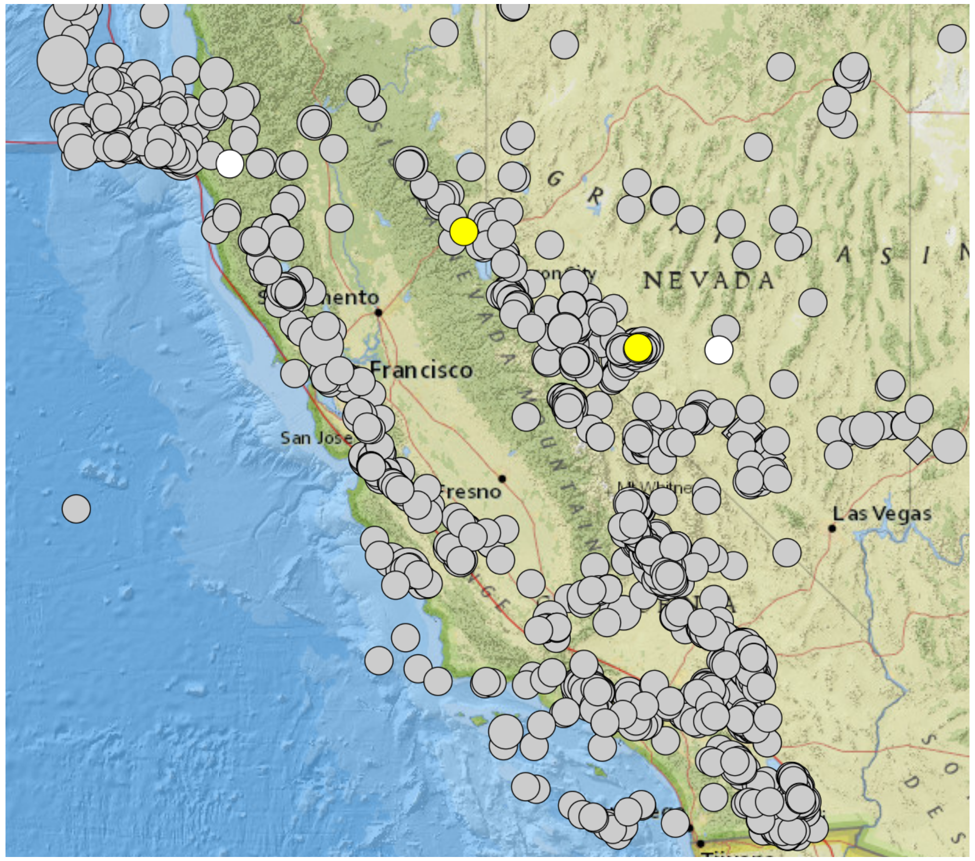
The Peculiar Case of Deep Sierran Earthquakes

Craig H. Jones, Jamie Ryan, Andy Frassetto, Jeffrey R. Unruh, and Hersh Gilbert

P.S.: June 2022, Thompson Field Forum in the Sierra addressing age of uplift
(Leaders: Cassel, Henry, Jones, Wakabayashi)

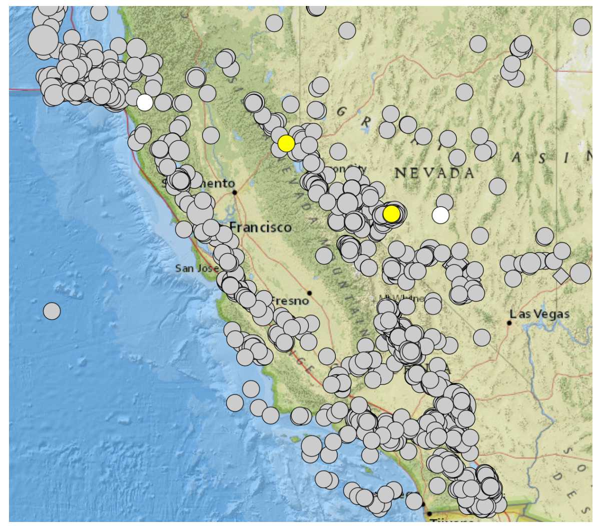
Cordilleran GSA, Spring 2021

USGS Earthquakes, 1990-present, M≥4

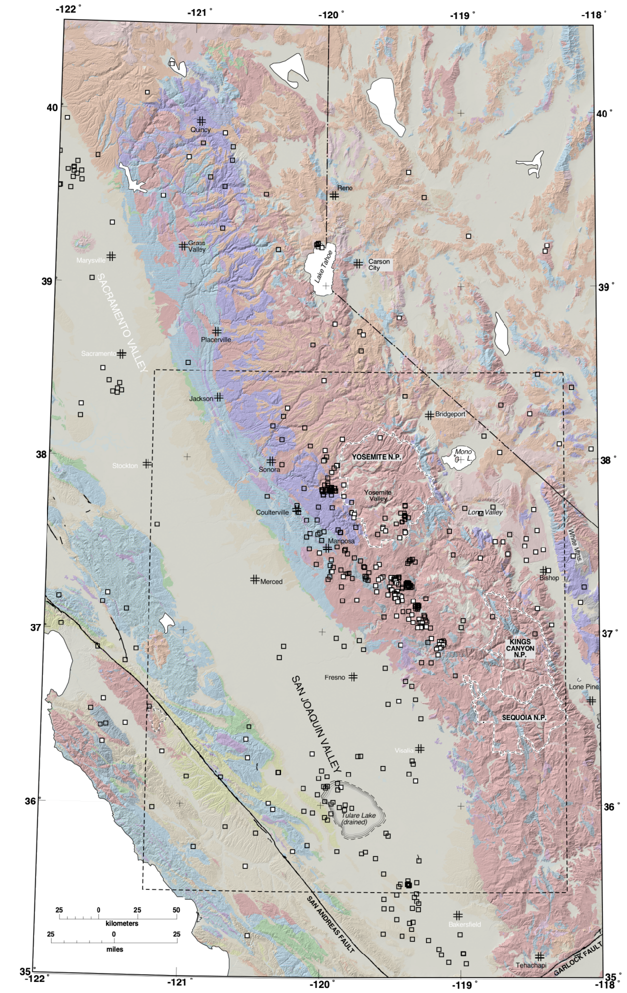


Usually when we worry about EQs in CA, we look at these places…and assume Sierra rigid.

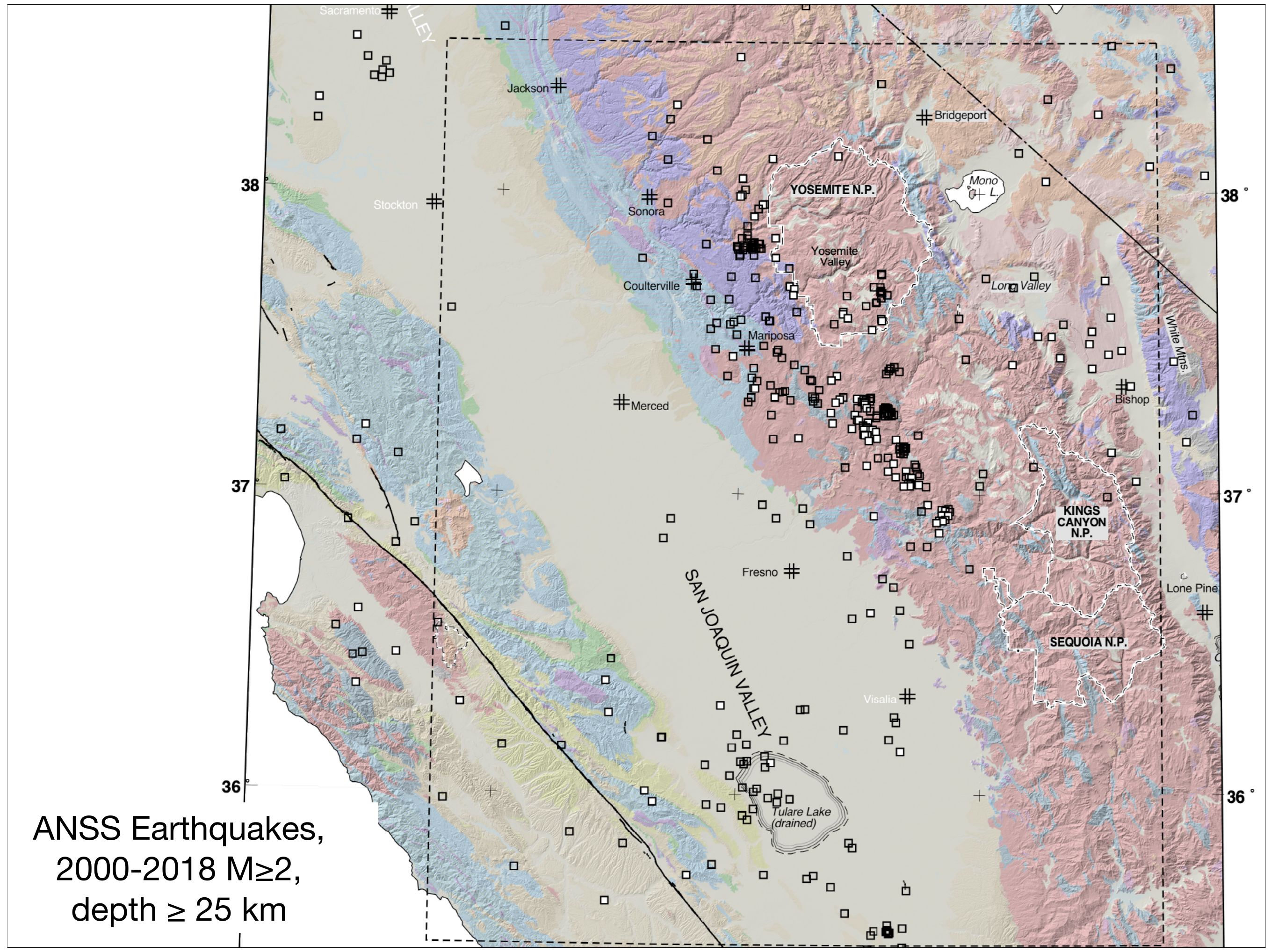
USGS Earthquakes,
1990-present, M≥4



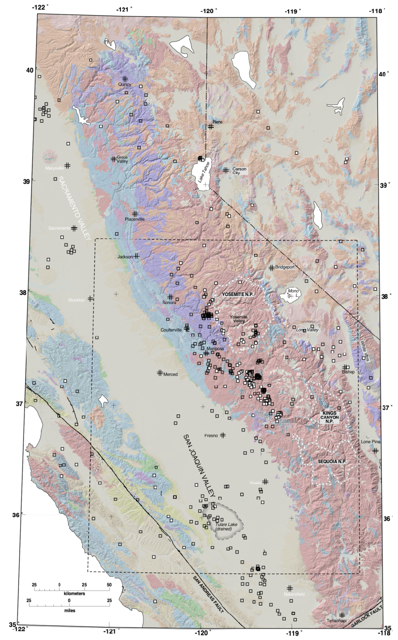
ANSS Earthquakes,
2000-2018 M≥2,
depth ≥ 25 km



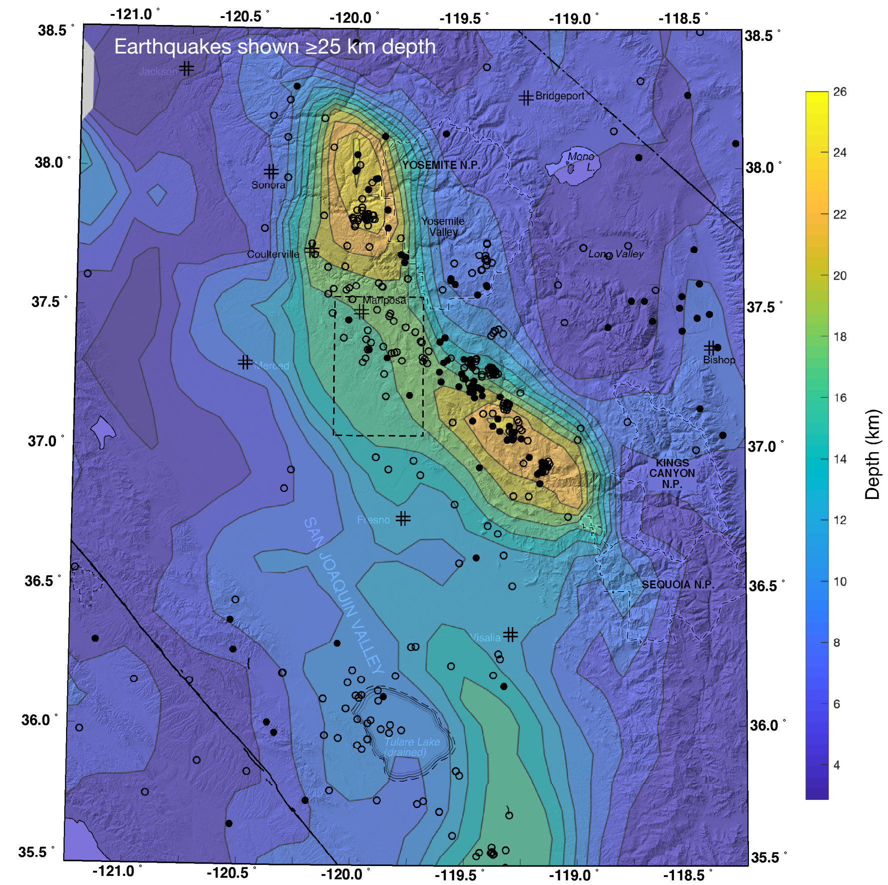
..but at a more detailed level, there are a lot of deep EQs in Sierra.



