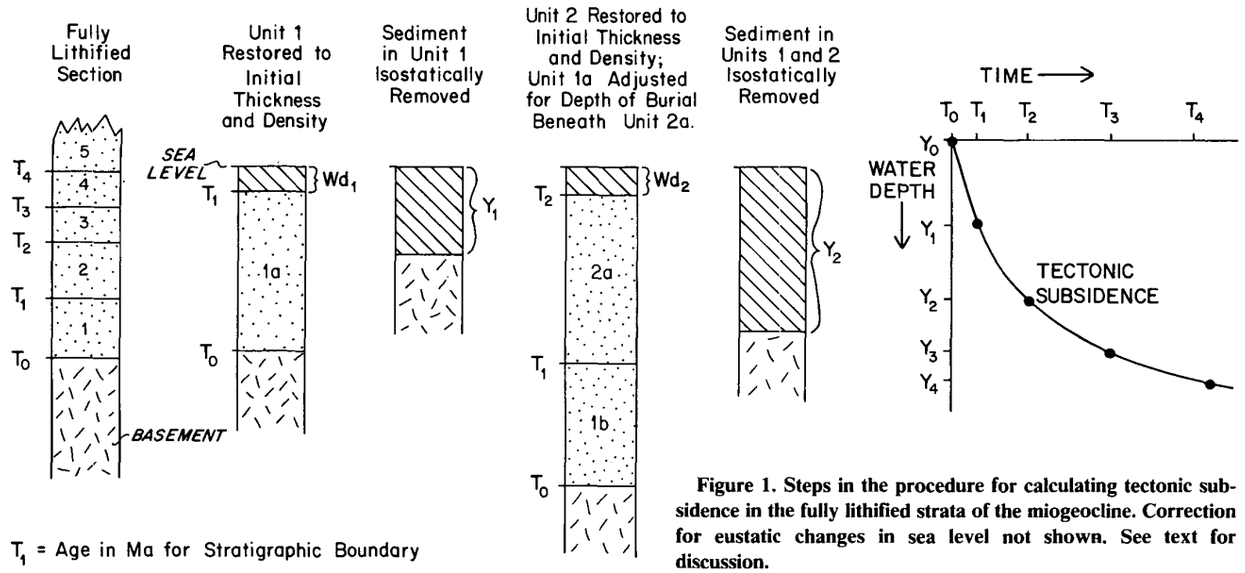
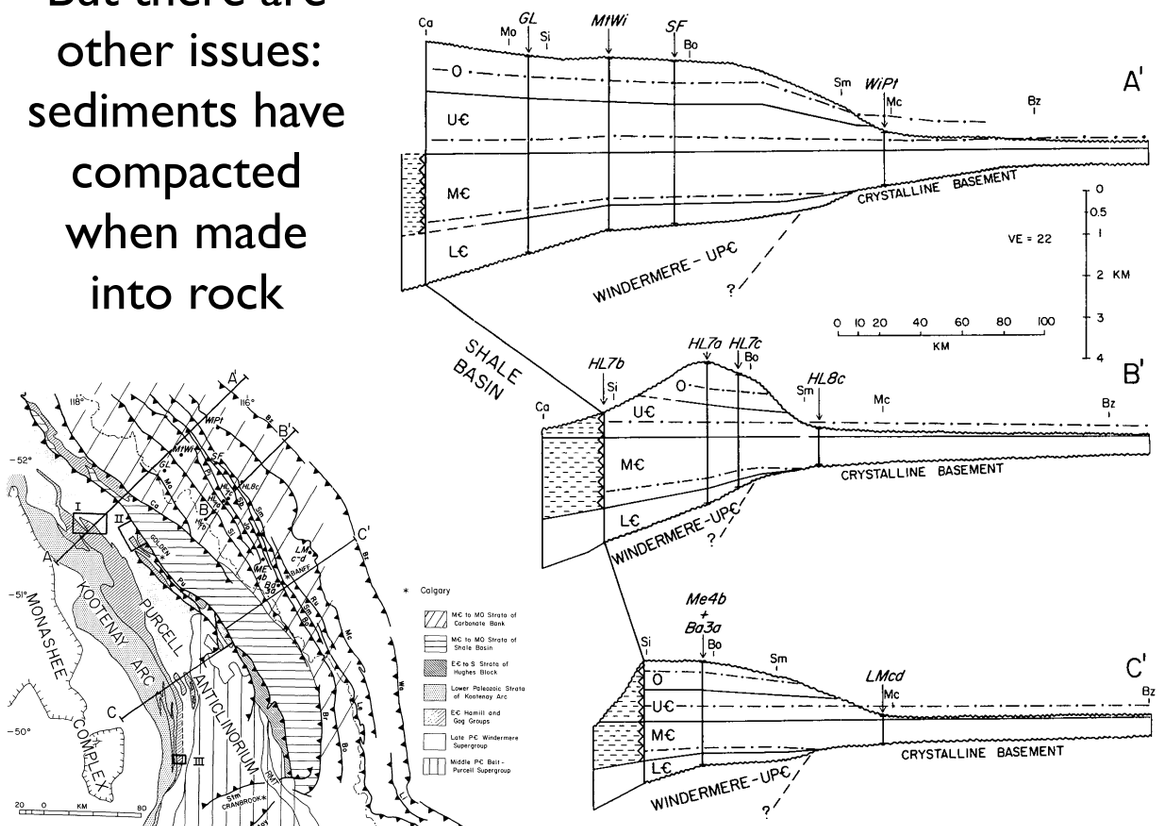
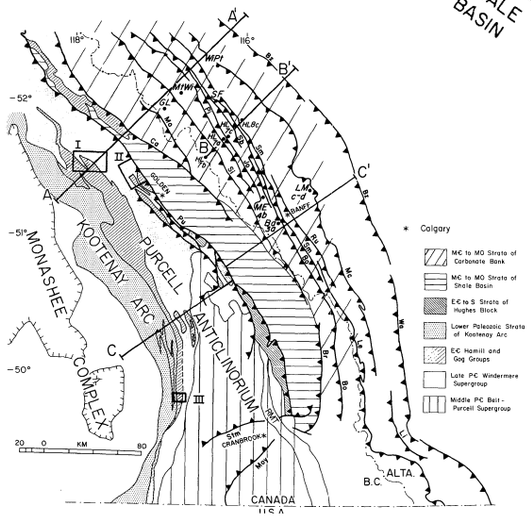


Figure 1. Steps in the procedure for calculating tectonic subsidence in the fully lithified strata of the miogeocline. Correction for eustatic changes in sea level not shown. See text for discussion.

