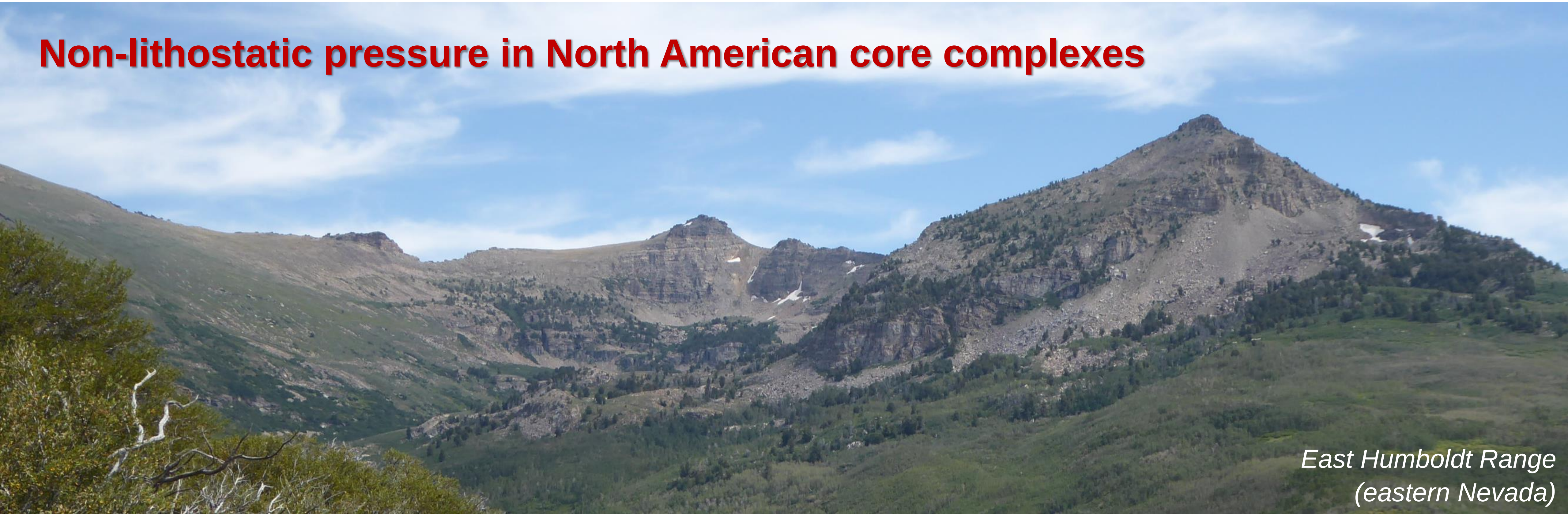
Non-lithostatic pressure in North American core complexes



East Humboldt Range (eastern Nevada)

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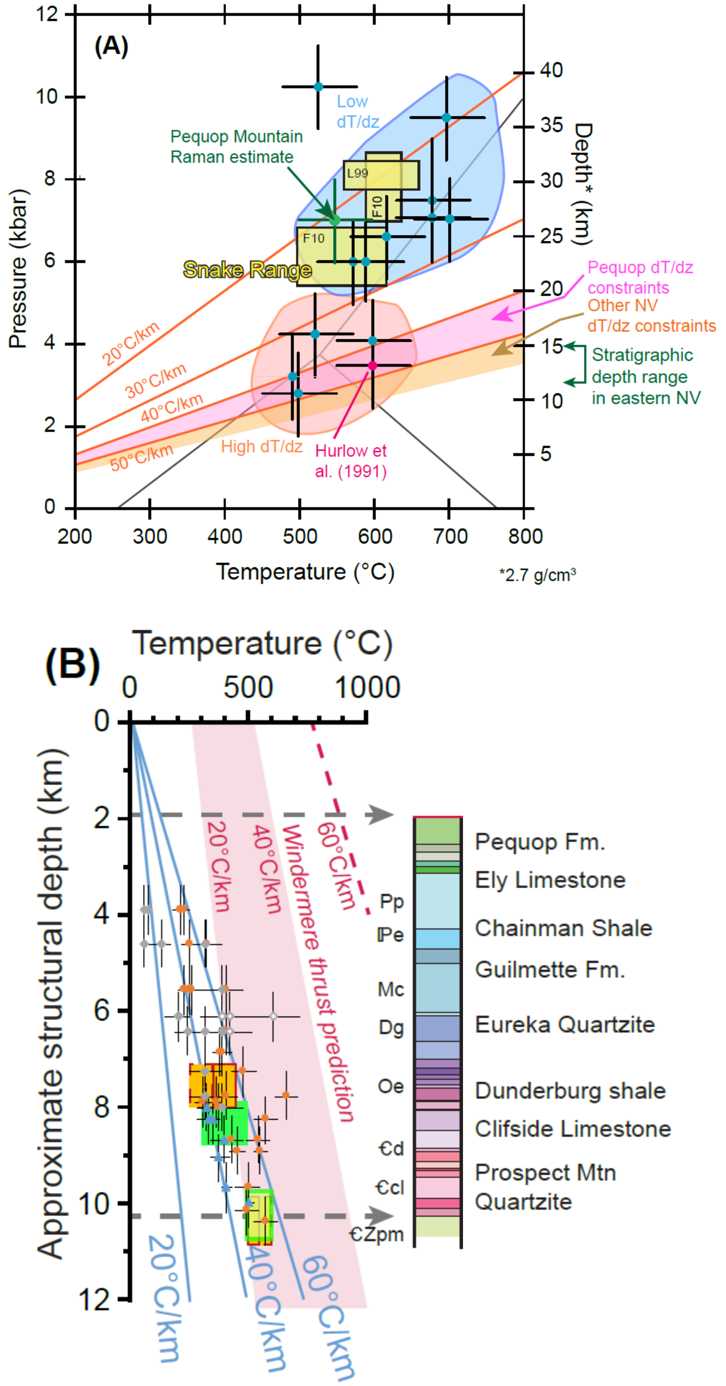
We argue the Ruby-East Humboldt and Snake Range core complexes record <u>non-lithostatic pressures</u>