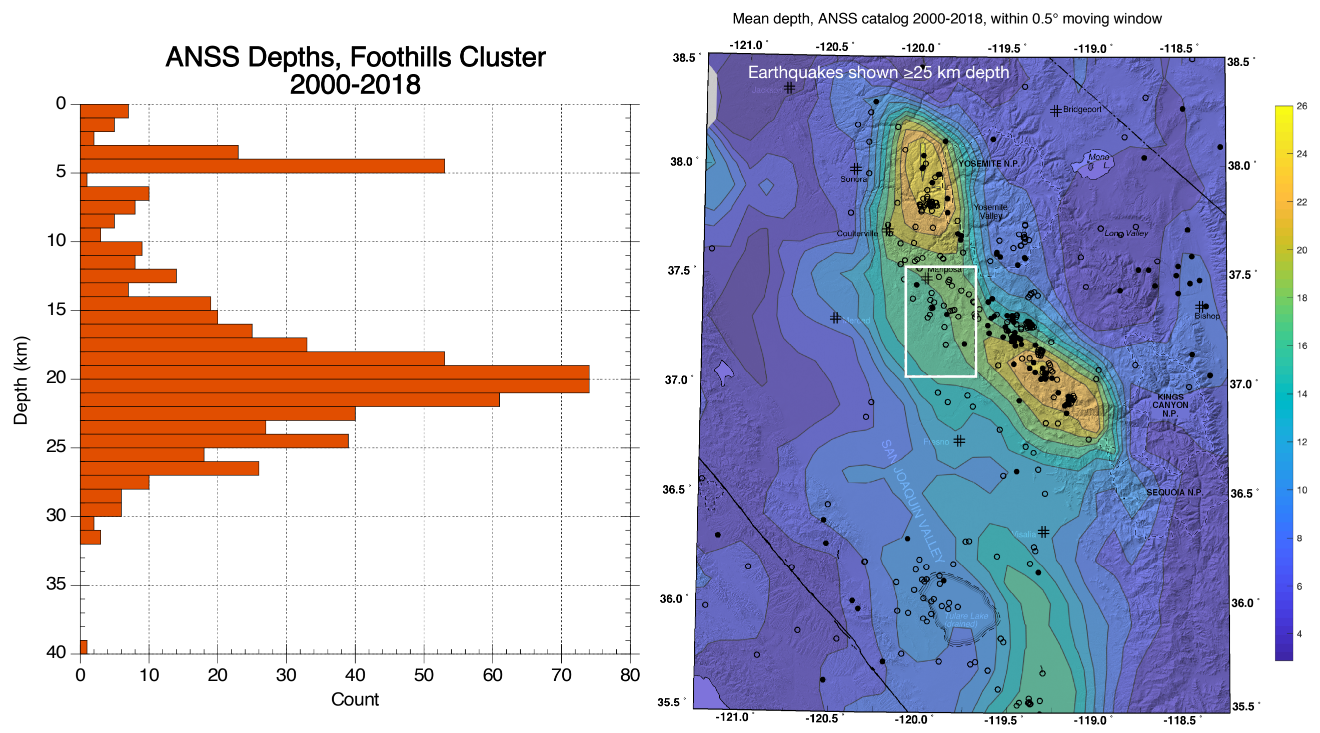
OK, so there are deep earthquakes…so what? Not any obvious connection to surface geology (unless you think Melones FZ continues deep in subsurface to SE). Recall lots of EQs to east and west. Not so many deep ones there…



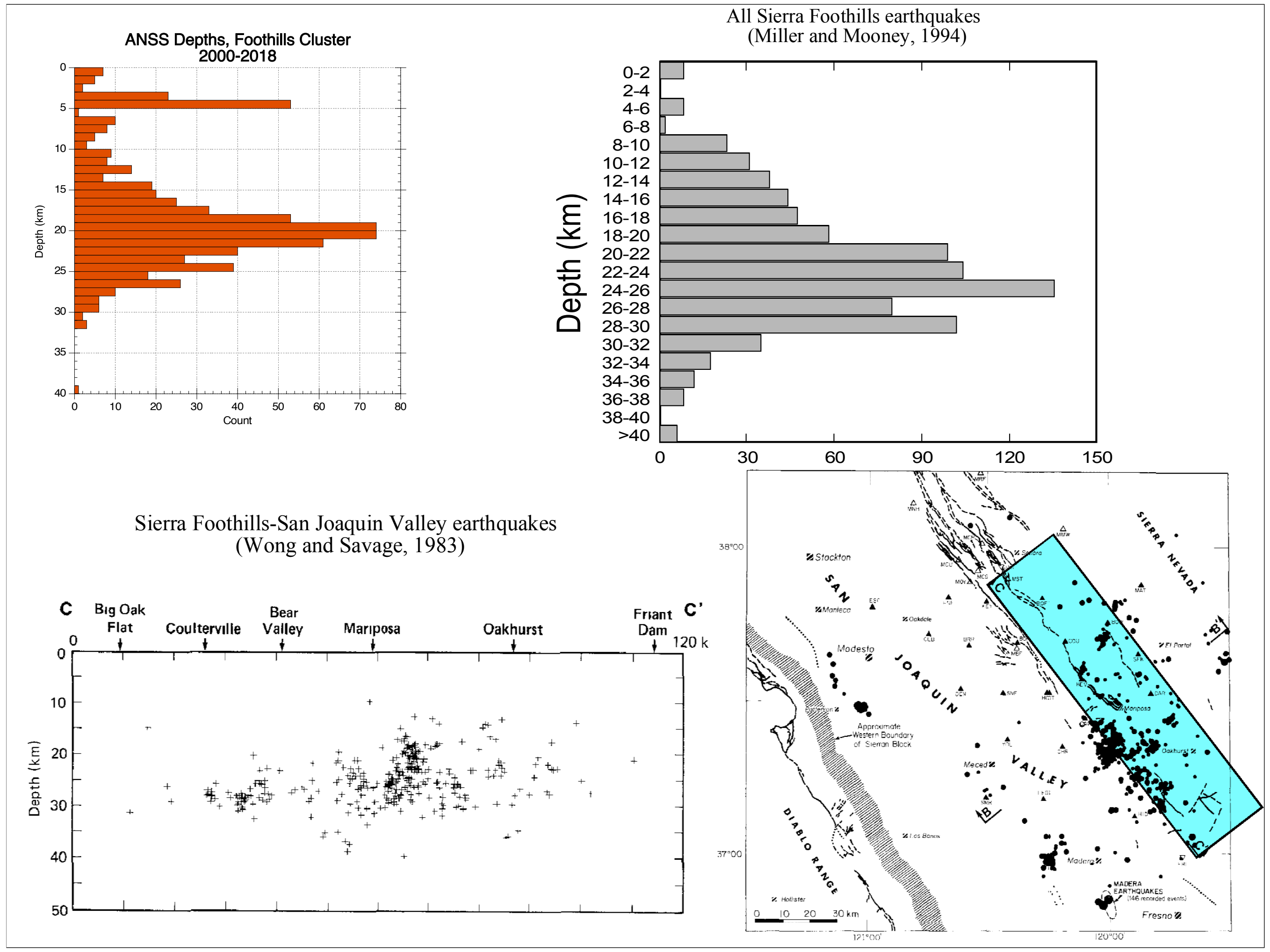
ANSS Earthquakes,
2000-2018 M≥2,
depth ≥ 25 km



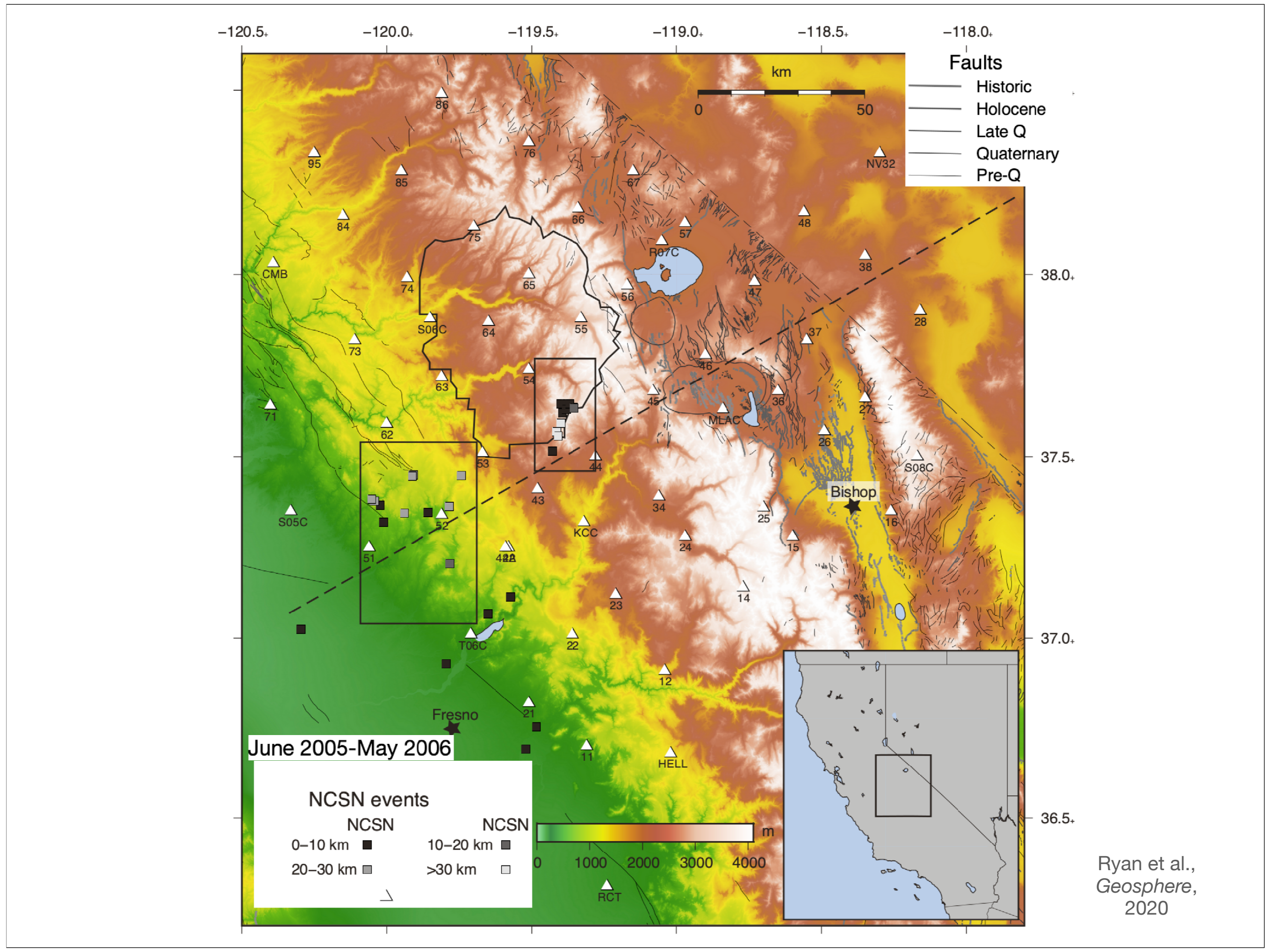
Not only are there deep EQs in the foothills, but few if any shallow ones, so the average is pretty deep.



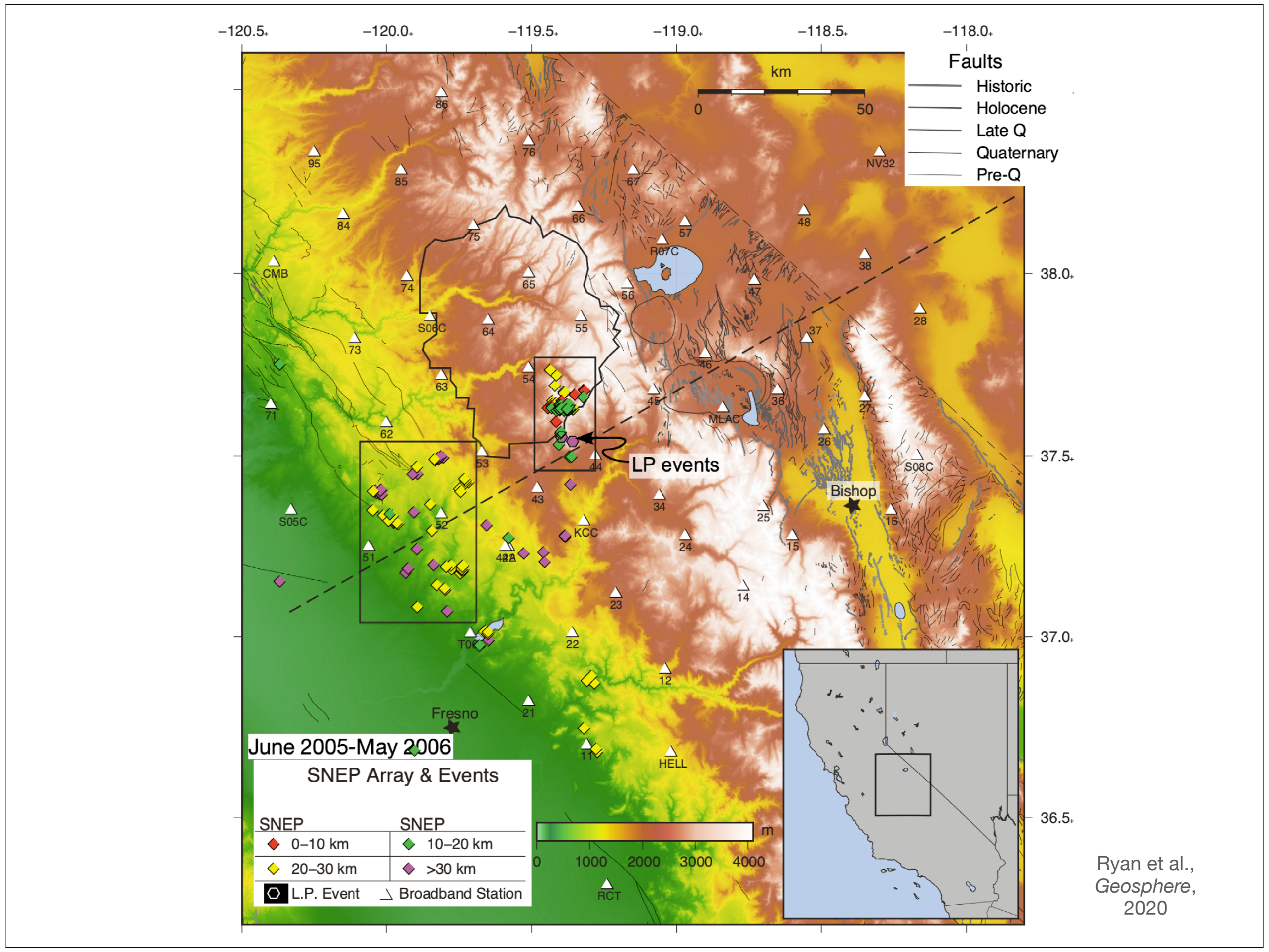
This has been observed for awhile, but this area is at the edge of the permanent networks where location quality could be substandard. How well established is this?