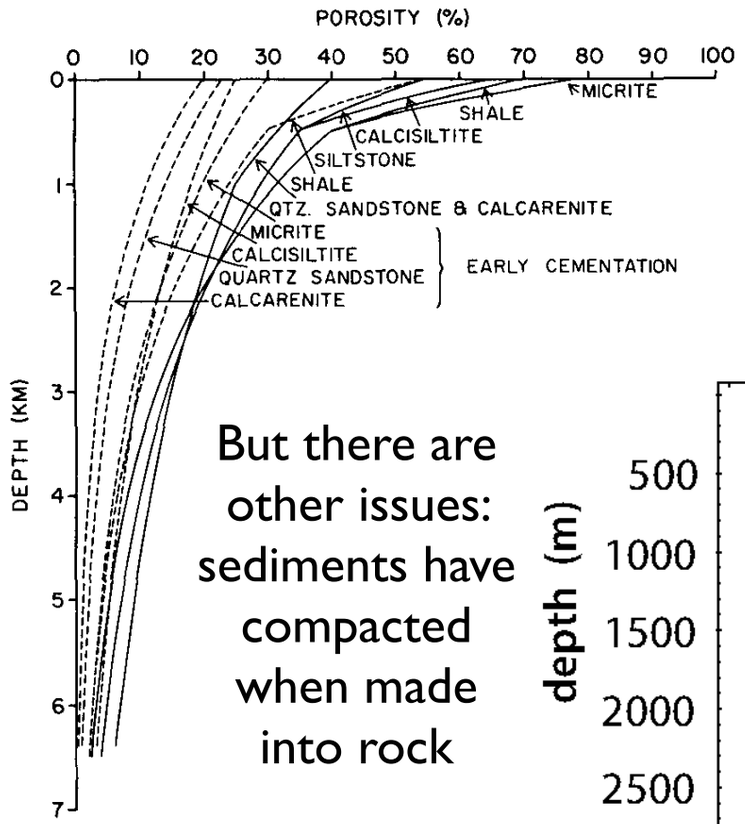
Bond and Kominz, GSA Bull, 1984

But there are other issues: sediments have compacted when made into rock





Bond and Kominz, GSA Bull, 1984



Bond and Kominz, GSA Bull, 1984

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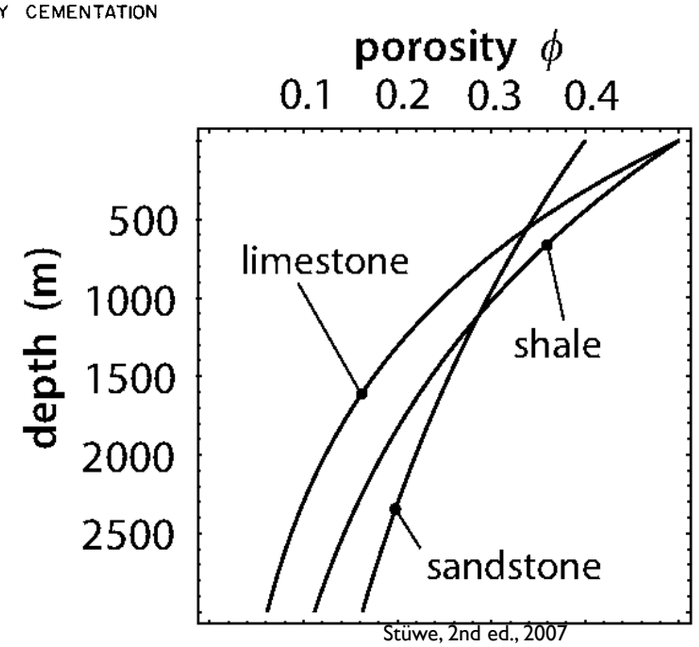


Stüwe, 2nd ed., 2007

Construction of Tectonic Subsidence Curves

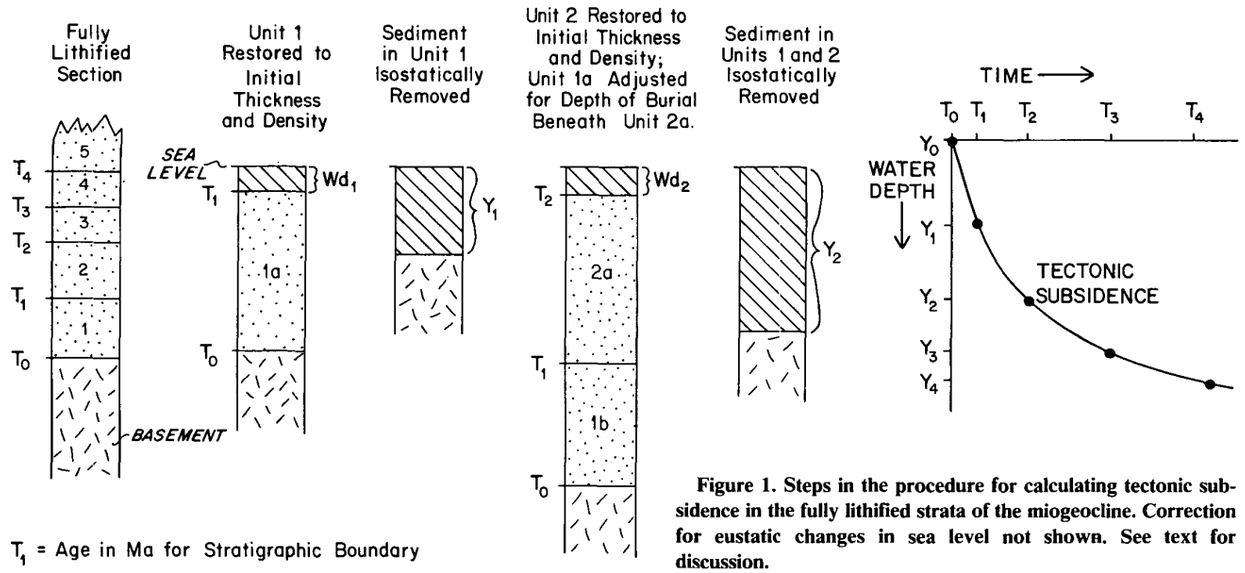
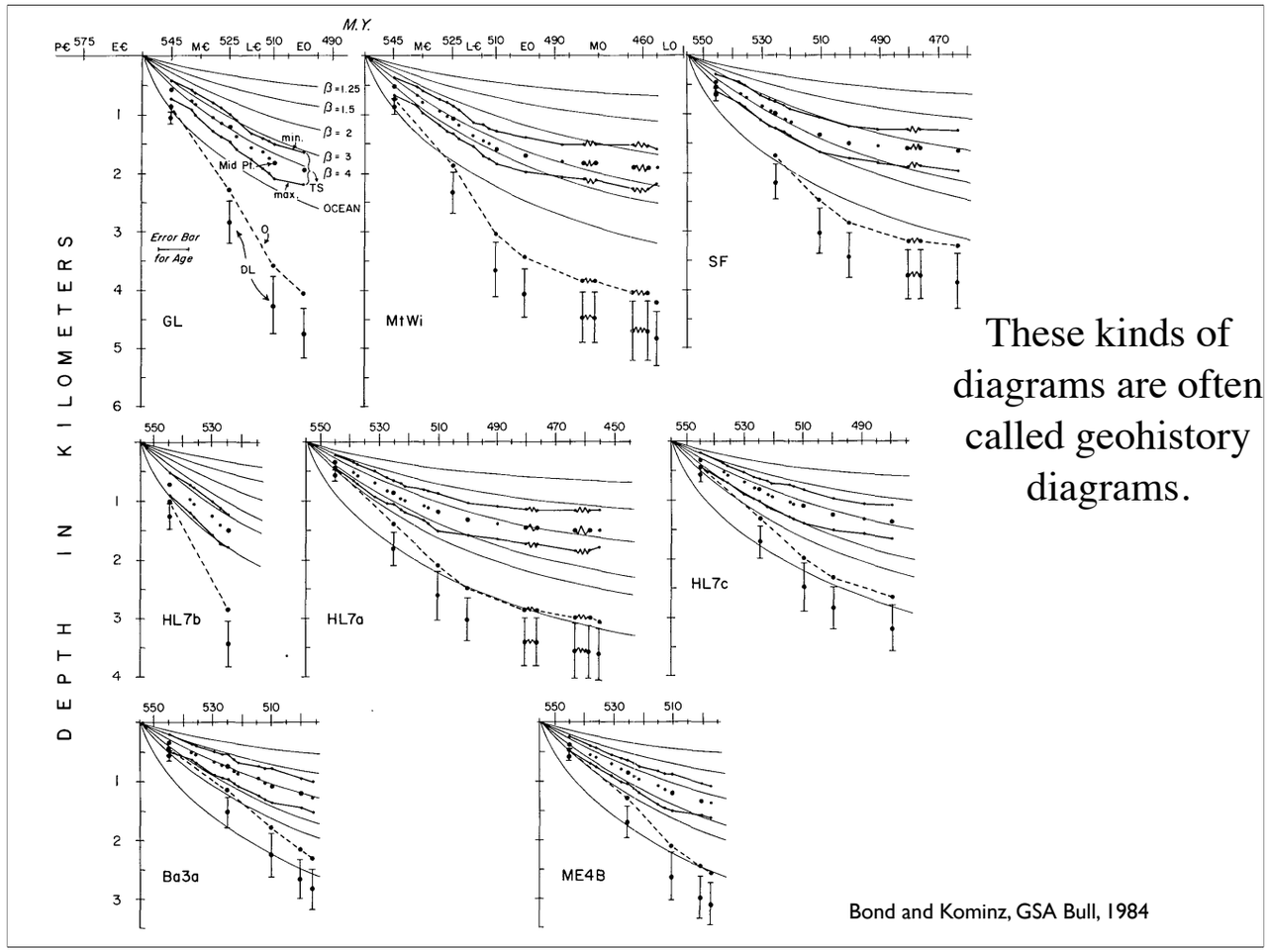