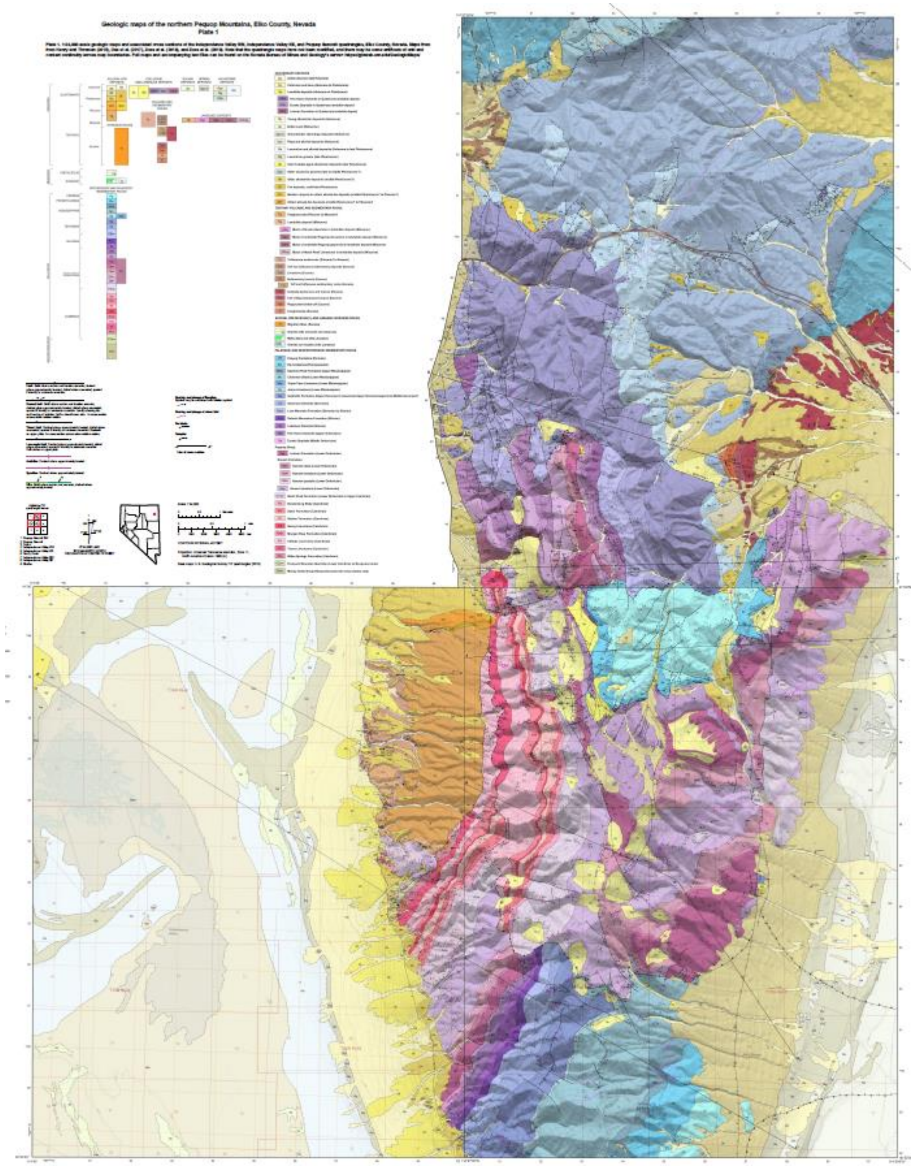
There has been debate for decades whether rocks were exhumed from 25-30 km (6-8 kbar, if lithostatic) ***or*** 10-12 km (2-3 kbar). Field relationships favor less burial and *P-T* estimates favor deep burial. We provide evidence for limited burial based on:

1. Observations of a high geothermal gradient (30-40°C/km) from a traverse across stratigraphy is at odds with predictions from high *P-T* estimates (≤25°C/km)
2. Field evidence of continuous stratigraphy that was not deeply buried
3. The implied deep-burial thrust faults would have an atypical geometry for North American and other global fold-thrust belts
4. A relatively new, economically important gold deposit mineralized at depths < 5km, but deep burial models suggest deeper mineralization

The consistent high *P* estimates over the past decades, despite evidence against deep burial, may be compelling evidence for non-lithostatic pressures



Geologic mapping still required to solve big tectonic problems:
STATEMAP funding through the National Cooperative Geologic Mapping Program of the US Geological Survey makes this possible



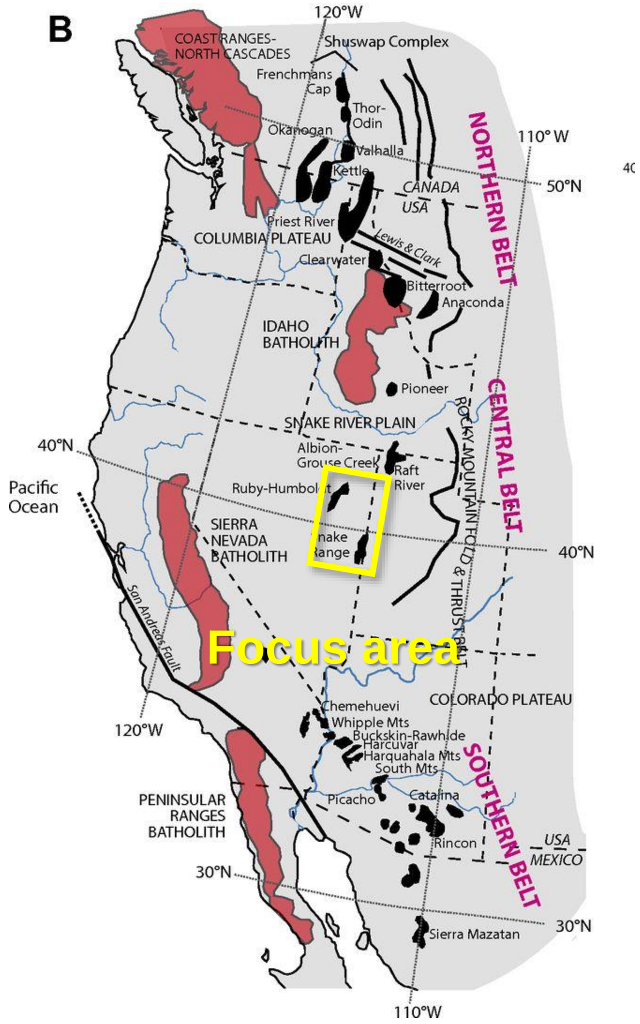
Three new 1:24k quads from NE Nevada:
Henry and Thorman (2015);
Zuza et al. (2018, 2019)

USGS
science for a changing world

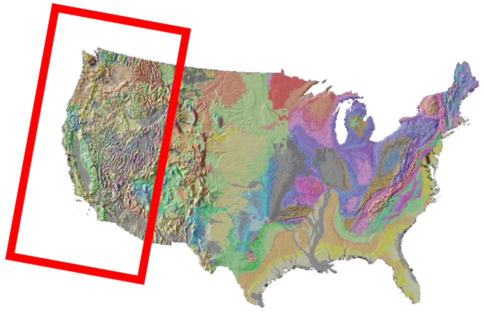
Maps accessible at https://gisweb.unr.edu/GeologicMaps/

Cordilleran core complexes across western North America concentrate within previously thickened crust