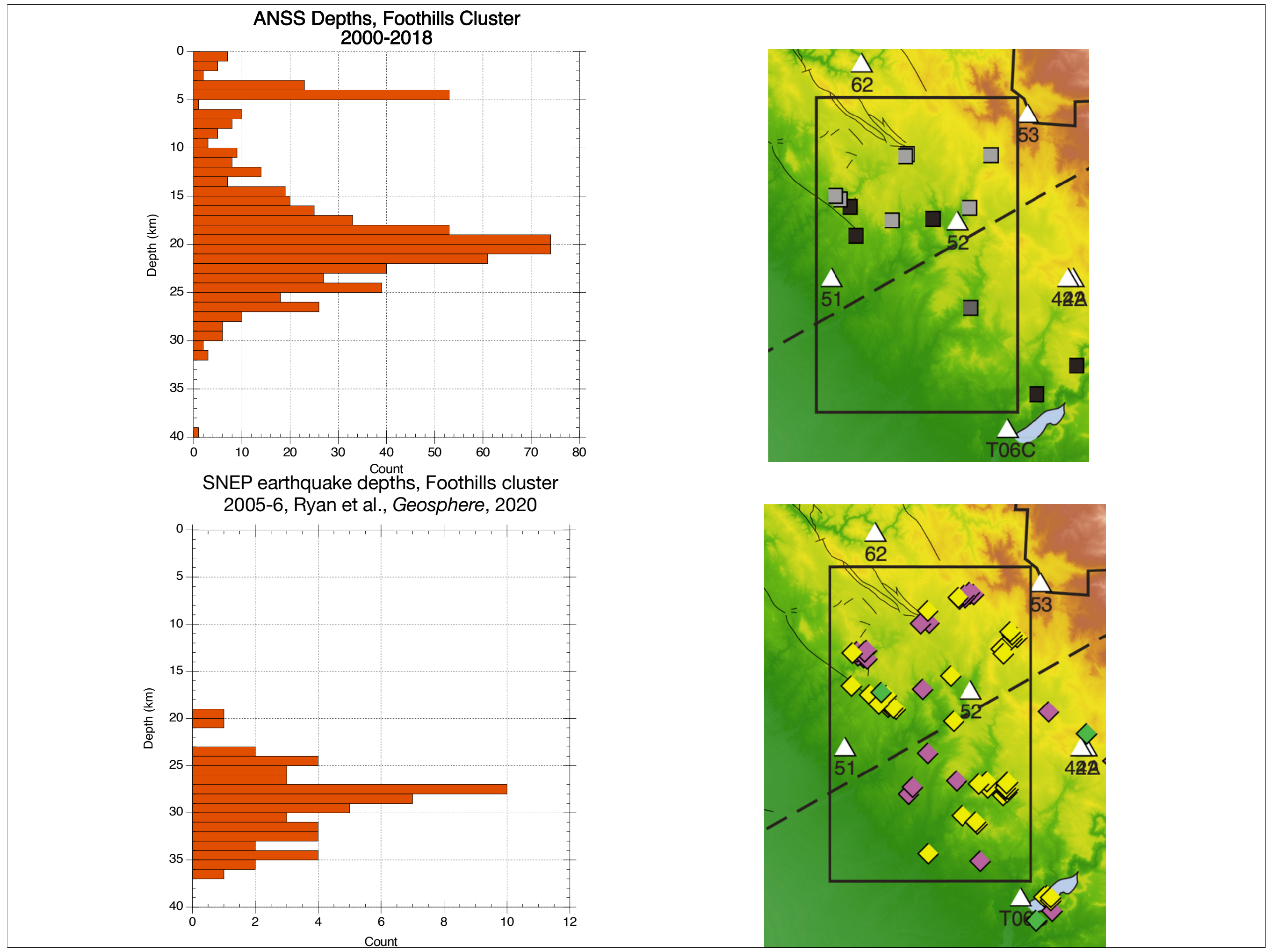
We’ve seen this pattern from 1970s to present. Wong and Savage had a local network for Woodward Clyde and quakes were below 10 km. Some of that data used in later Miller and Mooney work, which suggested some shallow seismicity but includes a broader region.



But otherwise most seismometers far away until SNEP deployment in 2005. First year of SNEP allowed examination of earthquakes in Sierra foothills. Network locations shown here…



But locations with the SNEP array moved shallow events in the west to greater depth (similar to Wong work)

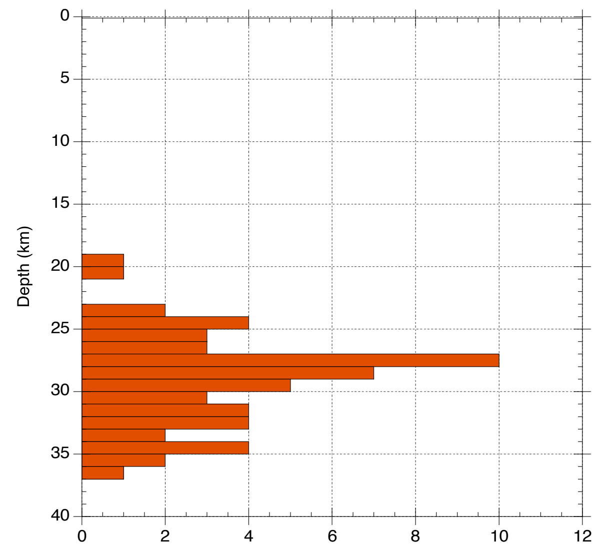


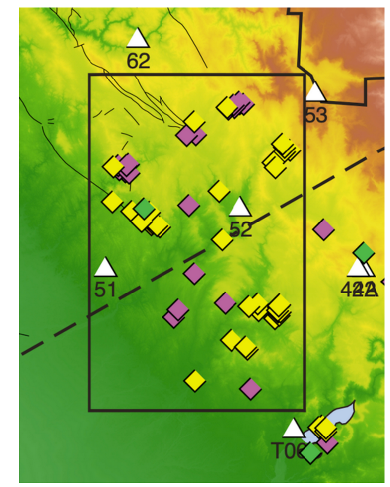
Absence of deep quakes in the foothills seems pretty strong—stations right above quakes.

Three Questions:

1. How special is this?
2. How might this work?
3. What might this mean for regional tectonics?

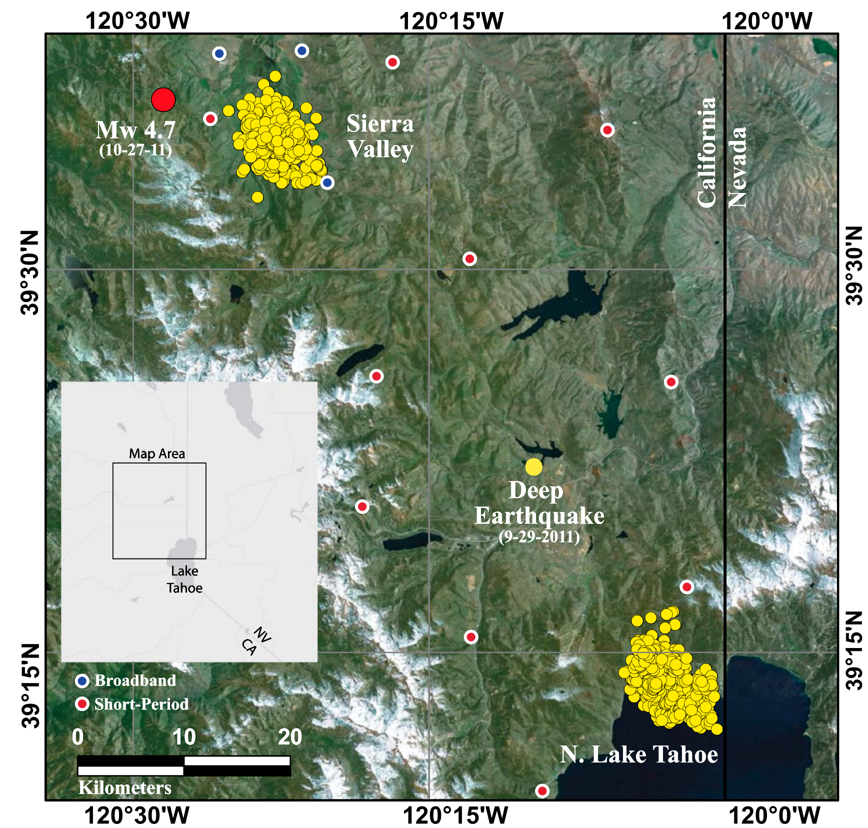
SNEP earthquake depths, Foothills cluster
2005-6, Ryan et al., *Geosphere*, 2020





Poses three questions…

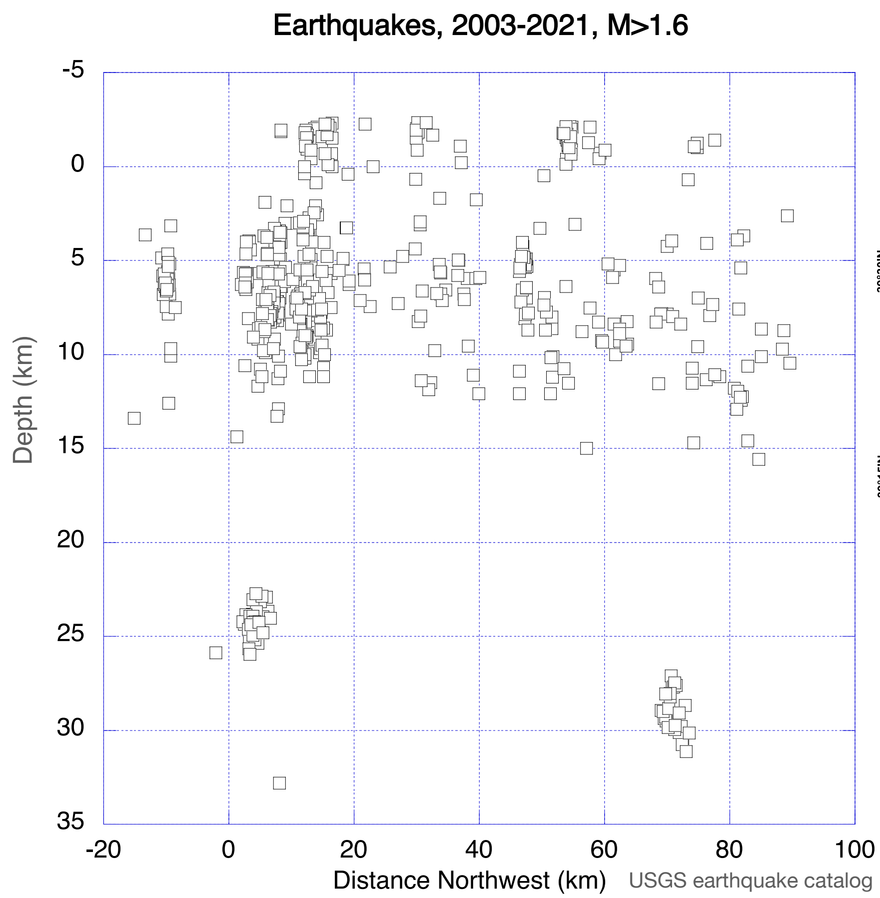
Deep Earthquakes, Northern Sierra



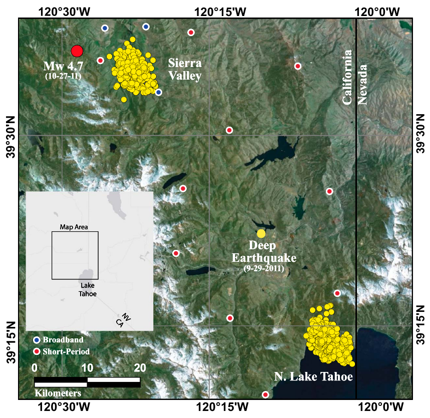
Smith et al., *GRL* 2016

Hearing "deep earthquakes in Sierra" you might think of 2003 swarm under North Lake Tahoe.