Figure 1. Steps in the procedure for calculating tectonic subsidence in the fully lithified strata of the miogeocline. Correction for eustatic changes in sea level not shown. See text for discussion.

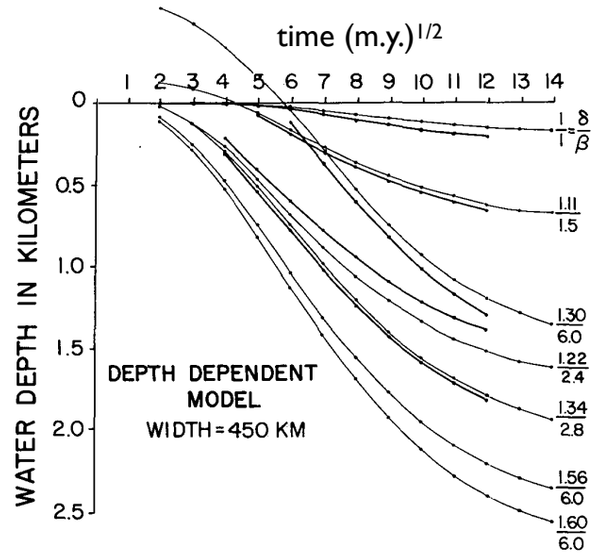
Bond and Kominz, GSA Bull, 1984



These kinds of diagrams are often called geohistory diagrams.

Bond and Kominz, GSA Bull, 1984

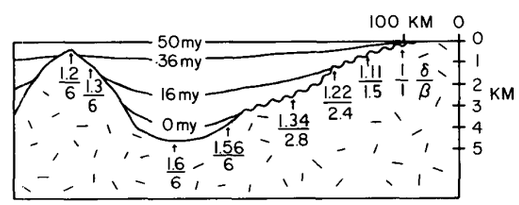
Lower dots with error bars are delithified sedimentary thicknesses (error bars show range of max and min delithified thicknesses); dots between parallel lines are tectonic subsidence



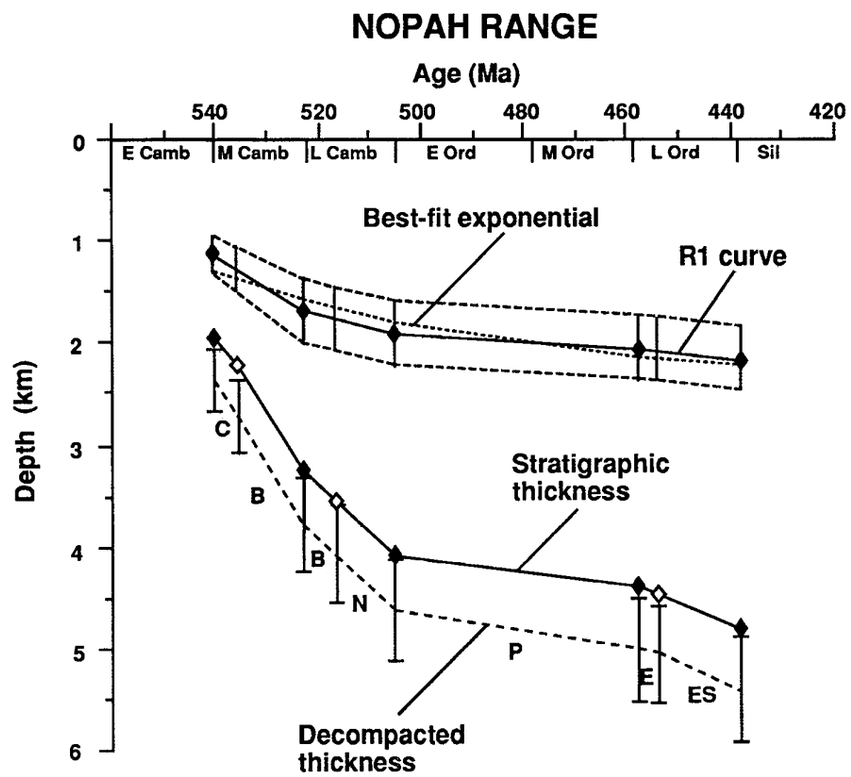
Life is more complex if crust and mantle lithosphere stretch differently—and the finite width of the basin is taken into account

— Tectonic subsidence in the hypothetical margins below in which flexure and lateral heat flow are active.