Present-day exposures

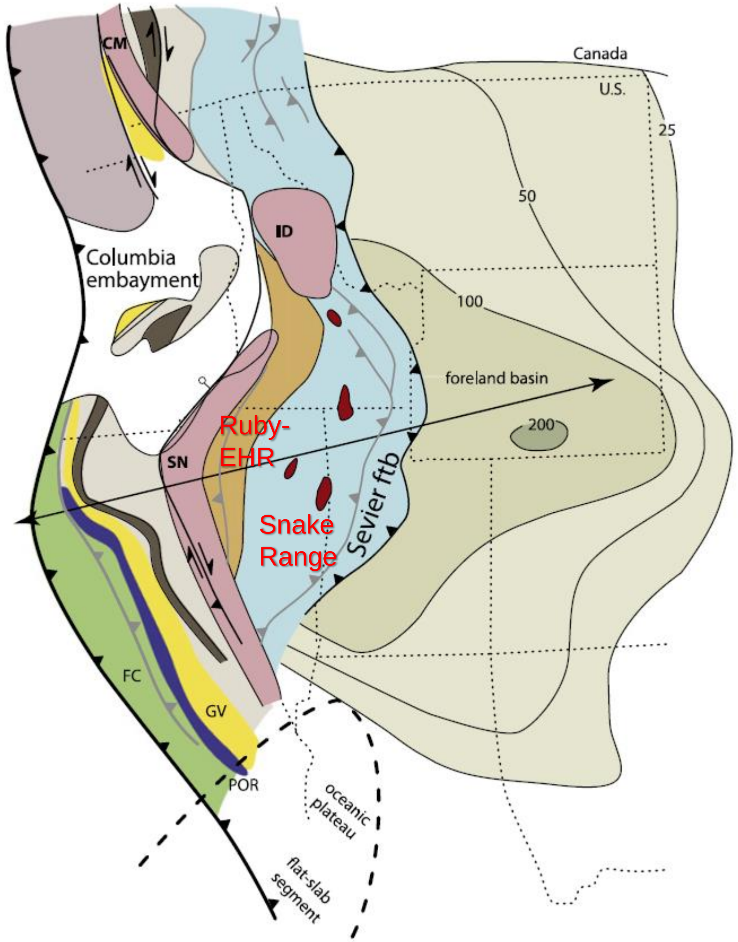


Whitney et al. (2013 GSAB)



This study is focused on the Ruby-East Humboldt Range and Snake Range core complexes (see yellow box to the left)

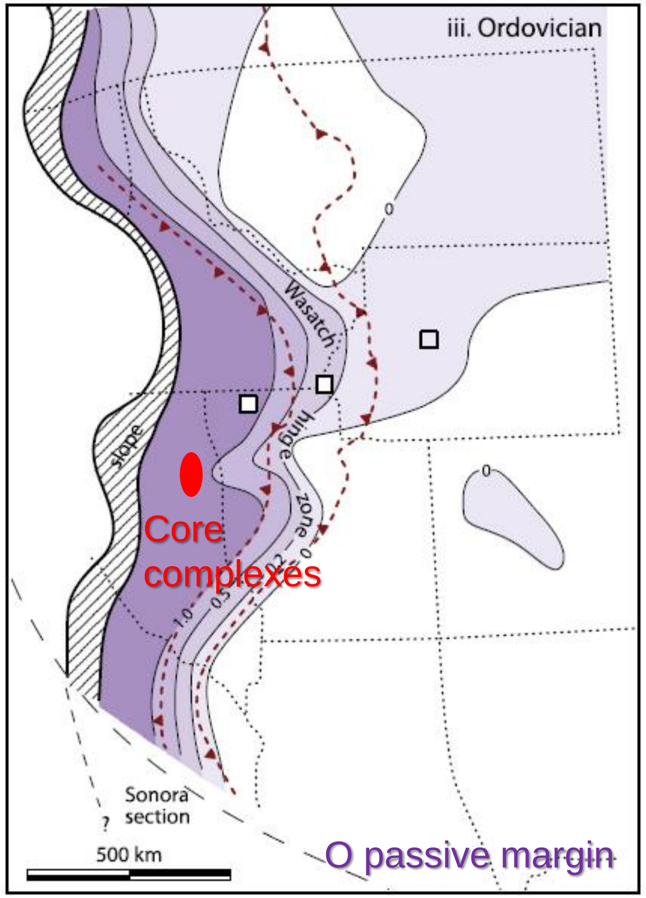
Late Cretaceous paleogeography



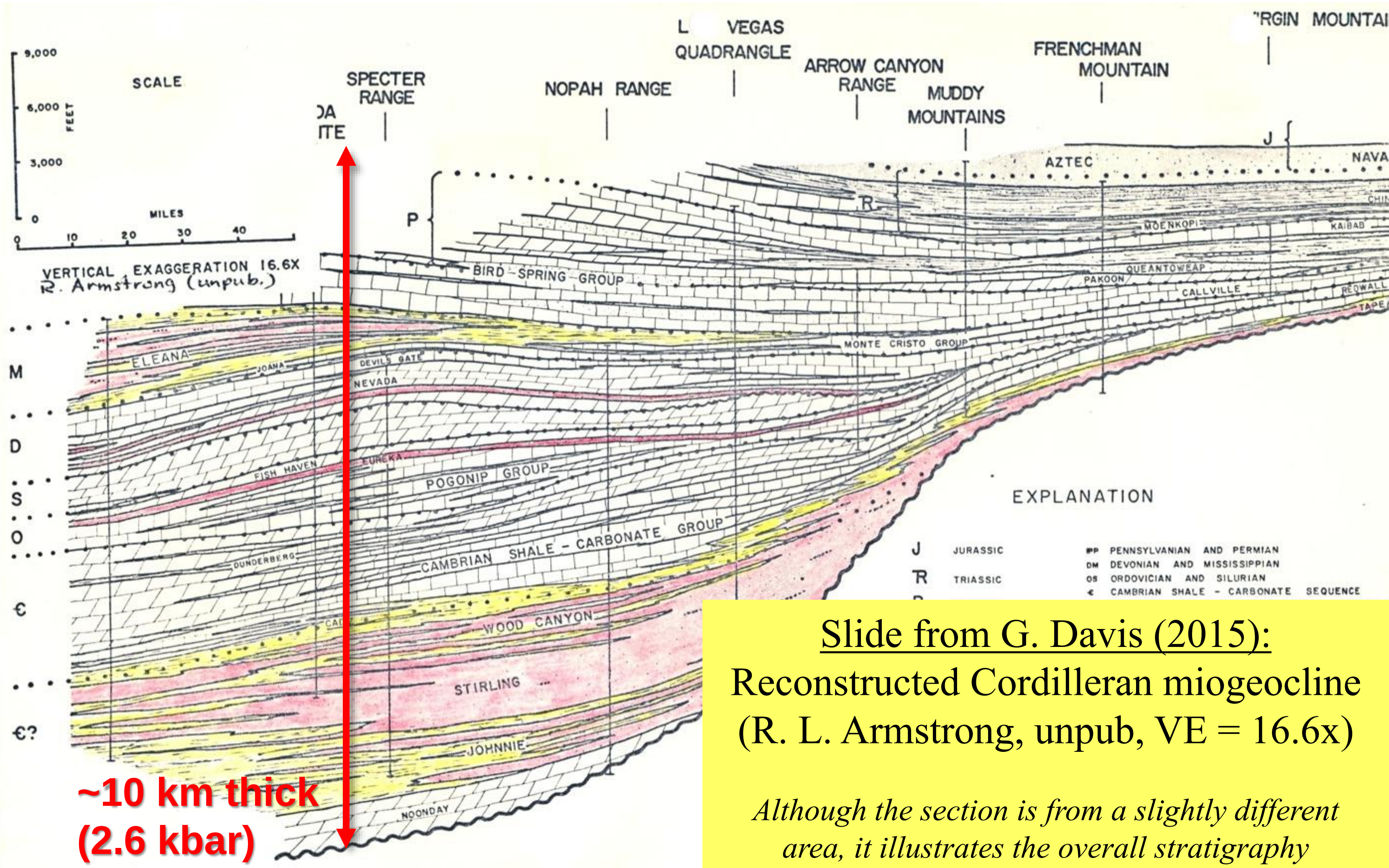
Yonkee and Weil (2015 Earth-Science Reviews)