Deep Earthquakes, Northern Sierra

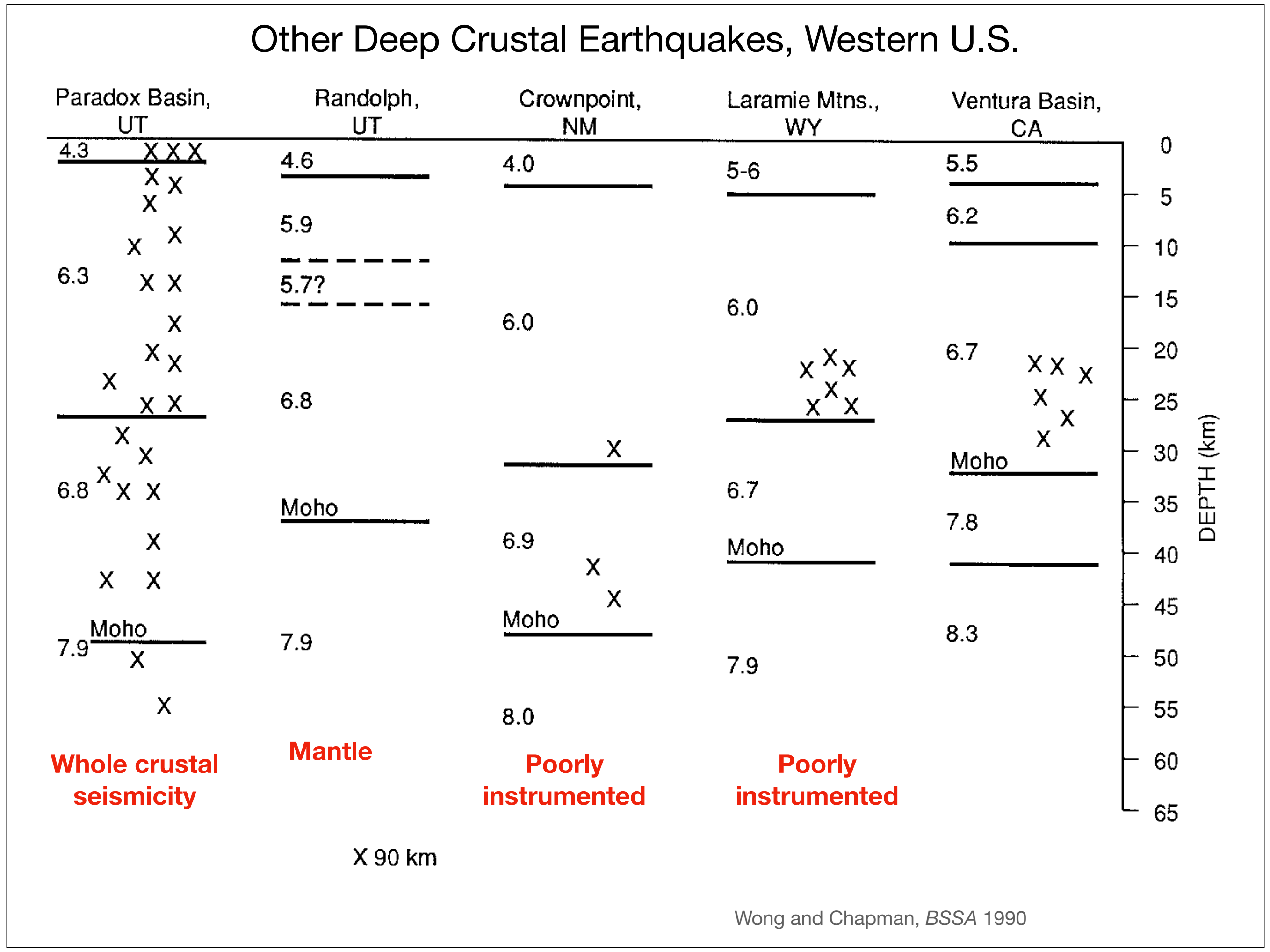


USGS earthquake catalog



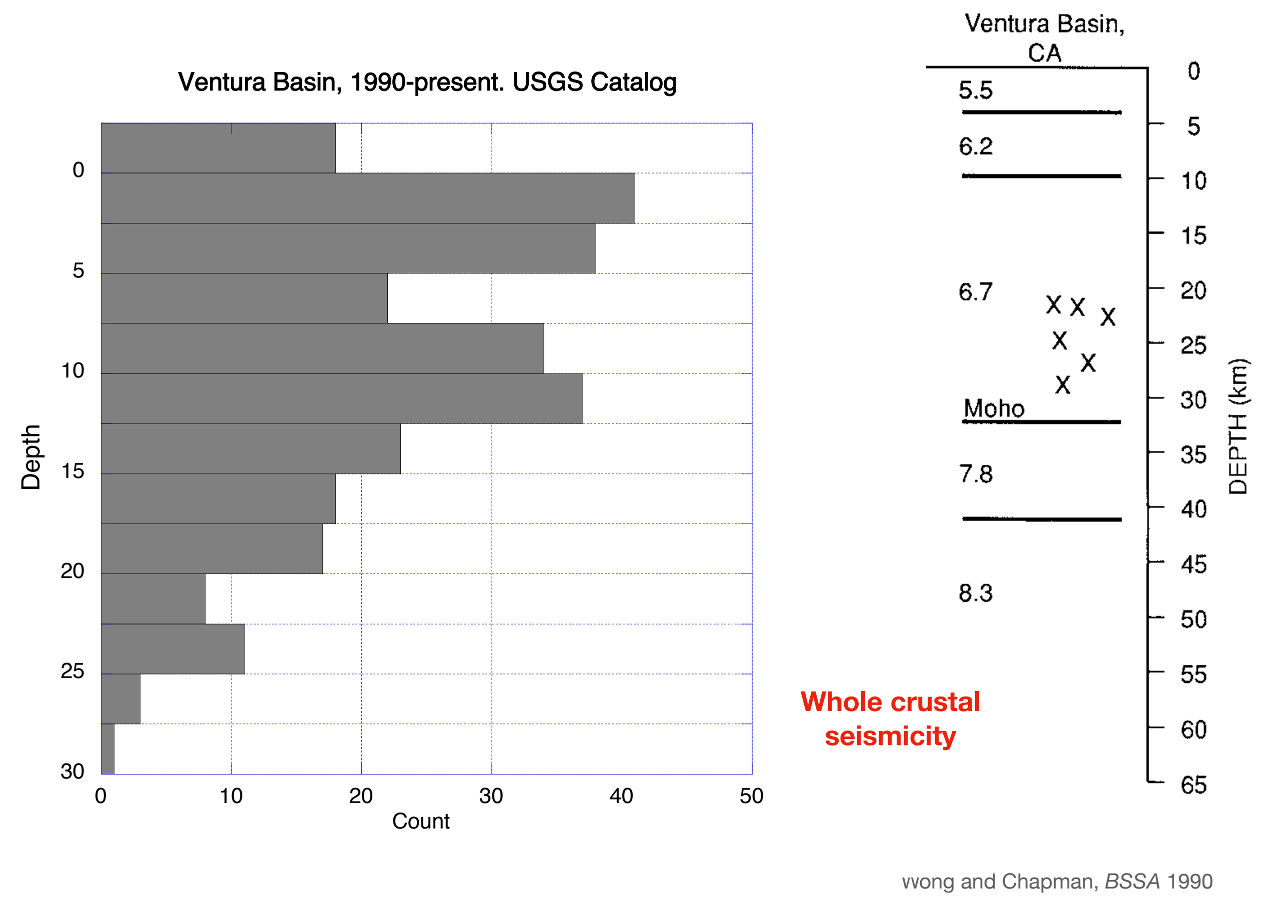
Smith et al., *GRL* 2016

But while those quakes are present, there is lots of upper crustal seismicity. Also note that there are fairly young surface volcanics present which don't exist in the Sierra foothills.



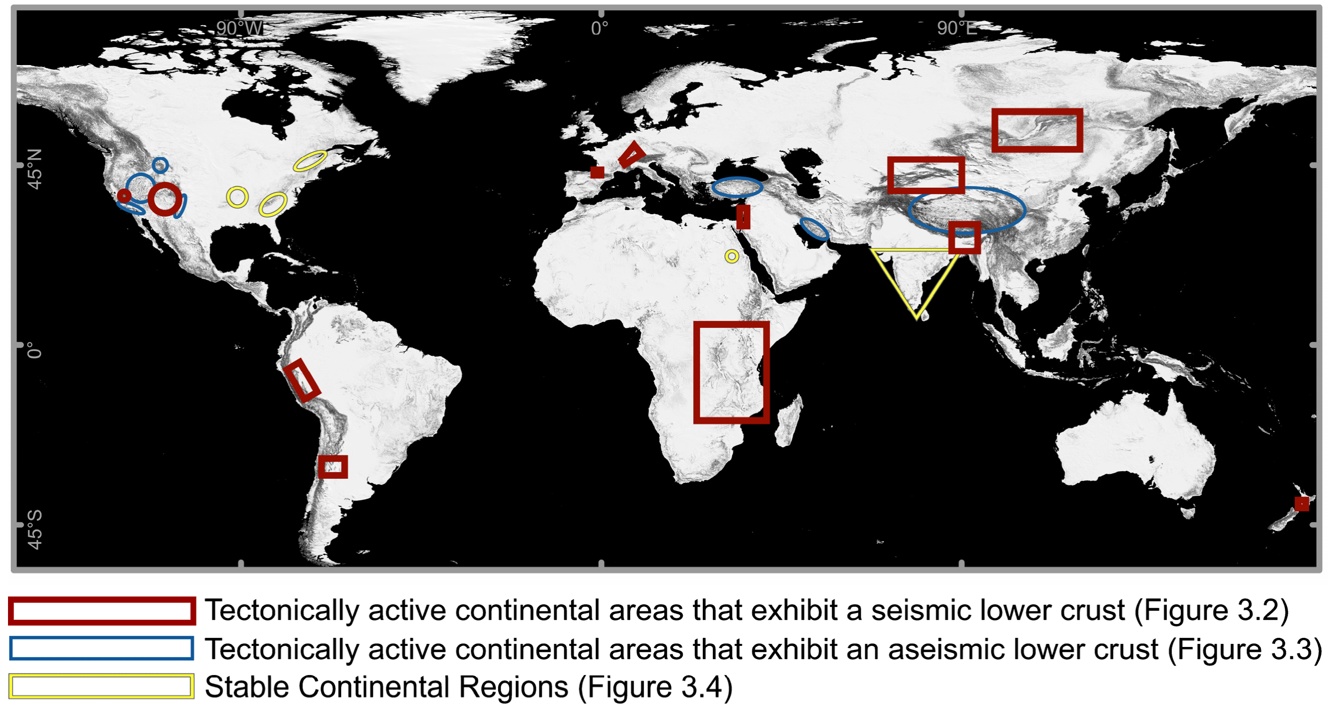
Other places in WUS with deep EQs. Most of these either have upper crustal quakes or are too poorly monitored to know. So while deep EQs aren’t that unusual, an absence of shallow EQs is.

Other Deep Crustal Earthquakes. Western U.S.



Ventura also has tons of shallow quakes.

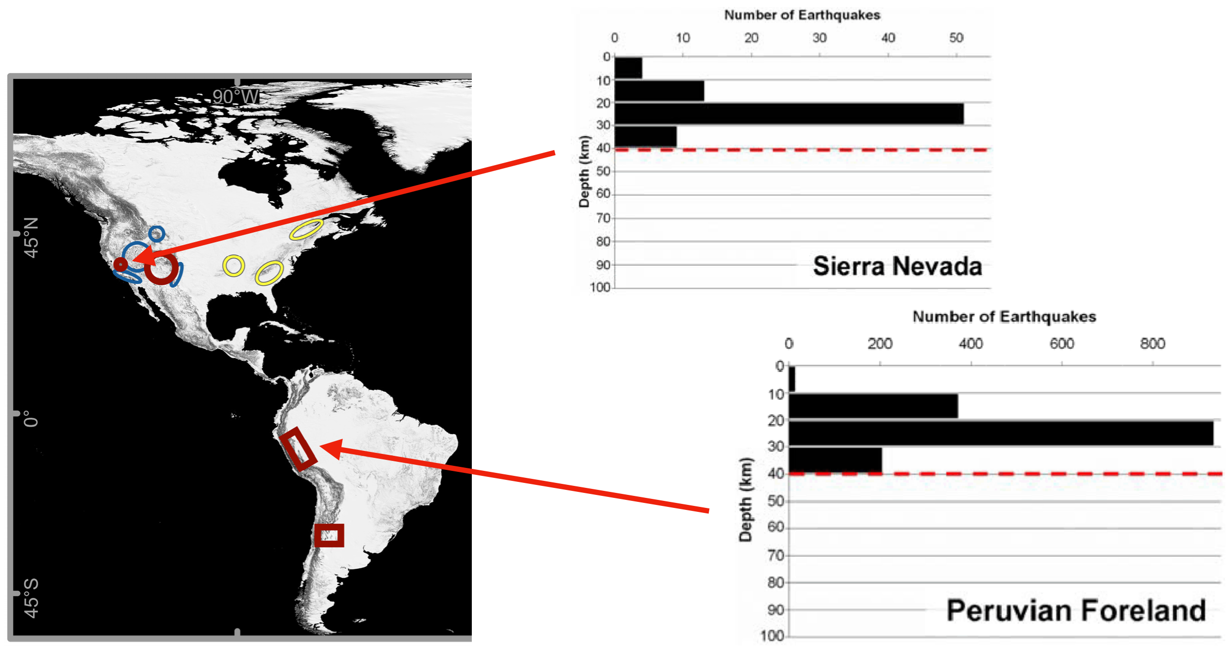
Other Deep Crustal Earthquakes, Global



Stephanie Devlin, PhD thesis, 2008

So how does this compare globally? Thesis by Stephanie Devlin sought out deep crustal earthquakes…