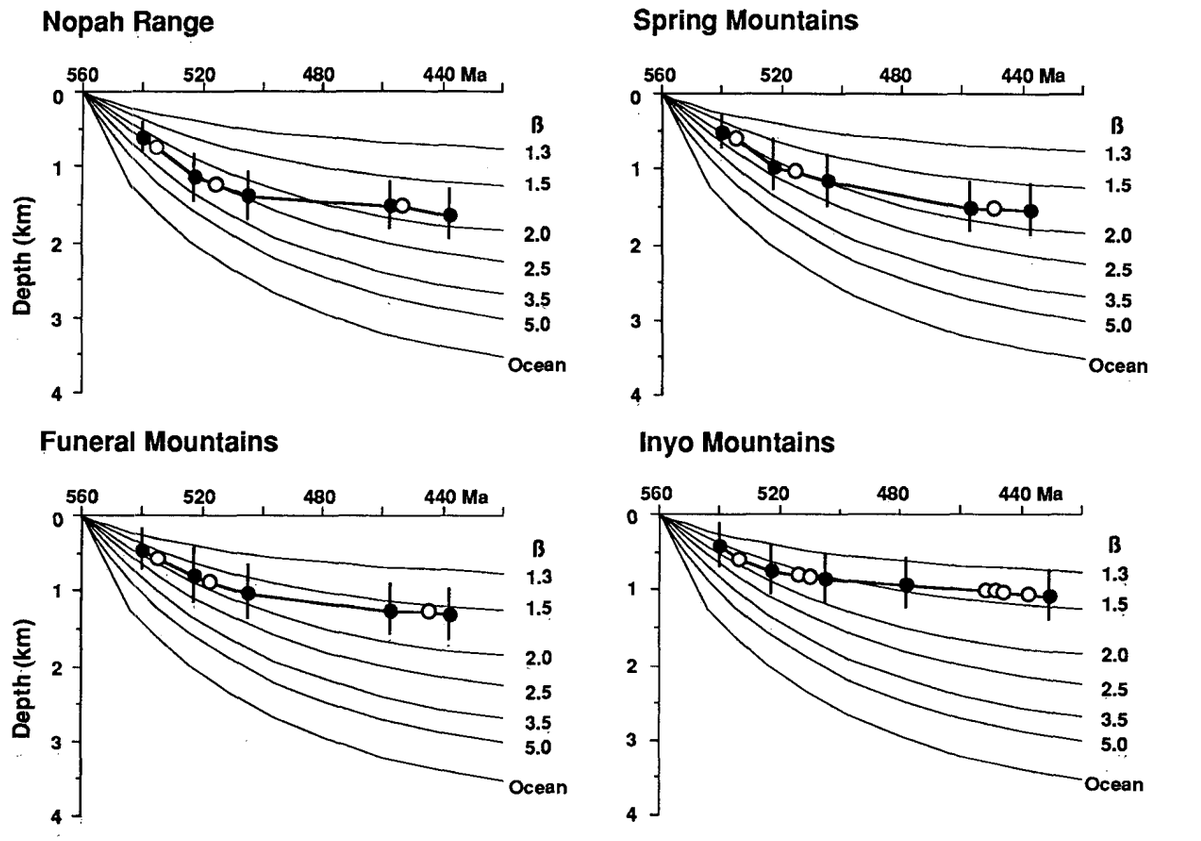
— Calculation of tectonic subsidence for same margins using Airy-type of isostatic model to unload sediment and no correction for lateral heat flow.



Bond and Kominz, GSA Bull, 1984

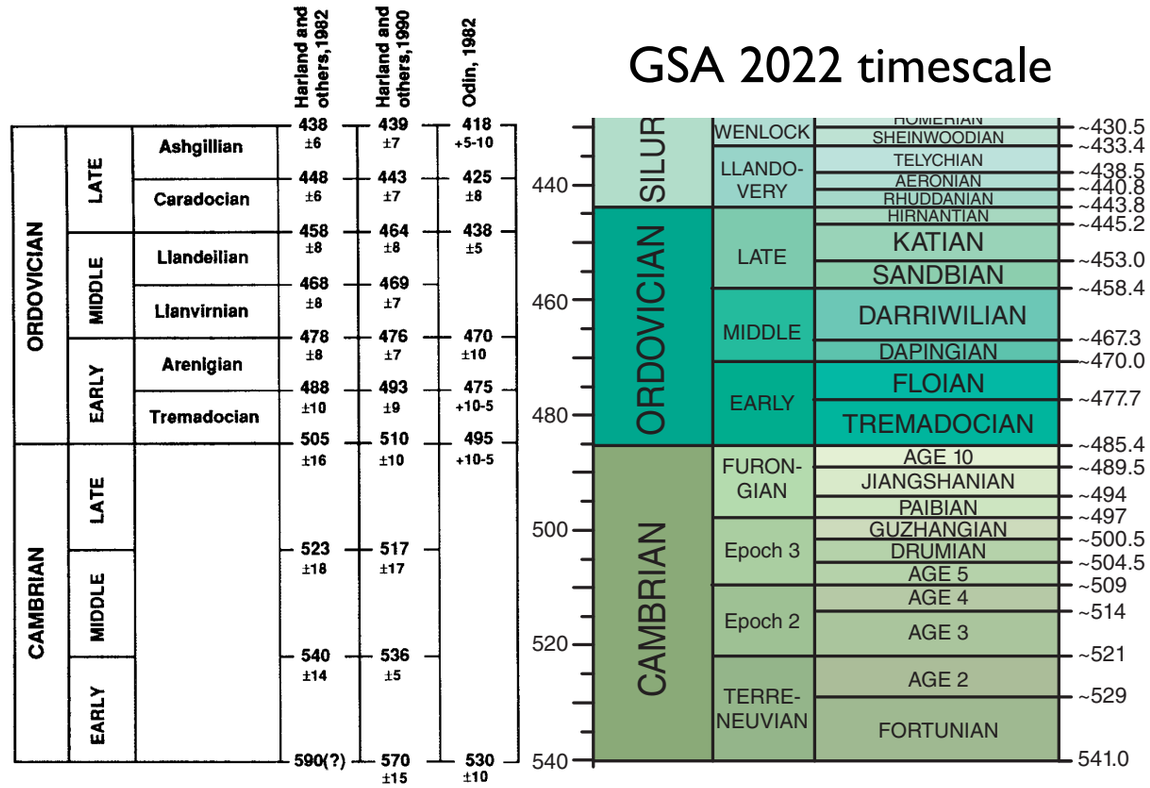


Levy and Christie-Blick, GSA Bull, 1991



Levy and Christie-Blick, GSA Bull, 1991

So best fit about 560 Ma, overall errors considered 590-550 Ma for start of thermal subsidence. The age is largely determined by the change in slope of the “R1” (tectonic subsidence) curve.