For these core complexes, the depth of the rocks that they exhume is debated:

- *P-T* estimates suggest peak burial to 25-30 km (6-8 kbar, if lithostatic; “deep,” in this study)
- The western US is covered by incredibly well characterized Paleozoic passive margin (see below), which allows for confident field-base palinspastic restorations. These restorations always suggest shallow burial (i.e., the rocks were exhumed from “stratigraphic depths” of 10-12 km, 2-3 kbar).



Yonkee and Weil (2015 Earth-Science Reviews)



Slide from G. Davis (2015):
Reconstructed Cordilleran miogeocline
(R. L. Armstrong, unpub, VE = 16.6x)

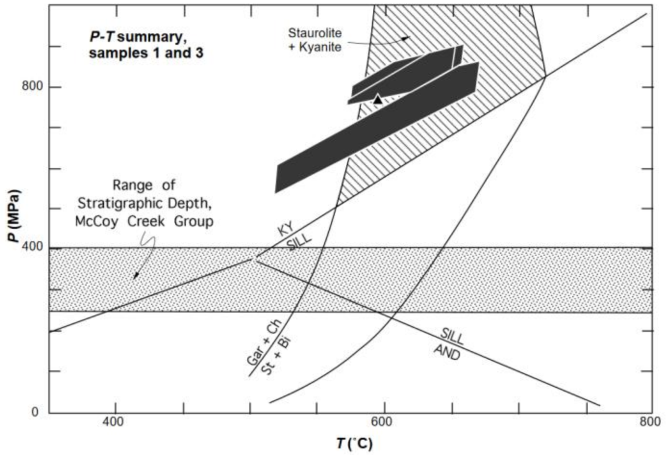
Although the section is from a slightly different area, it illustrates the overall stratigraphy

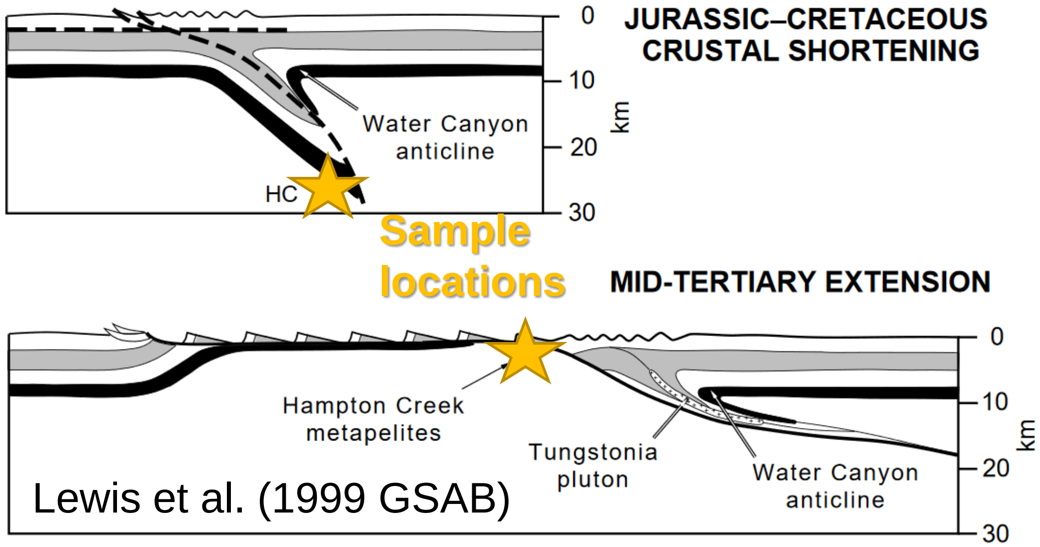
Whitney et al. (2013)

Were the lower passive margin rocks buried to depths of 25-30 km (6-8+ kbar)?

- Lithostatic interpretation of *P*-*T* estimates say yes
  (also see Hodges et al., 1992; McGrew et al., 2000; Cooper et al., 2010)
- Remarkable consistency in pressures, given two distinct core complexes and variety of methods over the years (1990s to present)