Deep Crustal Seismicity Lacking Upper Crustal Quakes: Global

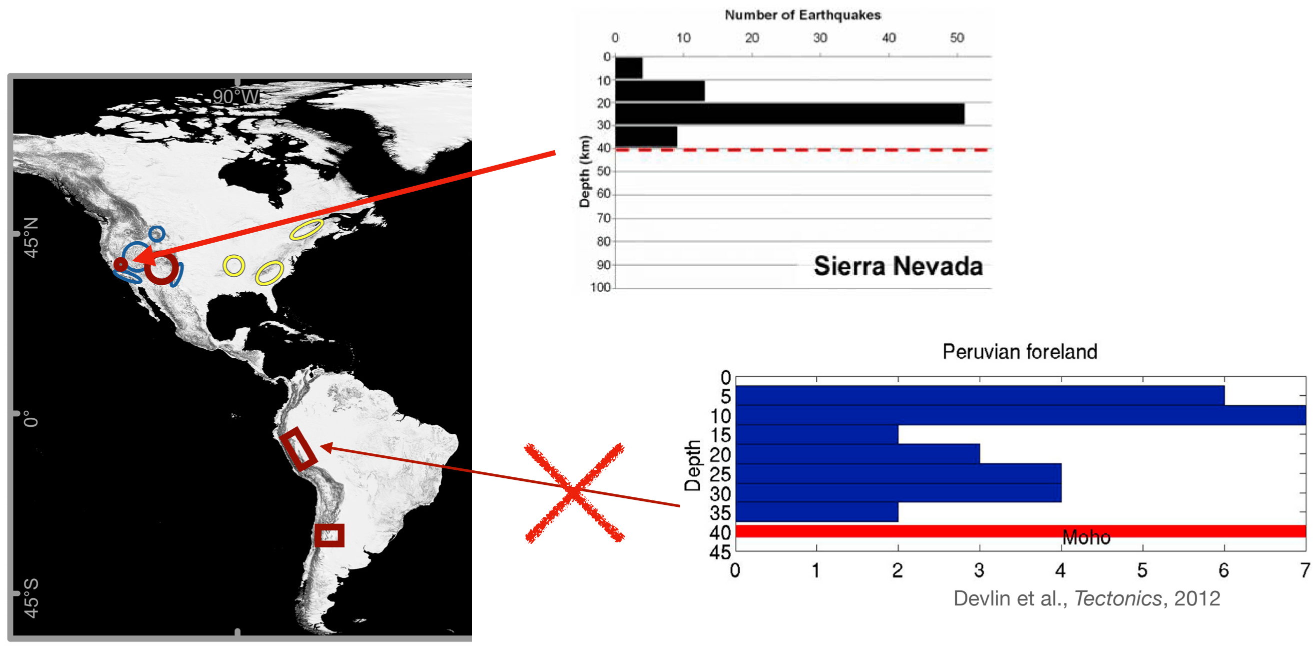


Tectonically active continental areas that exhibit a seismic lower crust (Figure 3.2)
Tectonically active continental areas that exhibit an aseismic lower crust (Figure 3.3)
Stable Continental Regions (Figure 3.4)

Stephanie Devlin, PhD thesis, 2008

..of those places, only two looked like they might have deep but very little shallow quakes.

Deep Crustal Seismicity Lacking Upper Crustal Quakes: Global



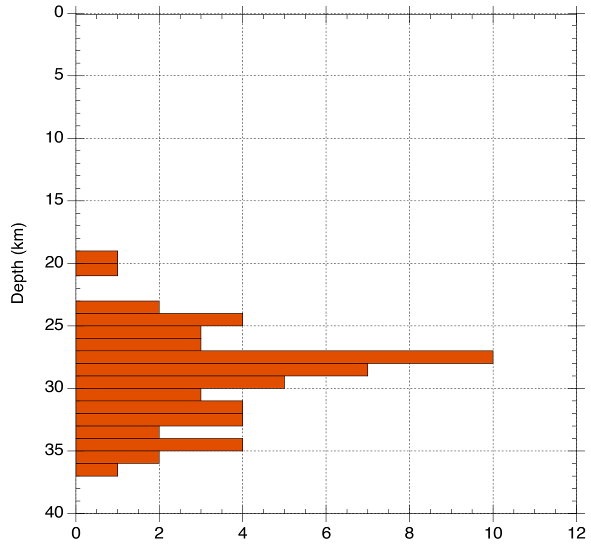
Tectonically active continental areas that exhibit a seismic lower crust (Figure 3.2)
Tectonically active continental areas that exhibit an aseismic lower crust (Figure 3.3)
Stable Continental Regions (Figure 3.4)

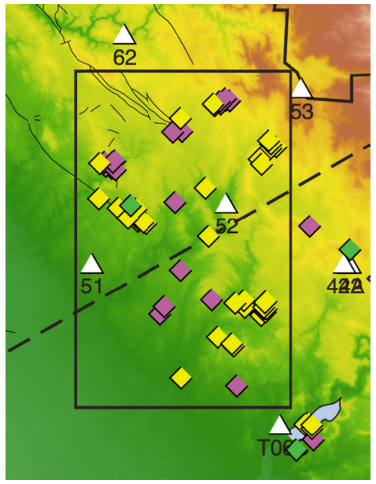
The other one of those, the Peruvian foreland, dropped out when later work by Devlin et al. revealed plenty of shallow quakes.

Three Questions:

1. How special is this?-**Seems pretty special**
2. How might this work?
3. What might this mean for regional tectonics?

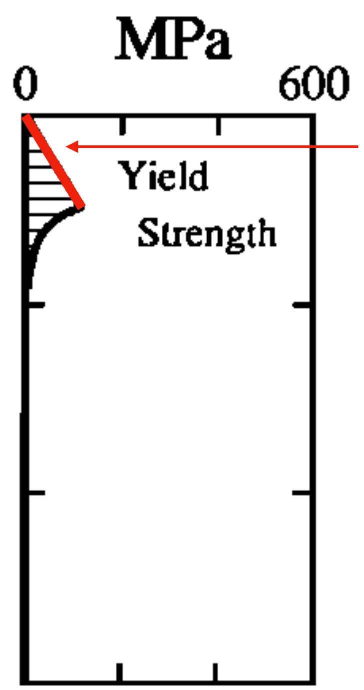
SNEP earthquake depths, Foothills cluster
2005-6, Ryan et al., *Geosphere*, 2020





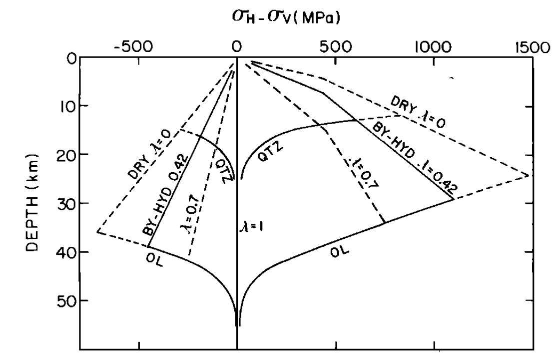
So this does seem quite unusual.