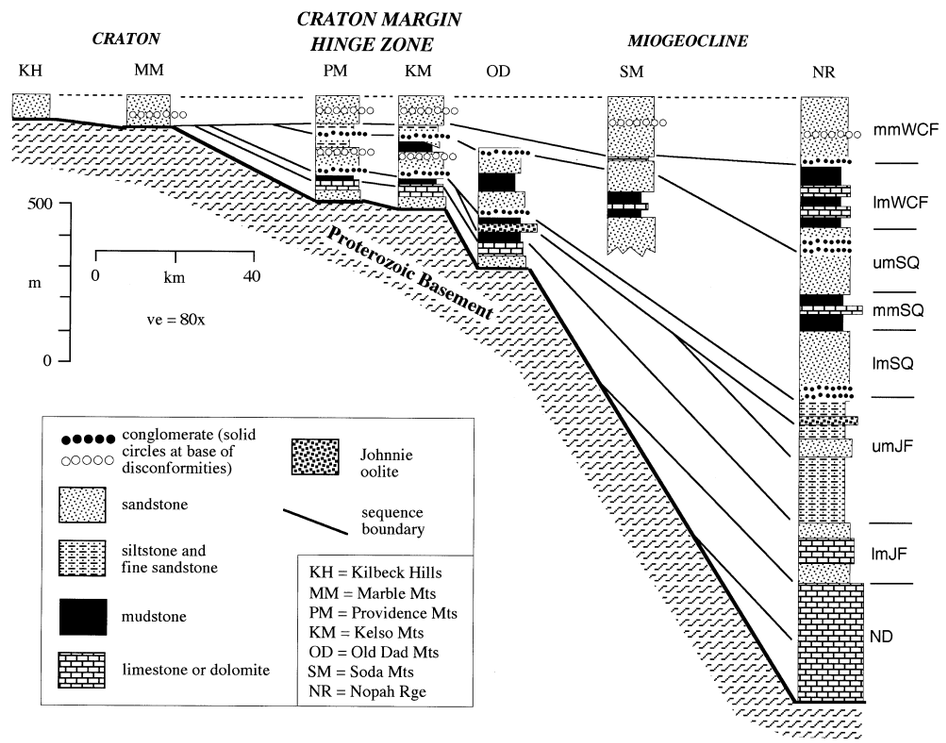
GSA 2022 timescale

Levy and Christie-Blick, GSA Bull, 1991

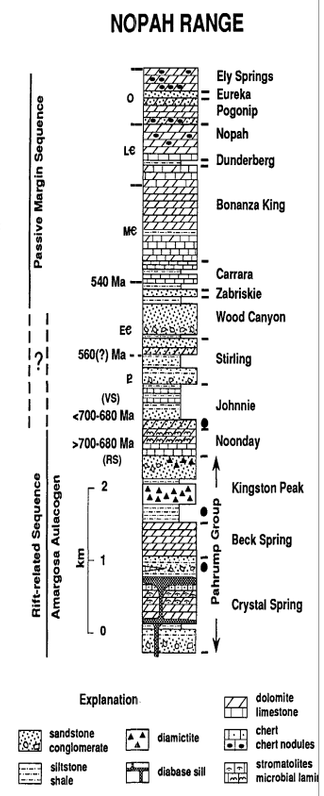
so maybe 530 Ma or 540 instead of 560?

Of course the timescale has been improved in subsequent years, so a proper age probably a bit younger (numerically)

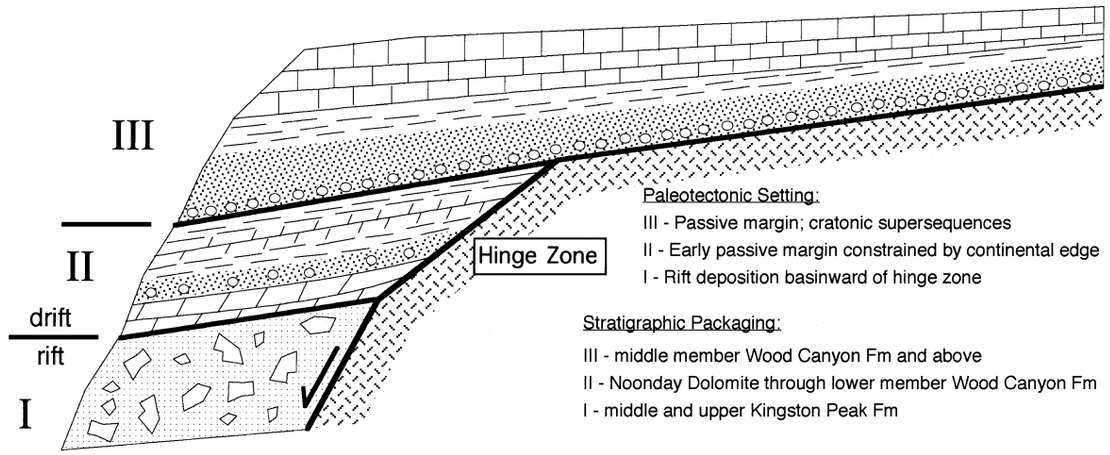
If rift cooling phase starts near base of Cambrian, what about the stuff below?