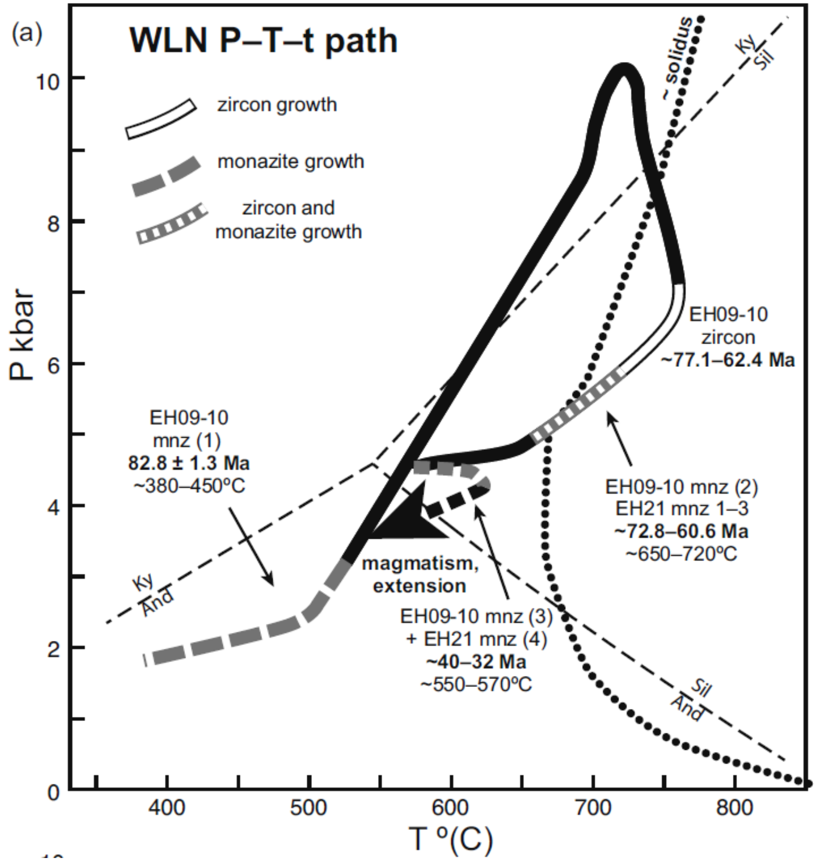
Snake Range





Lewis et al. (1999 GSAB)

Ruby Mountains-East Humboldt Range



Hallett and Spear (2015 Am. Min.)

Were the lower passive margin rocks buried to depths of 25-30 km (6-8+ kbar)?

- Geologists that have been mapping these rocks for decades argue against burial significantly deeper than stratigraphic depths (10-12 km) (literature from C. Thorman, E. Miller, P. Gans)
- Two primary arguments, among others:
  - Deep burial models require major thrust faults to bring basal section to 25-30 km depths; there is no observation of such structures
  - A lack of significant stratigraphic omission rules out removal of 10s+ km of stratigraphic section during normal-sense core complex activity
  - **No field evidence for structures that brought the rocks this deep, and no field evidence for structures returning from this depth**

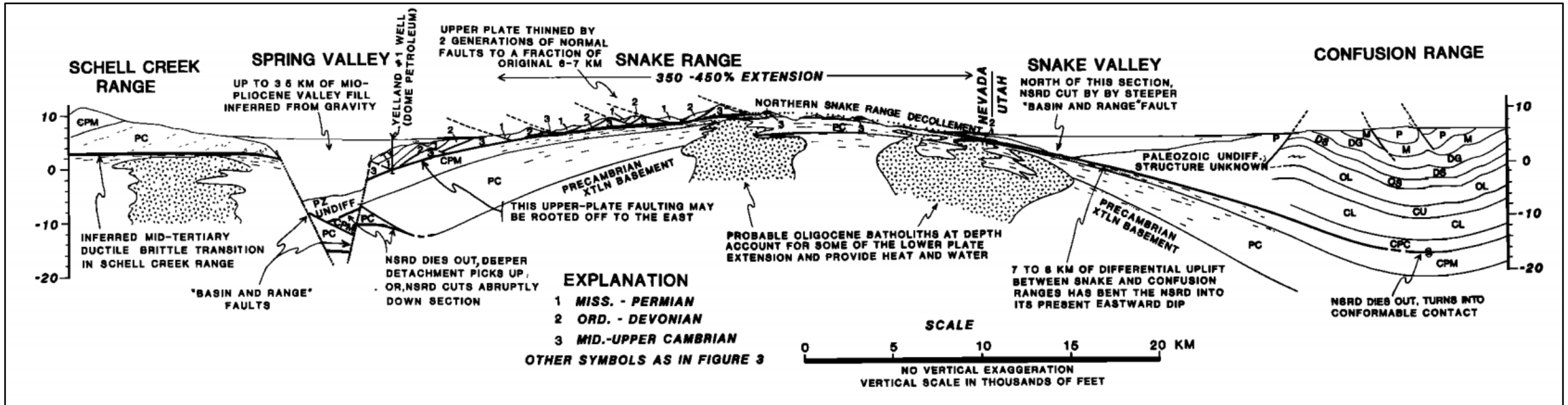
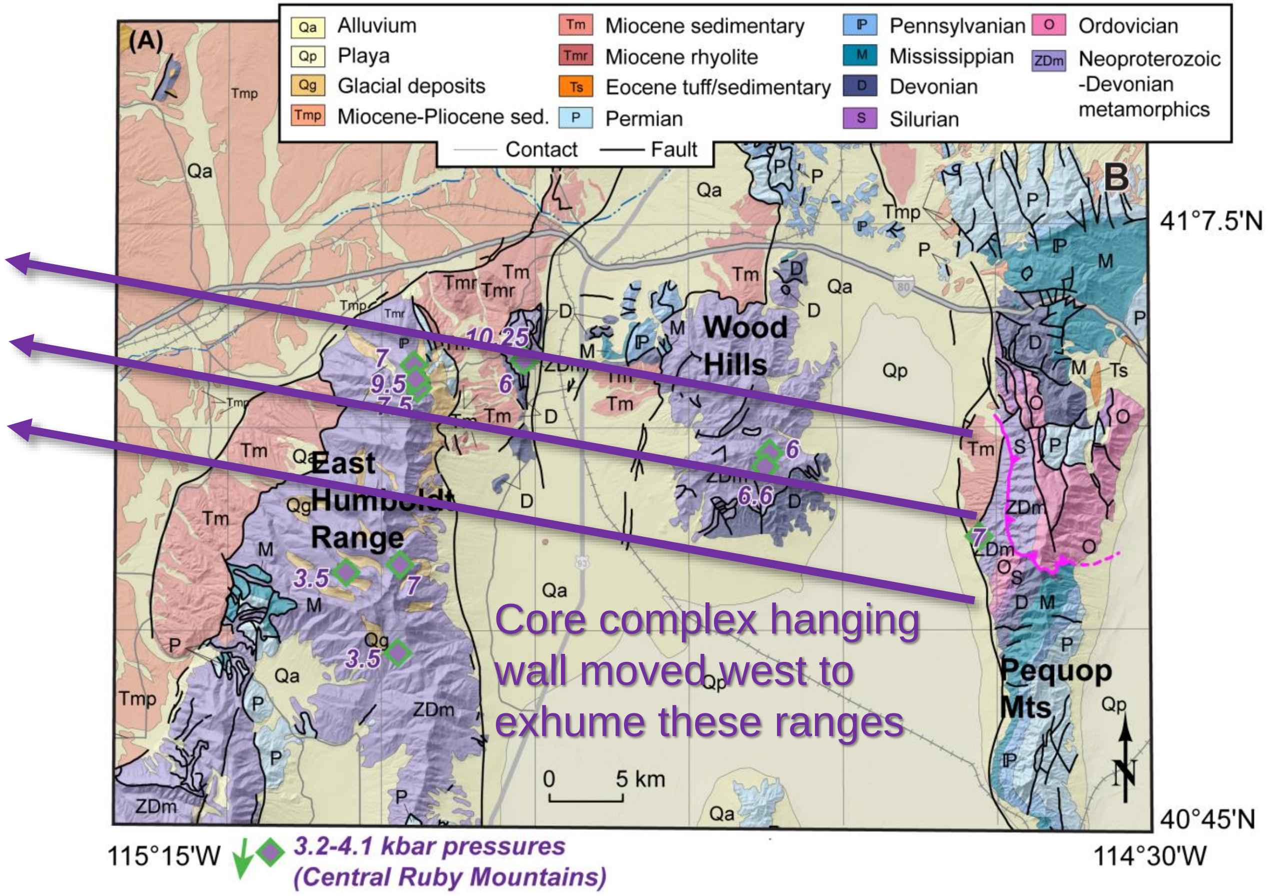


Fig. 10. Interpretive geologic cross section from the Schell Creek Range to the Confusion Range.