Hot lithosphere



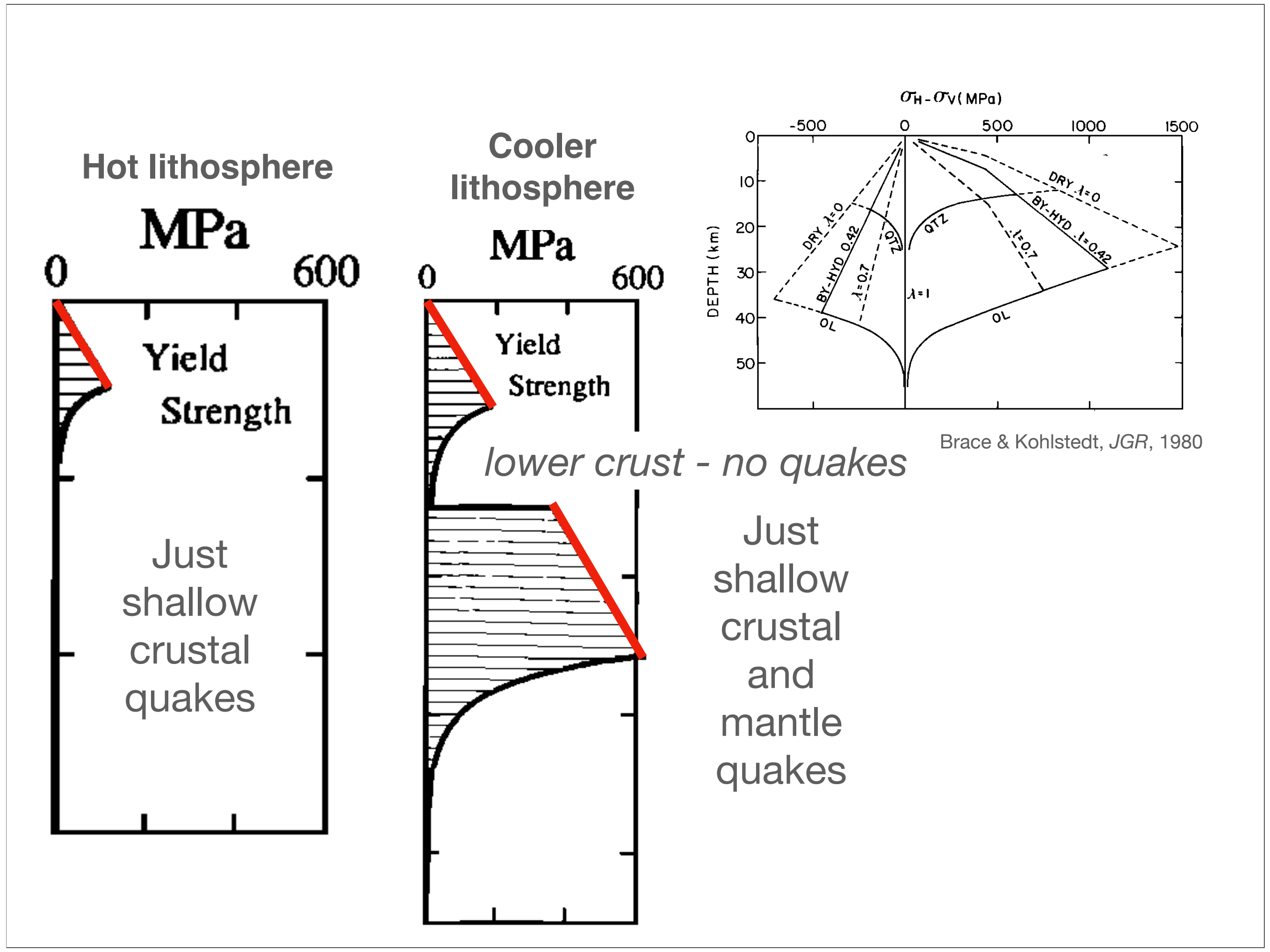
Brittle failure

Just shallow crustal quakes

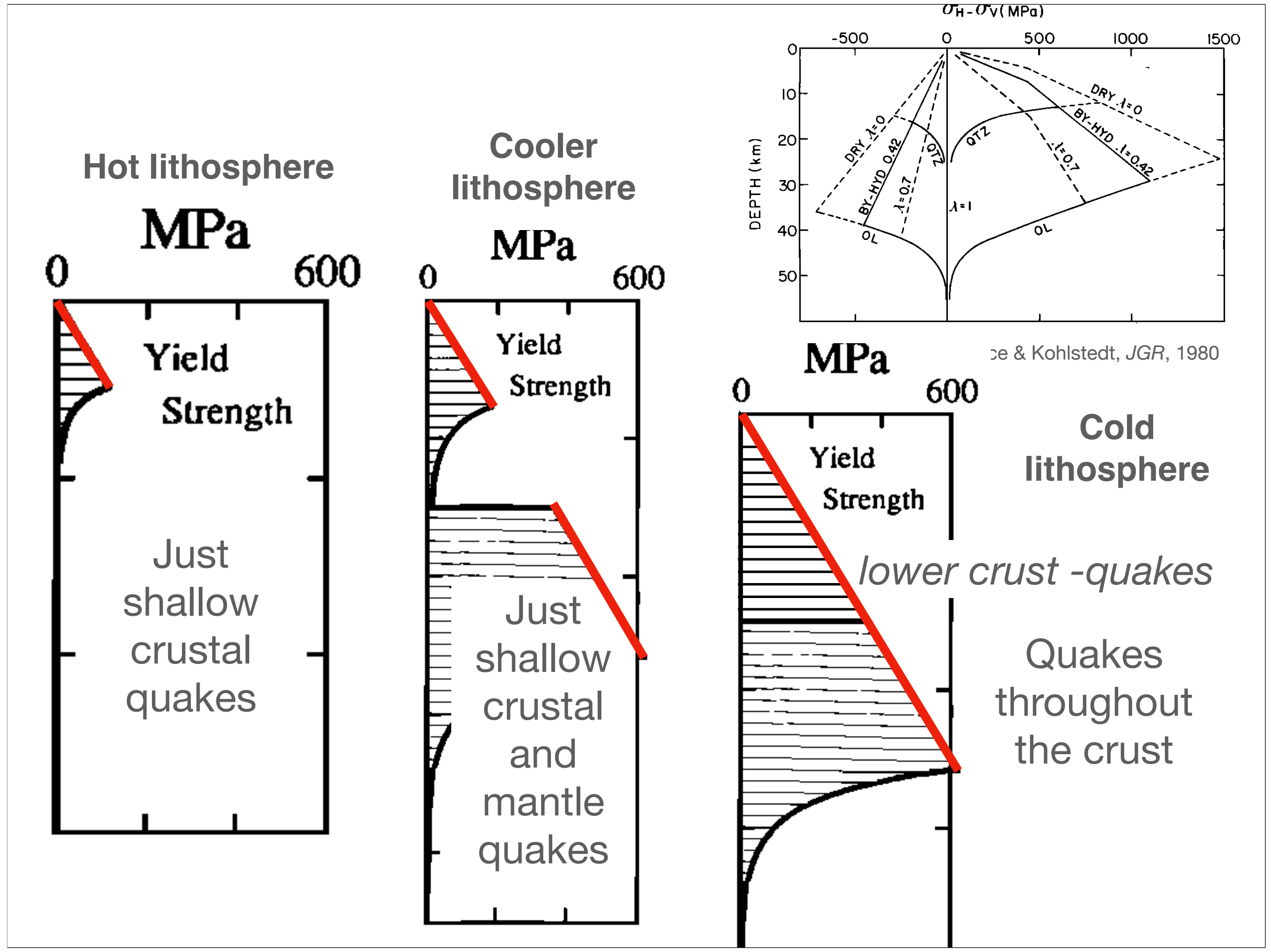


Brace & Kohlstedt, *JGR*, 1980

Normally we think of the lithosphere as behaving brittlely at shallower depths and ductilely at greater depths, with the brittle-ductile boundary reflecting an isotherm within a given petrology. SO if things are hot, just upper crust suffering brittle failure.



A lower geotherm might allow olivine based rheology in the mantle to fail with quakes, but the silica-rich lower crust should still fail ductilely.

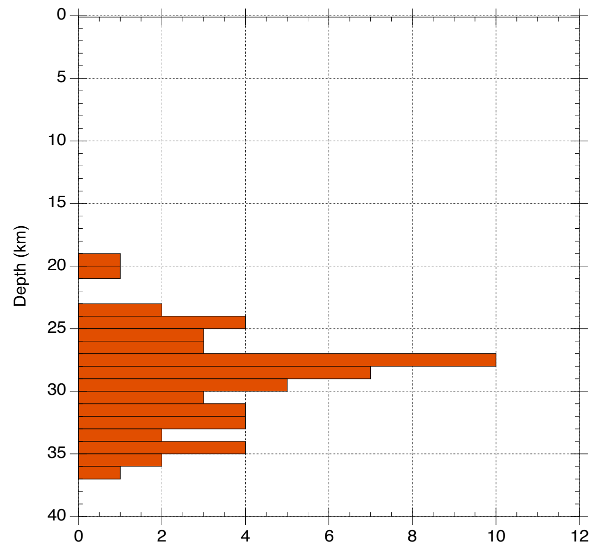


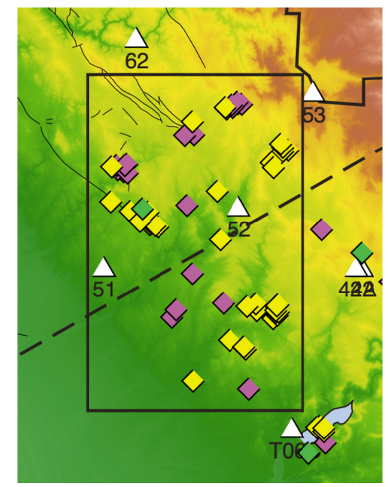
A really cold geotherm should result in seismicity throughout the crust—which would include the upper crust.

Three Questions:

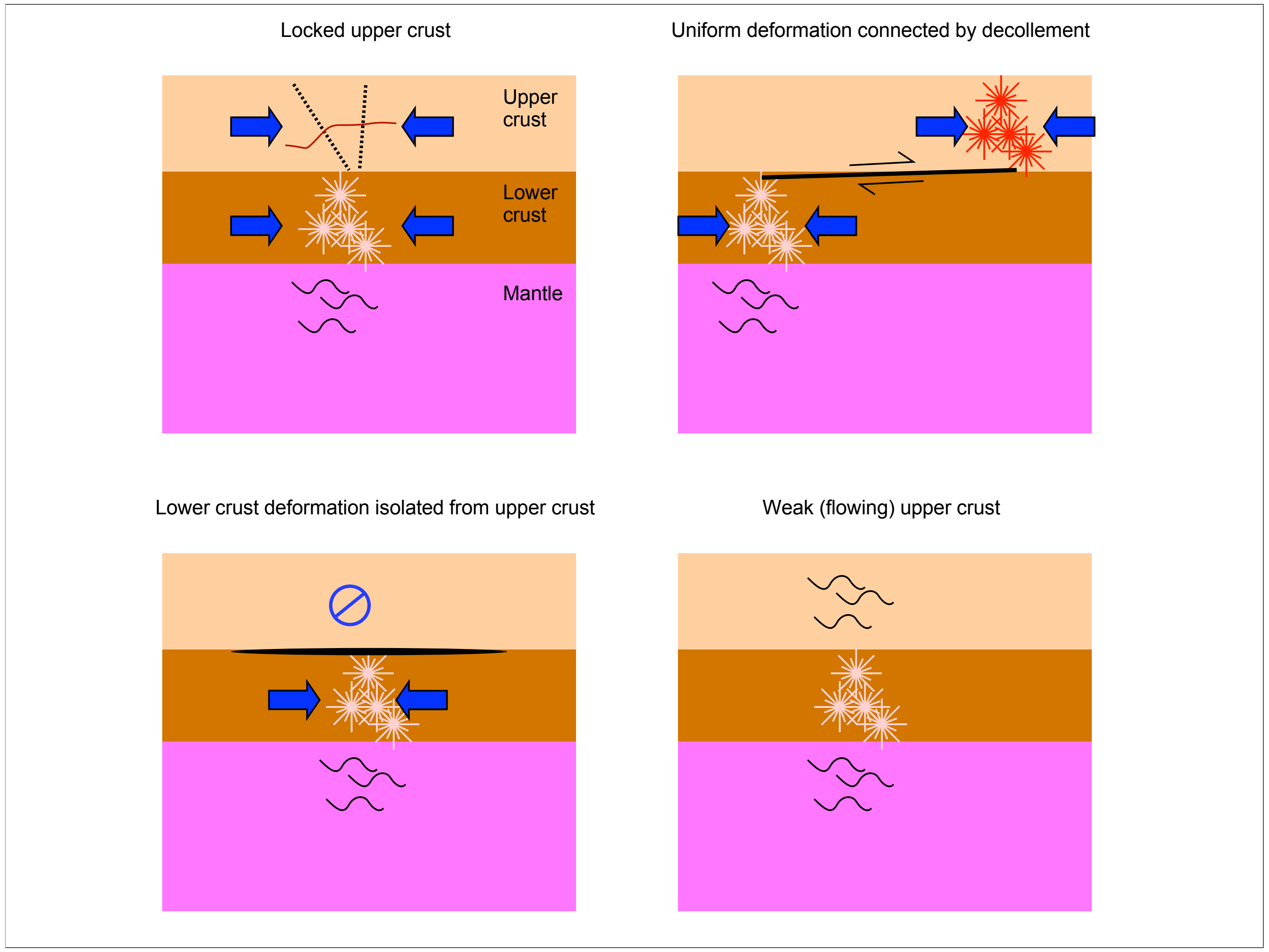
1. How special is this?-**Seems pretty special**
2. How might this work? **- Not simple thermal effect**
3. What might this mean for regional tectonics?

SNEP earthquake depths, Foothills cluster
2005-6, Ryan et al., *Geosphere*, 2020



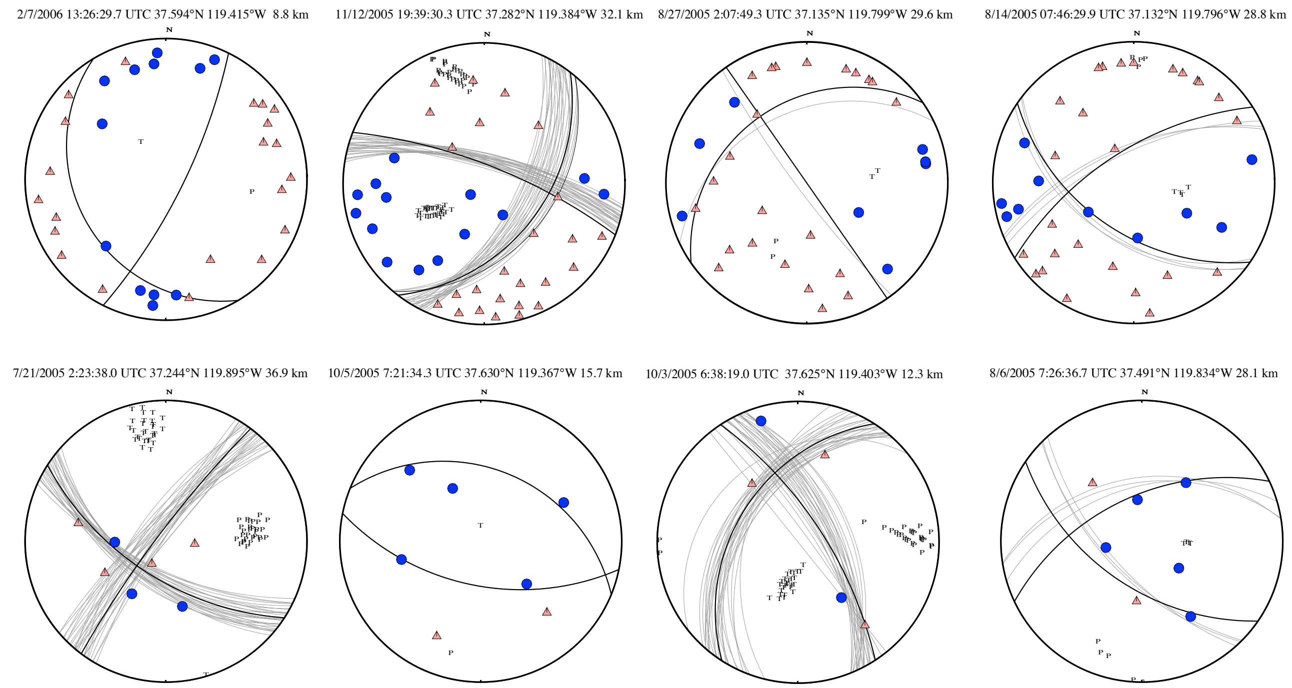


So this distribution of quakes is not easily reconciled with vertically uniform strain and a cold geotherm. What other possibilities are there?



Some possibilities. Note the top two possibilities would suggest that the stress field orientation would be uniform and presumably similar to surroundings.

A sampler of focal mechanisms

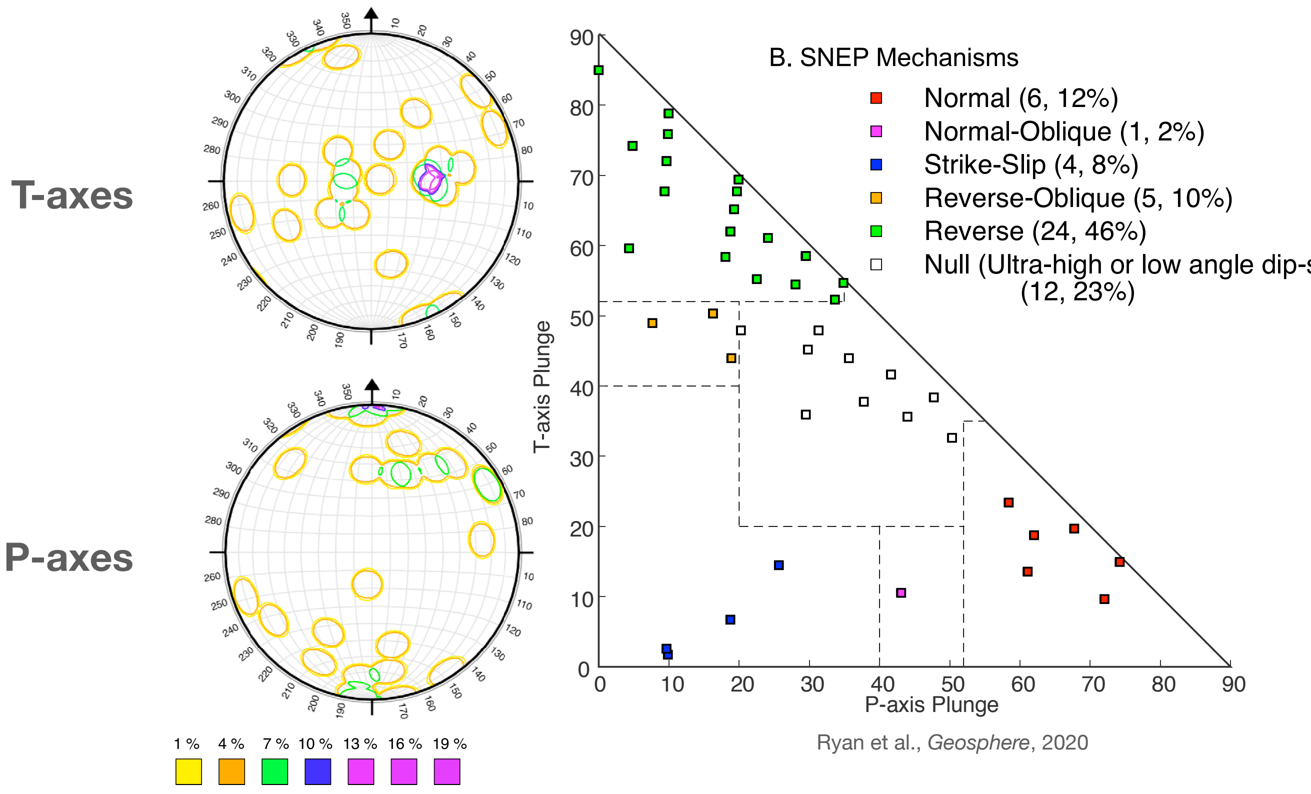


Ryan et al., *Geosphere*, 2020

A sampler of focal mechanisms. Note tendency towards thrust/reverse solutions.