Fedo & Cooper, Sed. Geol. 2001

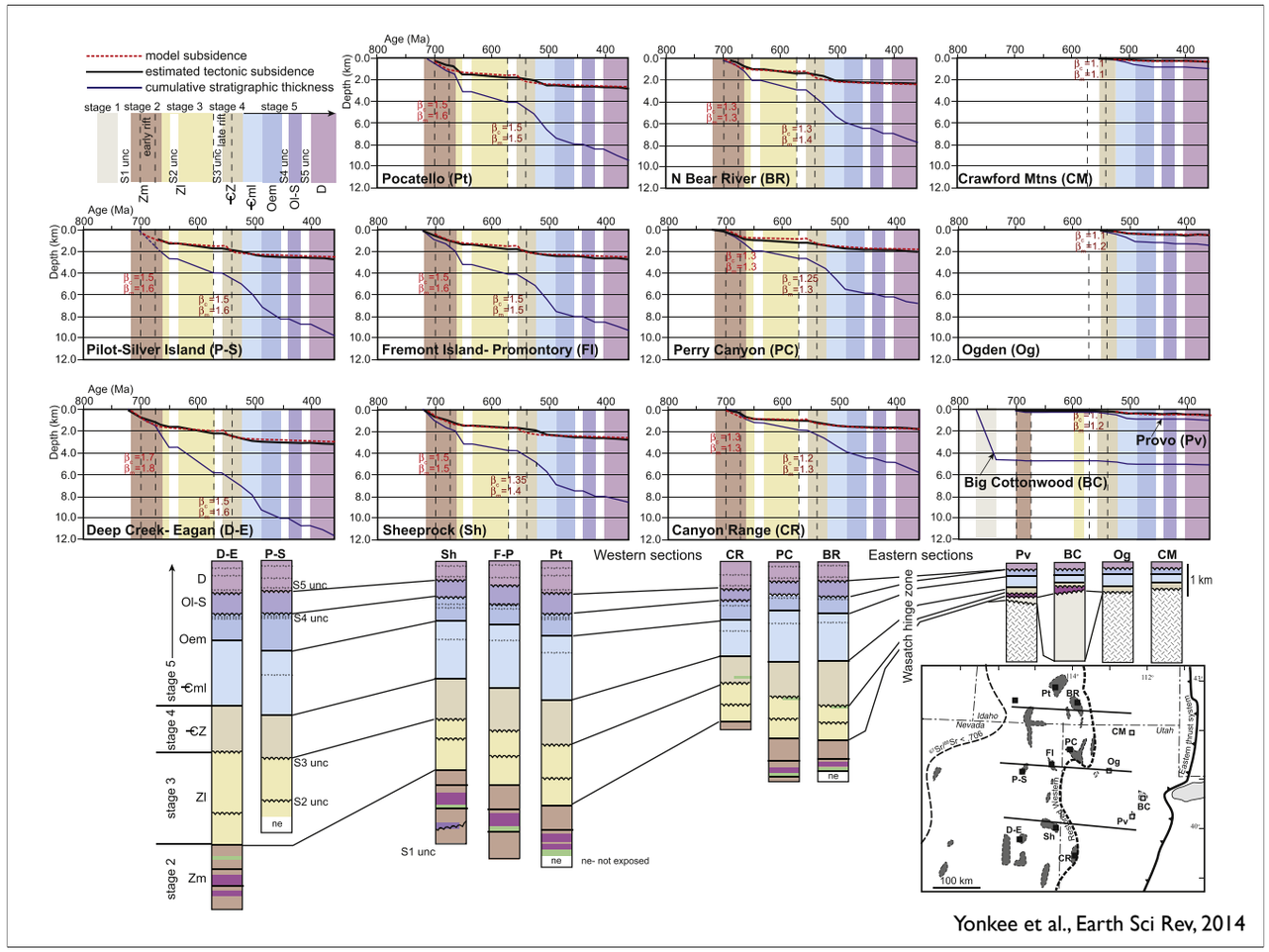


Levy and Christie-Blick, GSA Bull, 1991

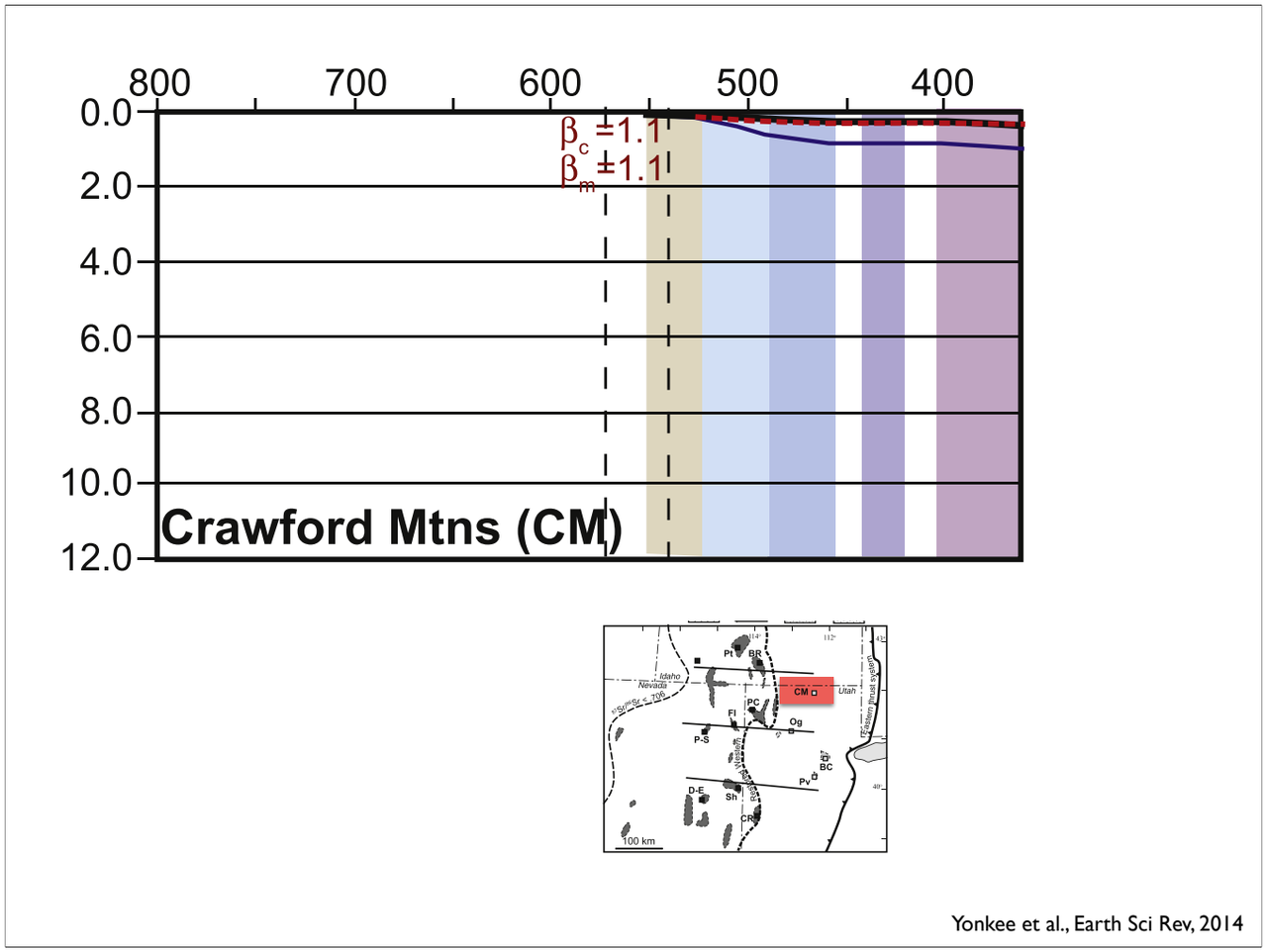


Fedo & Cooper, Sed. Geol. 2001

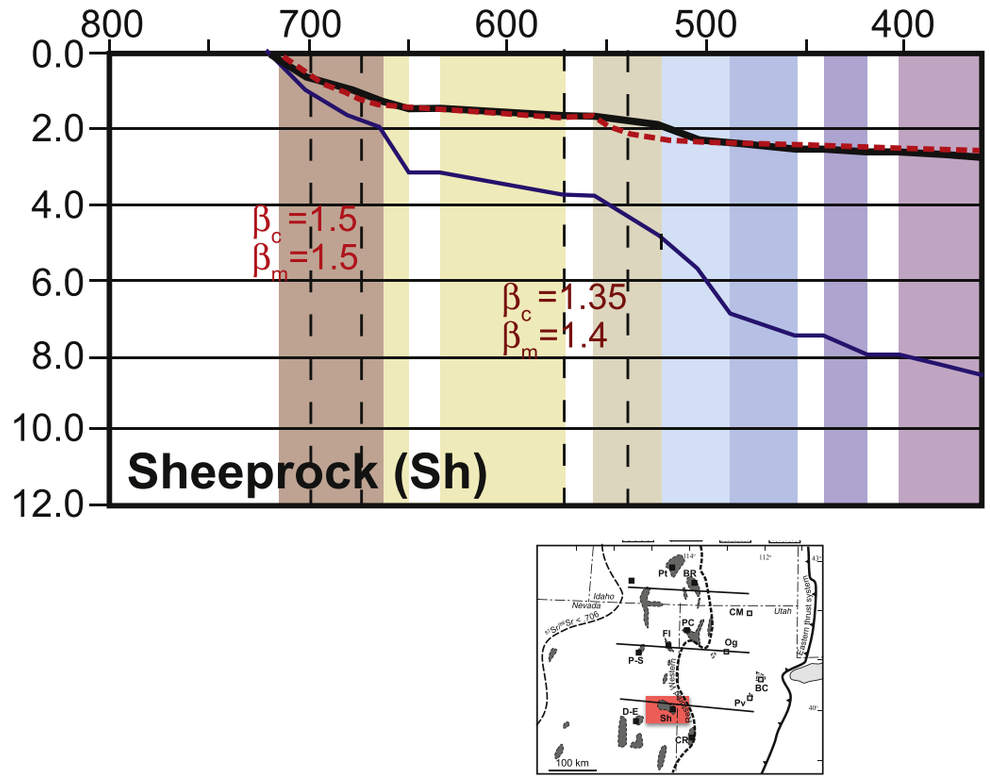
But if rift-drift is at Noonday, which is 2000m below base of C, then how does this work?