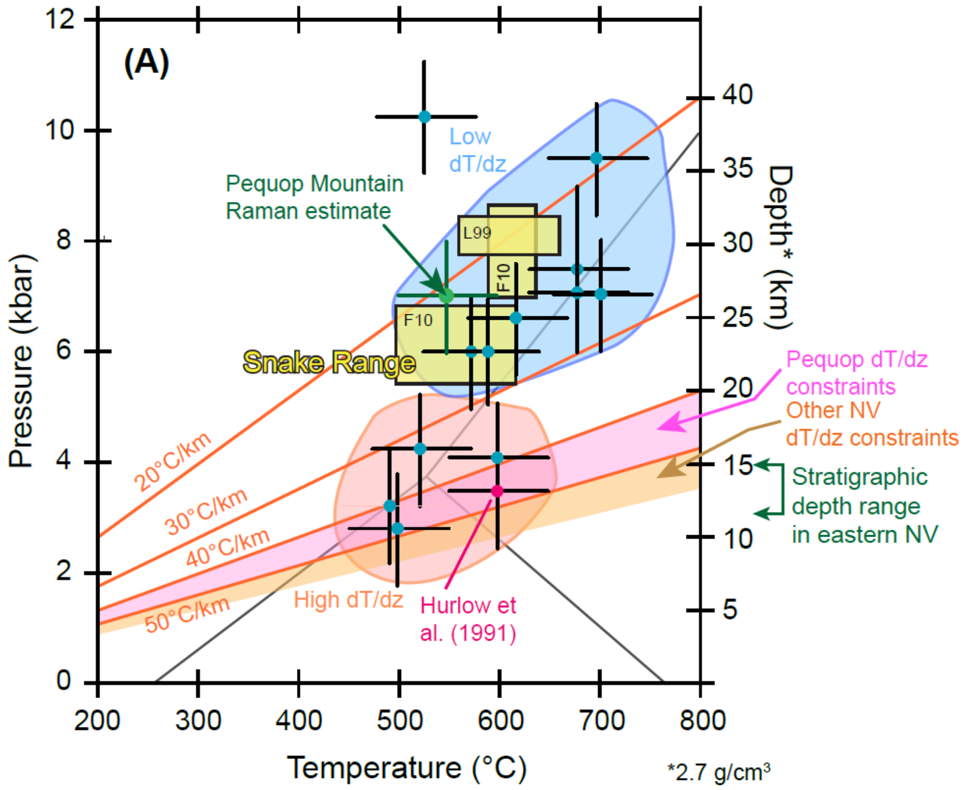
In this classic Miller et al. (1983 Tectonics) cross section, the Snake Range detachment is drafted juxtaposing Cambrian footwall rocks (CPM, Prospect Mountain quartzite) against Cambrian hanging wall rocks (CPC, Pole Canyon)

With this setup, we test deep vs stratigraphic burial in the Ruby-East Humboldt core complex, but note that our implications apply to the northern Snake Range

- What was the paleo-geothermal gradient? Which model does this best fit predictions of?
- Is there any field evidence for deep burial?



Study area, with deeper more deformed rocks to the west and stratigraphically higher rocks to the east (purple shows *P* estimates, kbar) (figure from Zuza et al., in press Lithosphere)



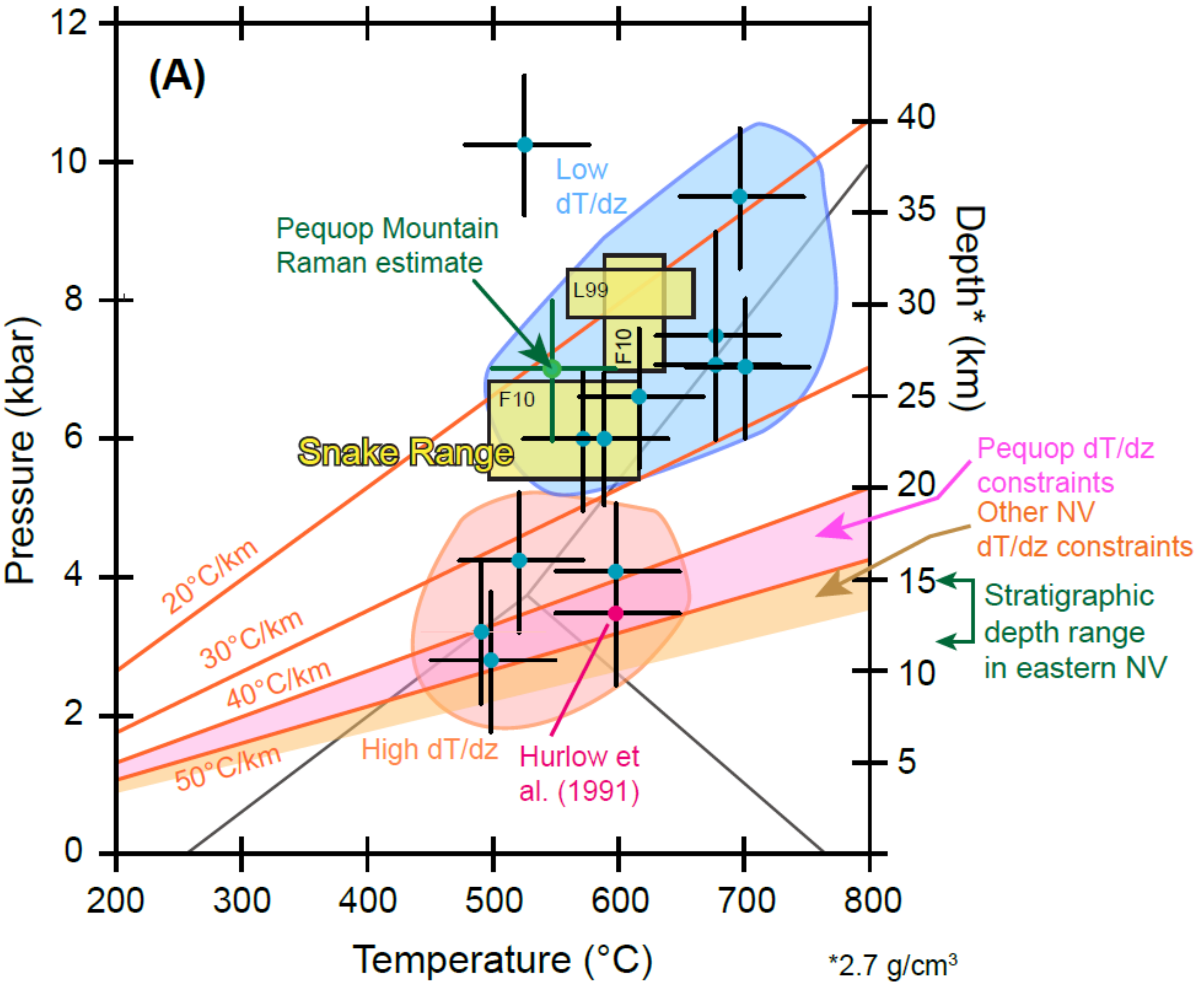
Compilation of Ruby-East Humboldt (data points) and Snake Range (yellow box) *P-T* estimates (sources at end of presentation)