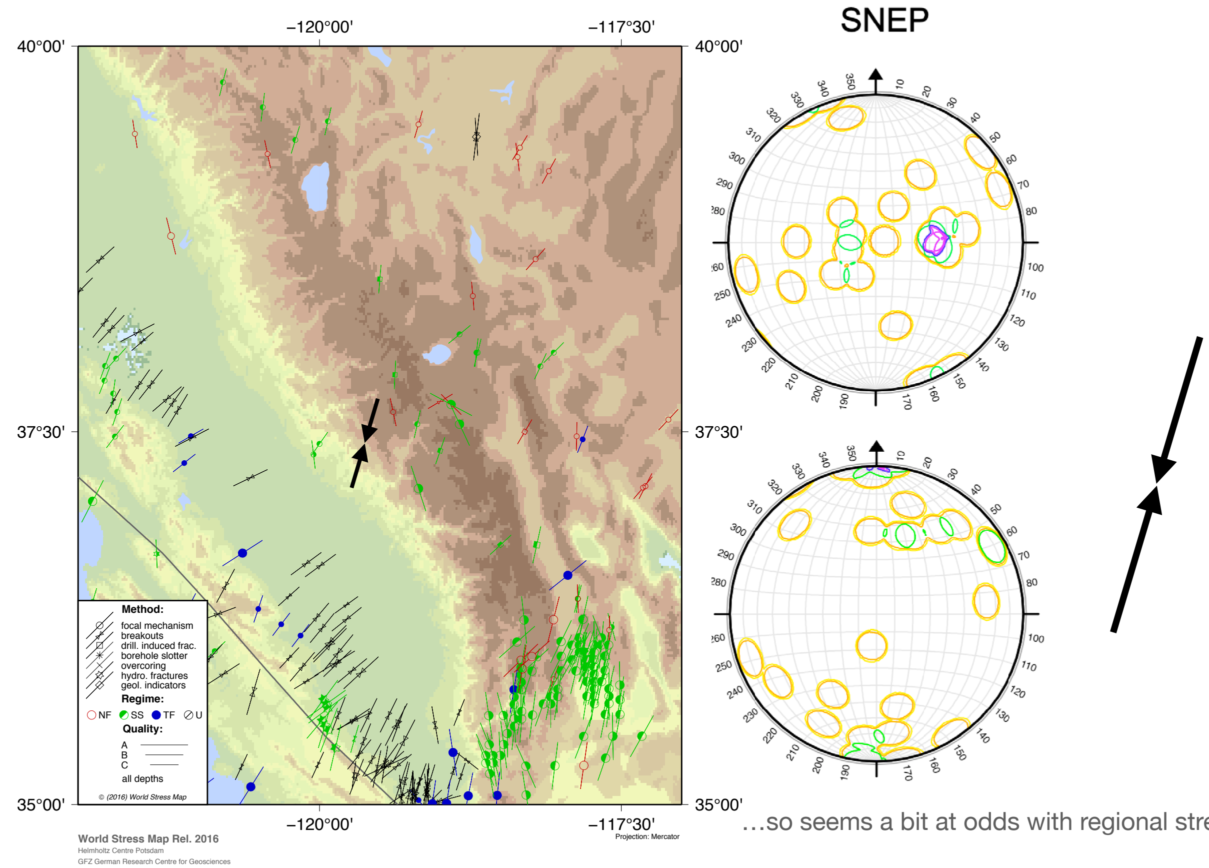
Foothills

SNEP



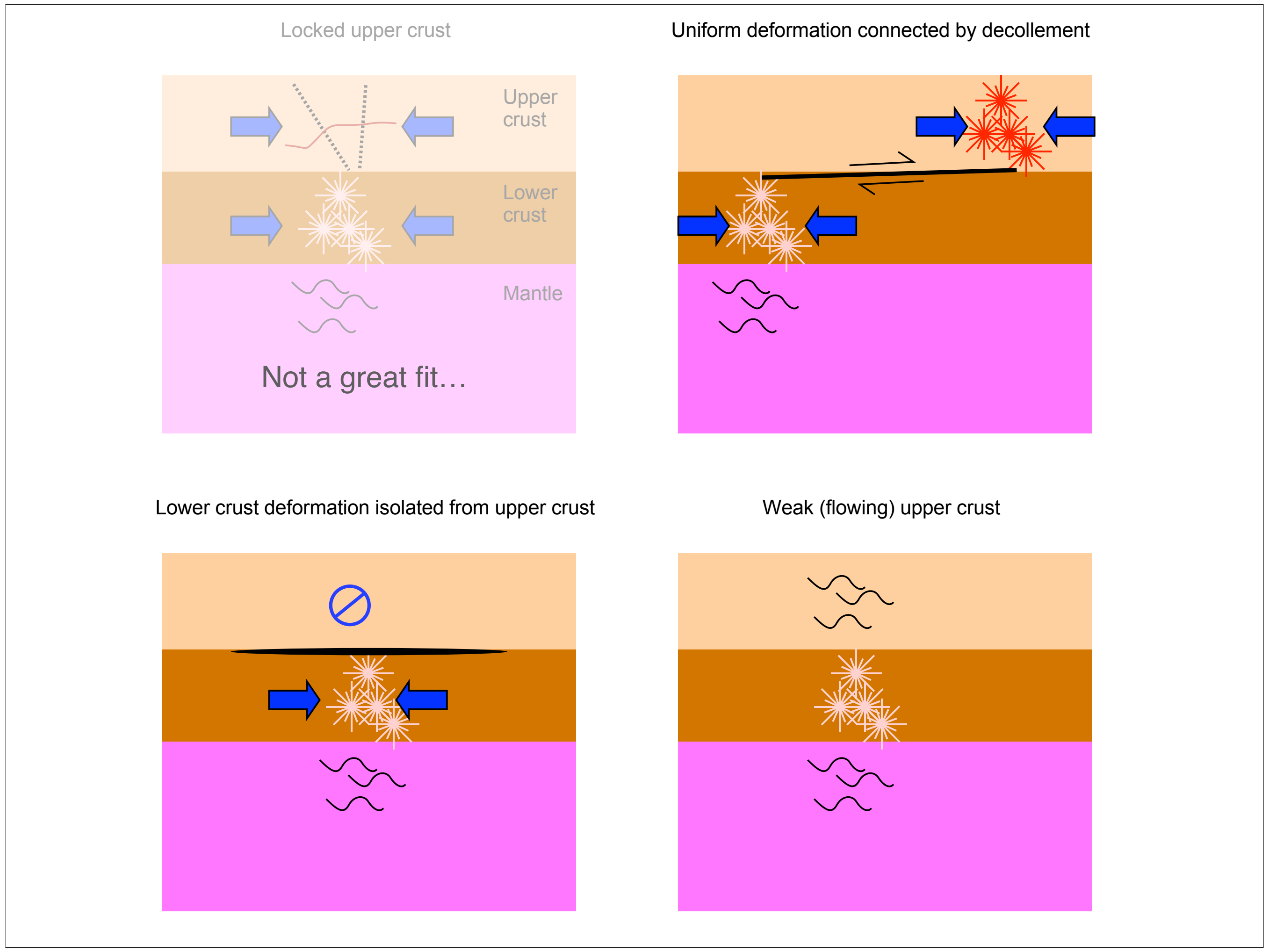
so generally horizontal shortening and vertical extension with tendency toward steep reverse or flat faults

Also the mechanisms are not trending towards strike-slip.



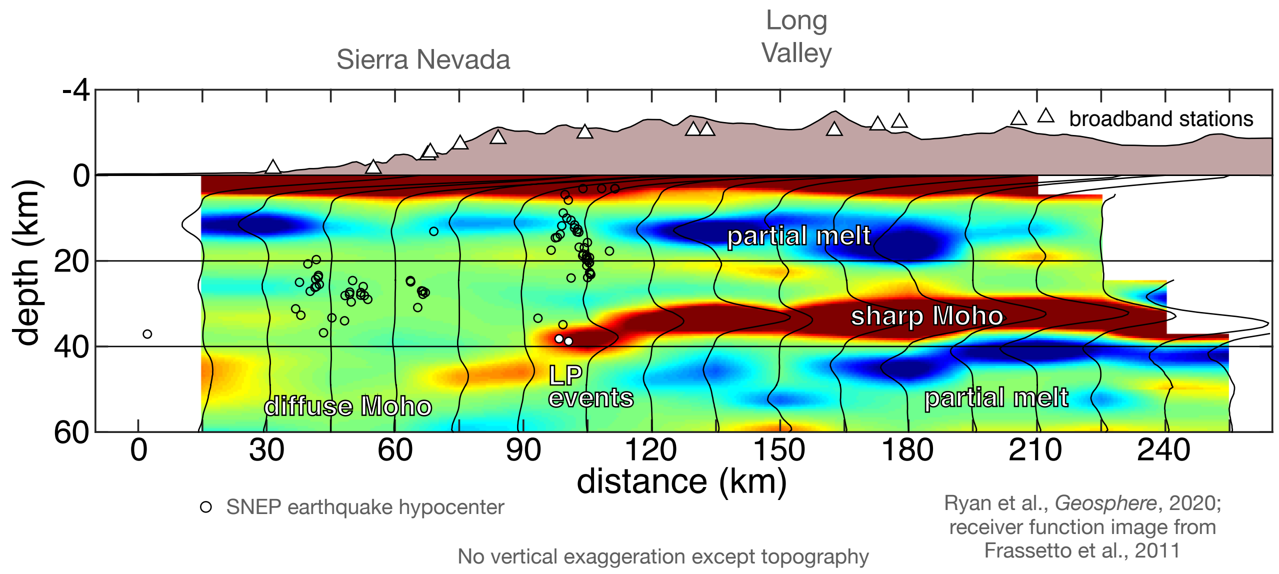
…so seems a bit at odds with regional stresses

Not the same as world stress map, which shows extension or strike-slip in foothill regions. And not N-S shortening.

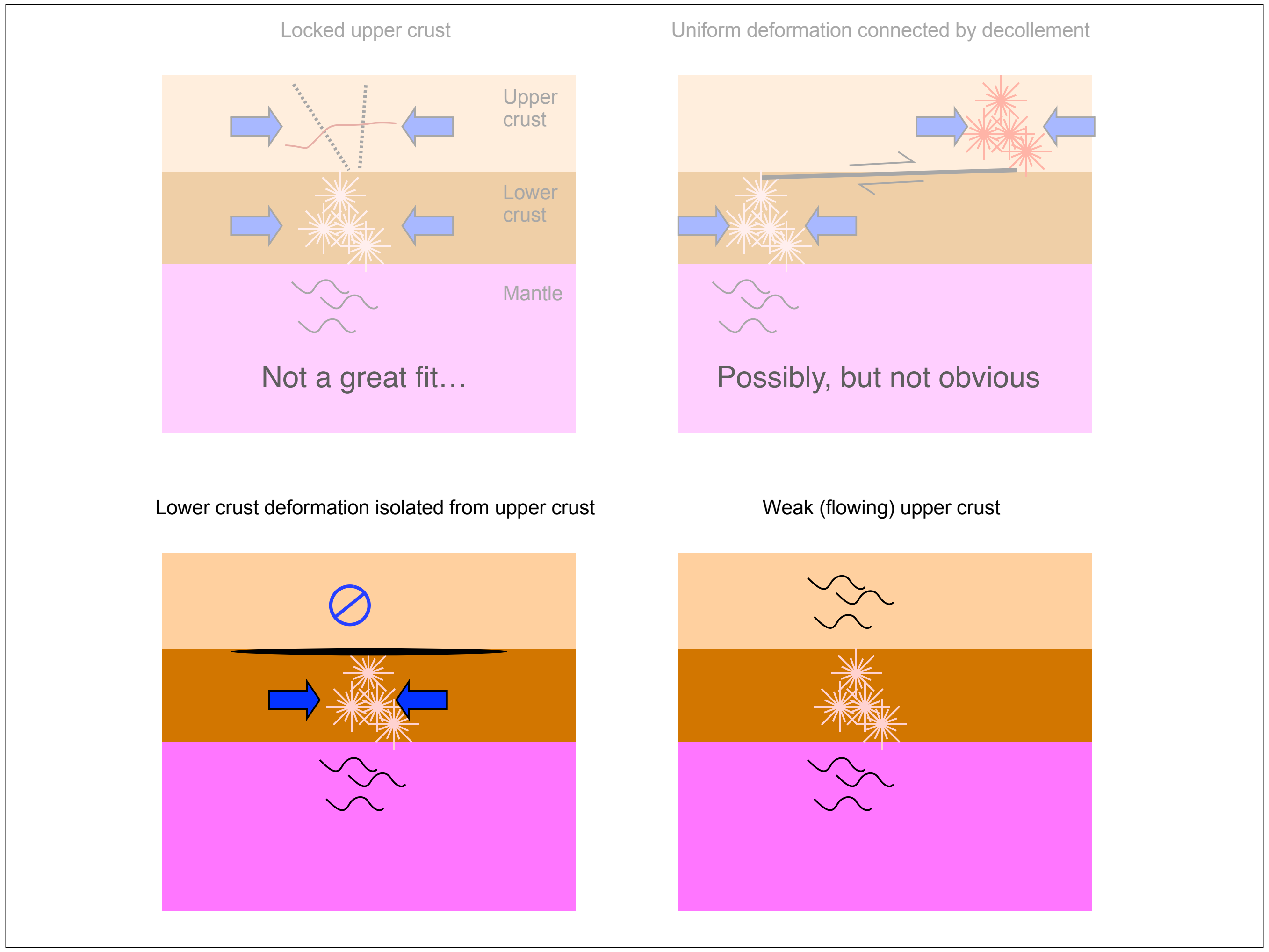


So the mechanisms aren't terribly consistent with a locked upper crustal fault responding to regional stresses.