An alternative might be multiple rifting episodes? One near 710 Ma, other near 550 Ma



Now can maybe go farther back and see how subsidence is including the “syn-rift” sediments. Seems to push things farther back.



Yonkee et al., Earth Sci Rev, 2014

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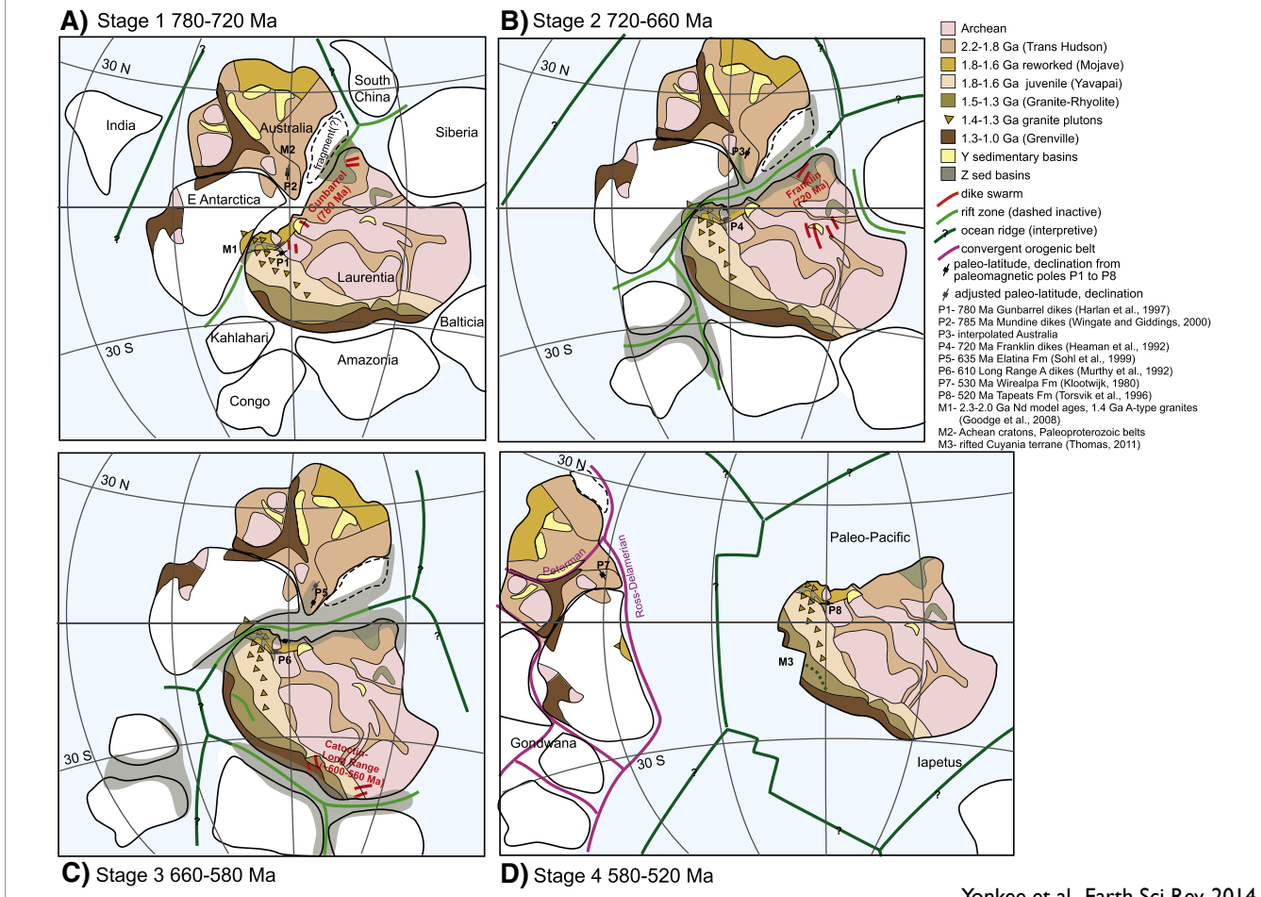
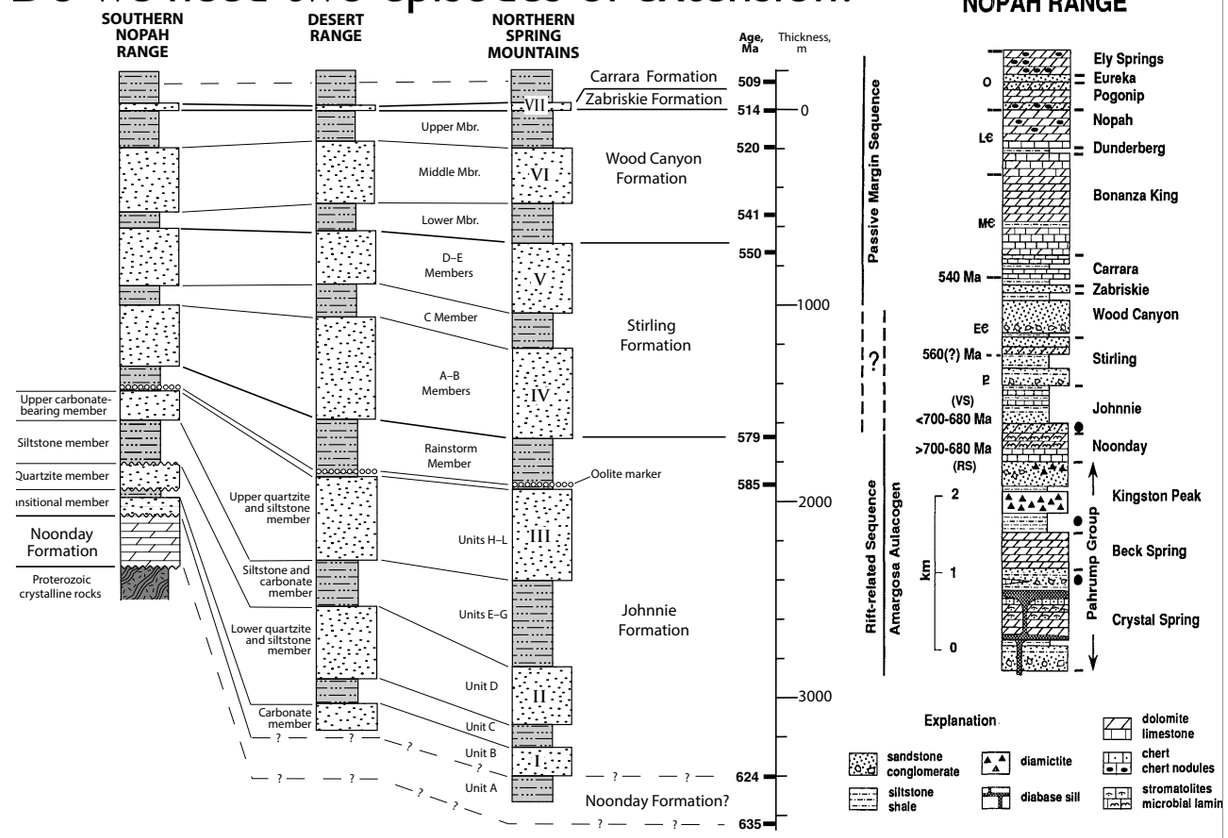