P-T compilation:

- Two groups of *P*, limited *T* variation
- High *P* requires low geothermal gradients of ≤25°C/km
- Set of low *P* estimates not structurally separated from high *P* rocks; these estimates overlap predictions of stratigraphic burial
- Stratigraphic, low *P* requires high geothermal gradients of 30-40+°C/km

To test geothermal gradient, we compiled peak temperature (T_p) dataset from new and published data:

- RSCM
- CAI
- Calcite-dolomite thermometry



Peak temperature (T_p) dataset from new and published data:

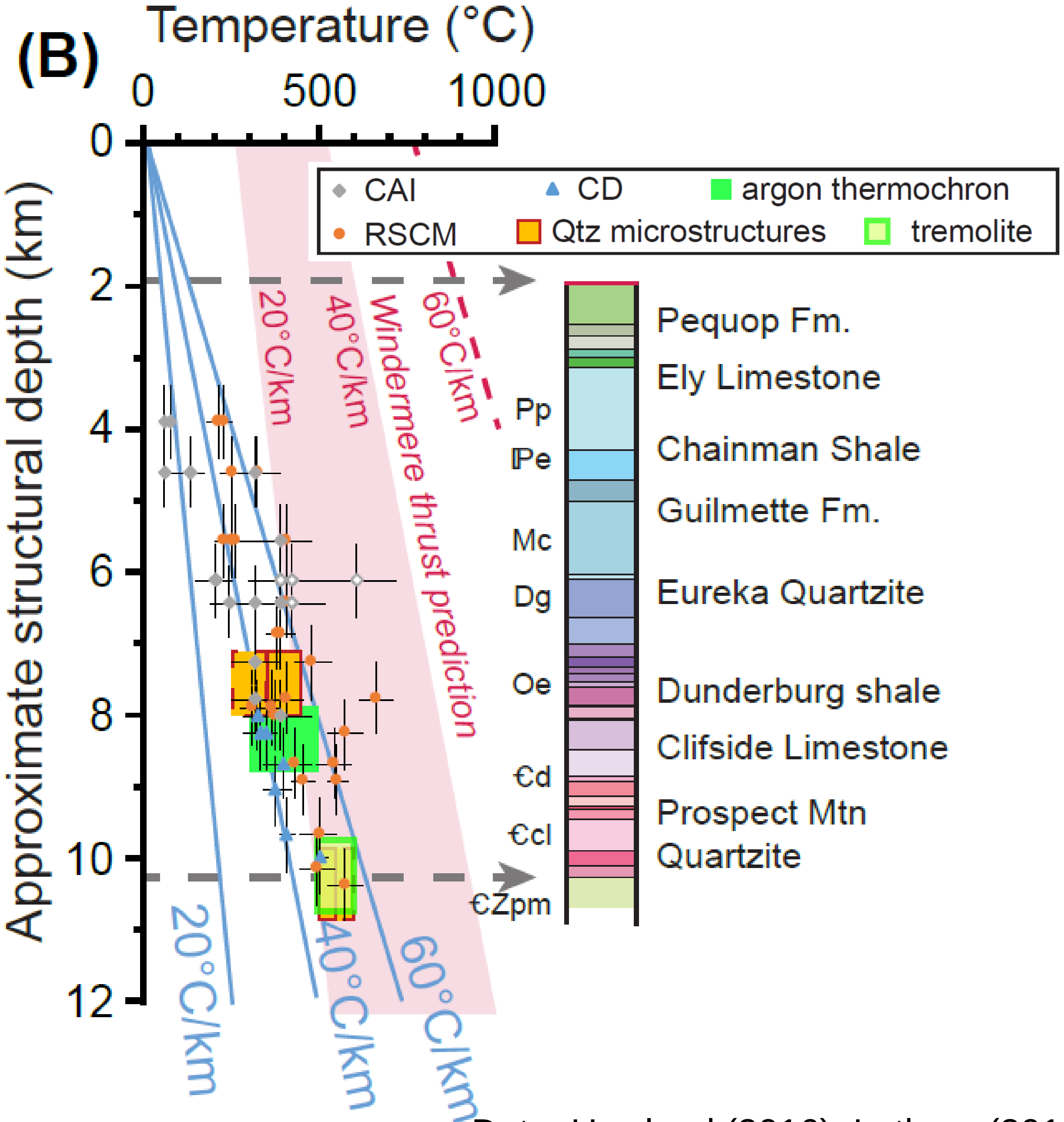
- RSCM
- CAI
- Calcite-dolomite thermometry

Red field shows predictions of published thrust-burial models (Camilleri and Chamberlain, 1997)

Data shows high ~40°C/km gradient

There is some spread, which we attribute to local thermal pulses and hydrothermal alteration