Is there a decollement?

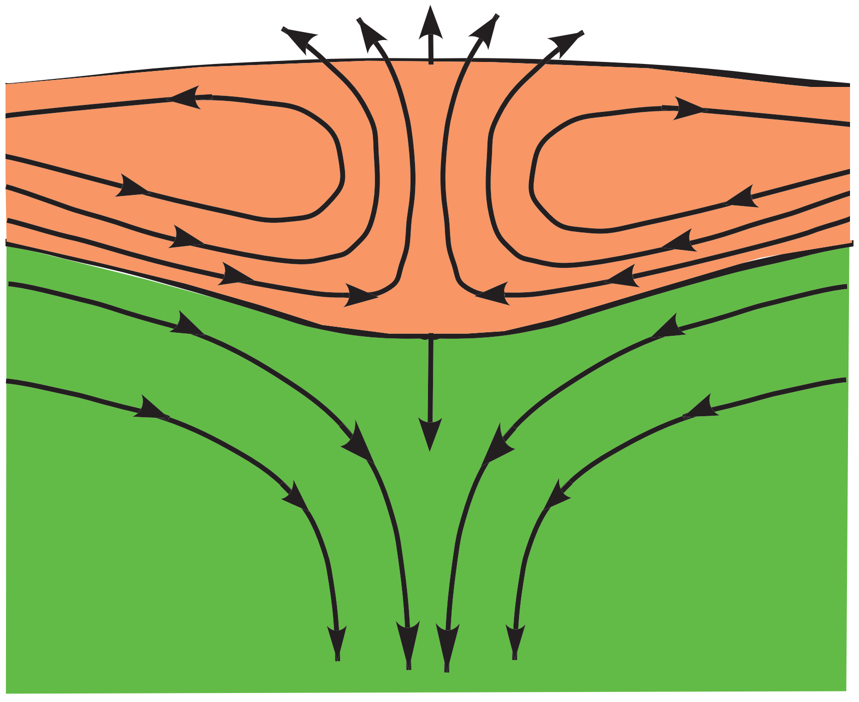


If there is a decollement, probably would be here. But no structure showing up in either structure or in seismicity.



So top two not great. How about the bottom two?

Decoupling of lower and upper crust



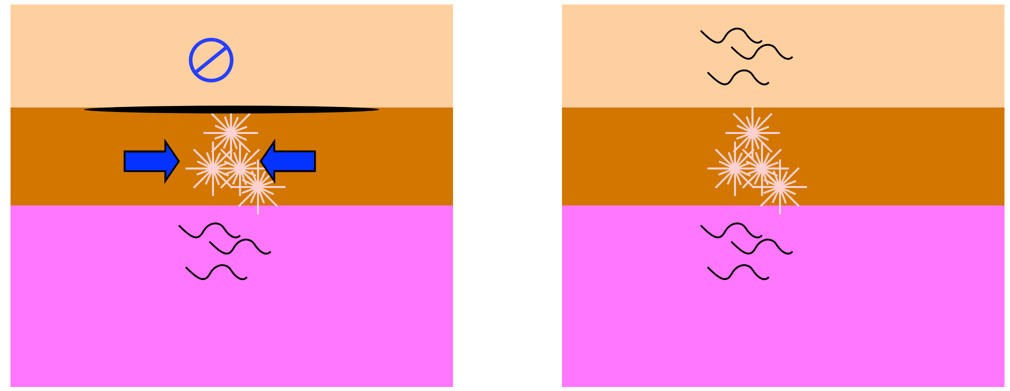
Molnar, *Tectonics*, 2015

Could unstable mantle lithosphere drive lower crustal convergence?

Molnar (2015) showed that for certain rheologies and mantle velocities that the lower crust could be entrained into a thickening area above a mantle downwelling while the upper crust might be in extension or neutrally deforming.

Lower crust deformation isolated from upper crust

Weak (flowing) upper crust



Plausible if driven from below

Consistent with focal mechanisms

What is top detachment?

Physics of a “fluid” upper crust?

Would require reexamination of understanding of rheology in low-strain rate regions.

So maybe these quakes are caused by shortening in the lower crust over some mantle downwelling, but if so, then there should be a detachment above which we don’t directly image. The alternative is that there is some unusual rheology in the upper crust that does not fail seismically.

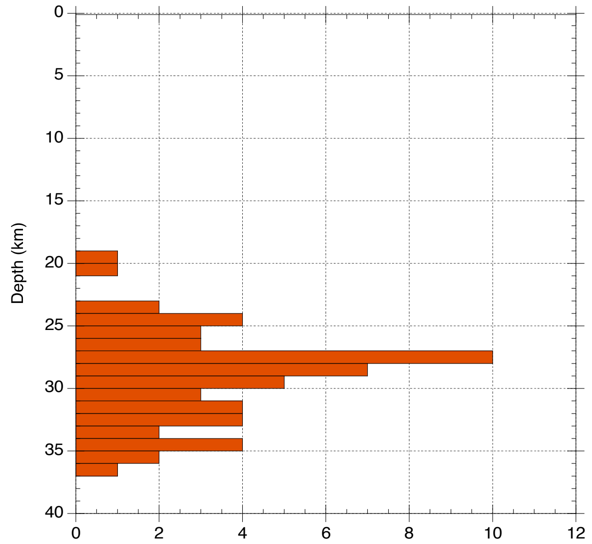
Three Questions:

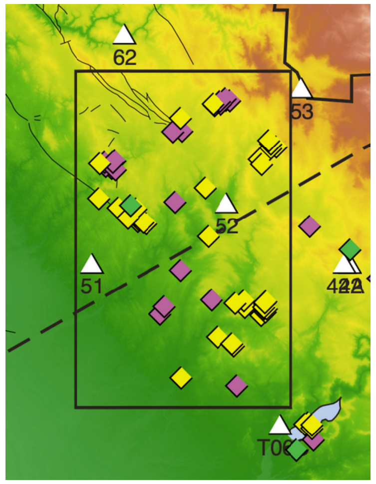
1. How special is this?-**Seems pretty special**

2. How might this work? **-Different rheology or above a drip?**

3. What about regional tectonics?**-possible foundering start?**

SNEP earthquake depths, Foothills cluster
2005-6, Ryan et al., *Geosphere*, 2020

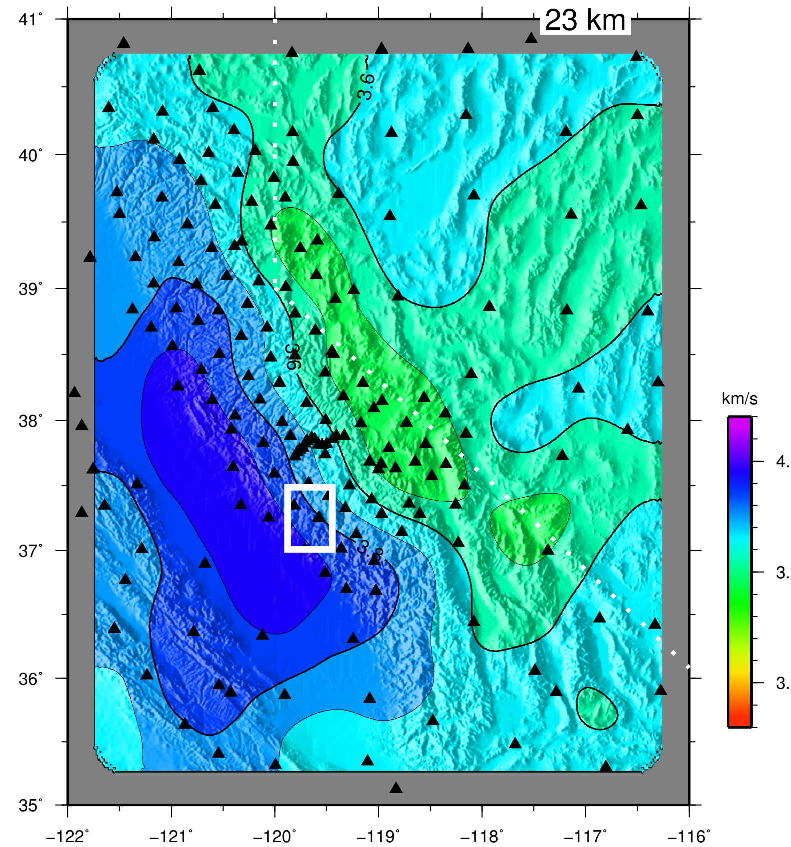




So this seems a worthy target of study. [Oral talk ended here]

Potential issues:

-Quakes located with 1-D velocity structure; possibly biases depths?



Josh Stachnik, unpublished SNEP ANT, used in Jones et al., 2014

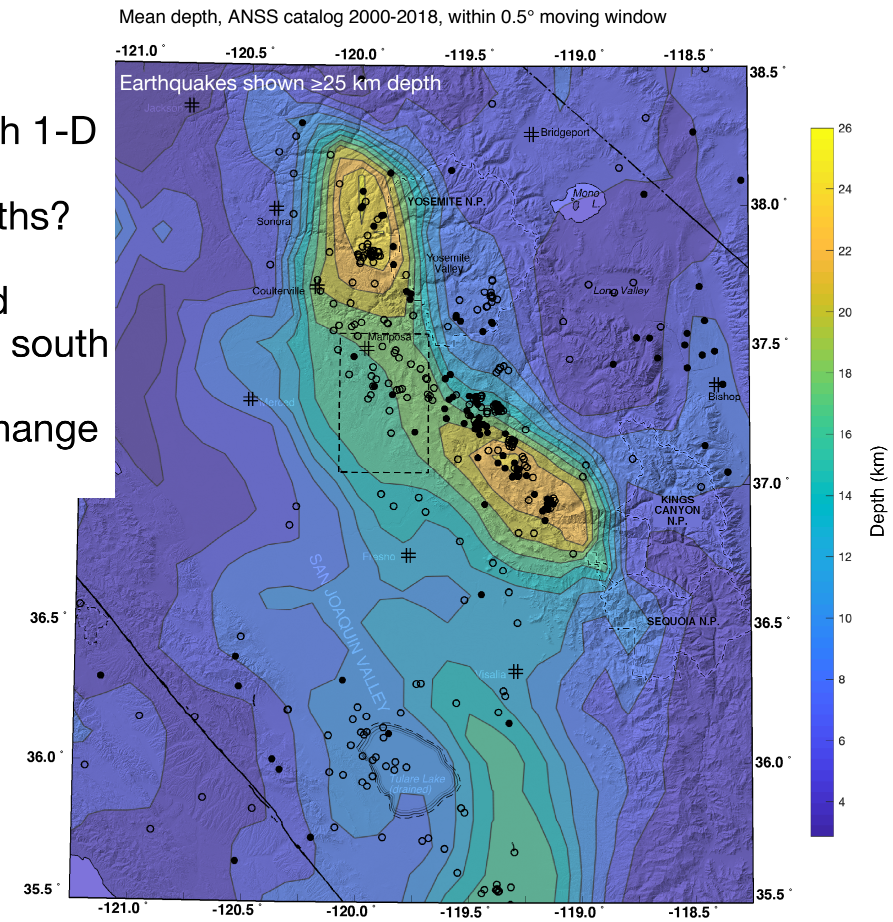
[Not shown in talk]. All the previous seismicity was located in a 1-d model, but there are pretty profound variations in crustal velocities; would be good to redo this in 3-D.

Potential issues:

-Quakes located with 1-D velocity structure; possibly biases depths?

-Lots of unexamined quakes to north and south

-As always, could change with time.



…and the catalog seismicity suggests that even deeper quakes are to the north and southeast of the area where Ryan et al. focused.

Conclusions

Sierra foothills has a persistently strange cluster of earthquakes limited to the lower crust.

This might be globally unique: does it reveal hitherto unrecognized rheologies?

Focal mechanisms suggest a possible horizontal shortening in the lower crust.

Is this the start of delamination or foundering?

More work could examine the broader extent of these events suggested from ANSS catalog.