So this interpretation is of slow rifting for about 200 my and then full creation of Laurentia.

Do we need two episodes of extension?



Witkosky and Wernicke, Geosphere, 2018

Levy and Christie-Blick, GSA Bull, 1991

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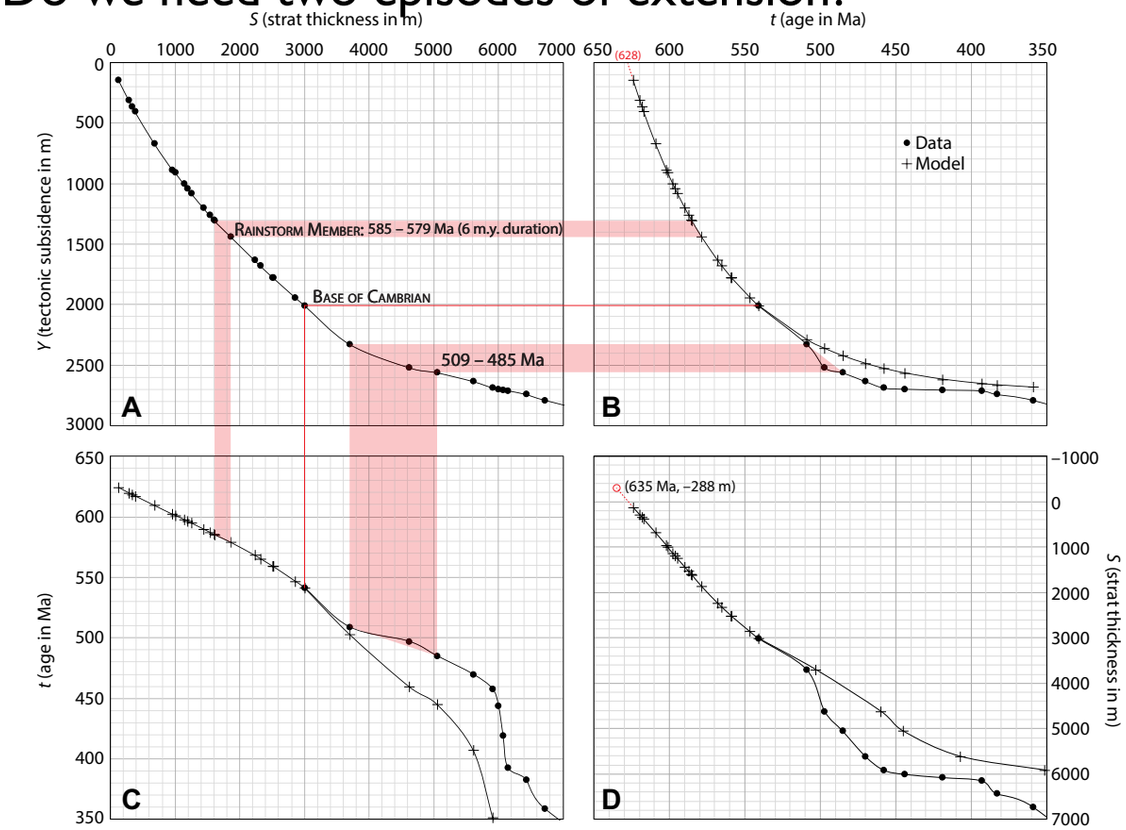

Witkosky and Wernicke, Geosphere, 2018

Goal of the paper was to date late pC section, but this required looking at the subsidence history. Relation from strat thickness to tectonic subsidence from backstripping and assuming no large unconformities. Note upper left panel does not require time. Ages before Cambrian extrapolated but compare well to global glacial episode (e.g., Rainstorm Member). From this, infer that ~540 Ma extension is artifact of carbonate compression and expansion of oceans onto land (509-485 Ma rapid accumulation but little subsidence). That change in slope is what drove the pick from earlier models.
(There is a lot of subtlety here. Estimate of the thermal decay timescale from 541 and 509 Ma points 55-53 m.y., comparable to Phanerozoic thermal decay times elsewhere, indicating a purely thermal subsidence is plausible. Explore models with and without underlying Pahrump group. They don't need time of start of subsidence.