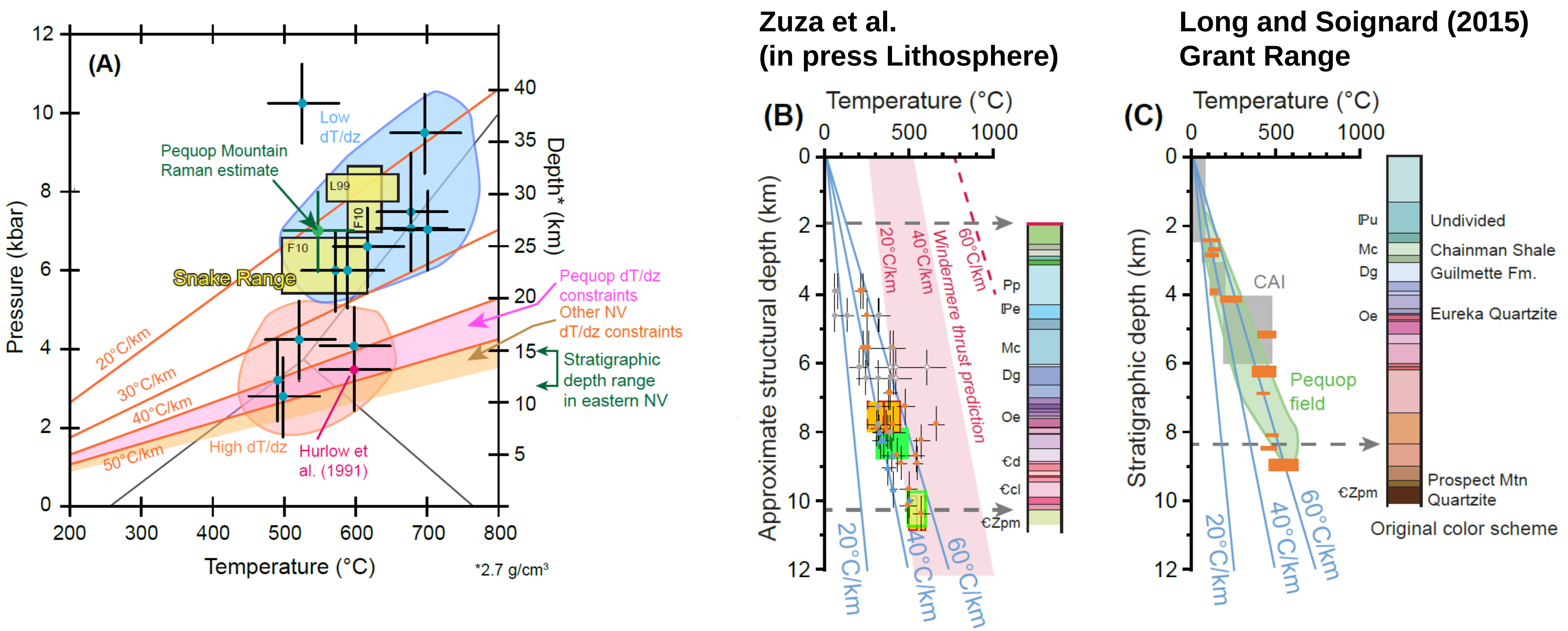
Some conodonts from CAI analyses had a sugary cryptocrystalline that we interpreted as hydrothermal alteration



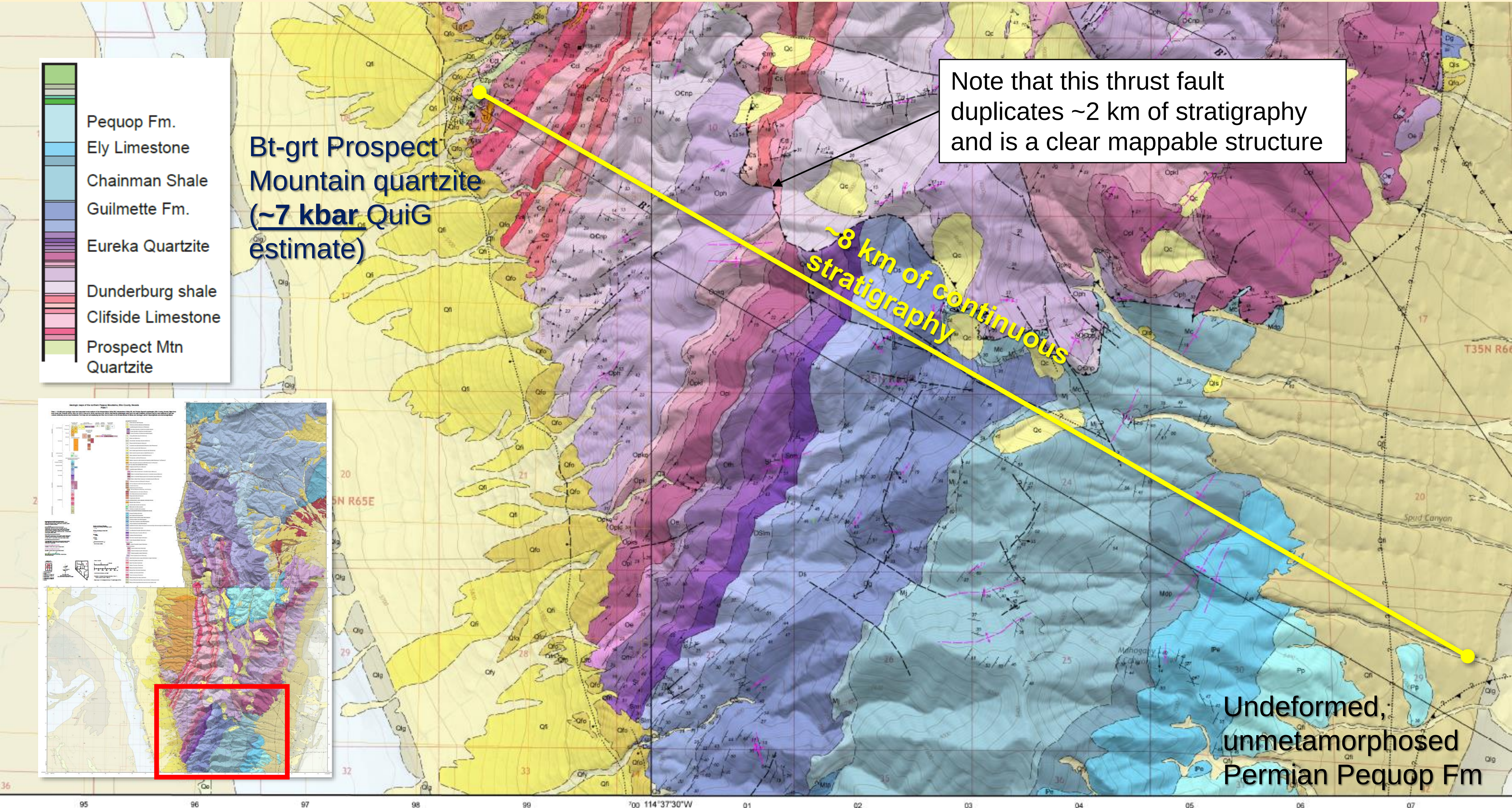
Data: Howland (2016), Latham (2016), and Zuza et al. (in press Lithosphere)

In summary, temperature data is at odds with deep burial

- Eastern NV paleo-thermal gradients are >40°C/km
- Required gradient of ≤25°C/km is at odds with pervasive intrusions and mineralization
- Other orogen’s have high gradients: Andes or Tibetan Plateau
  (e.g., Francheteau et al., 1984; Derry et al., 2009; Cardoso et al., 2010)

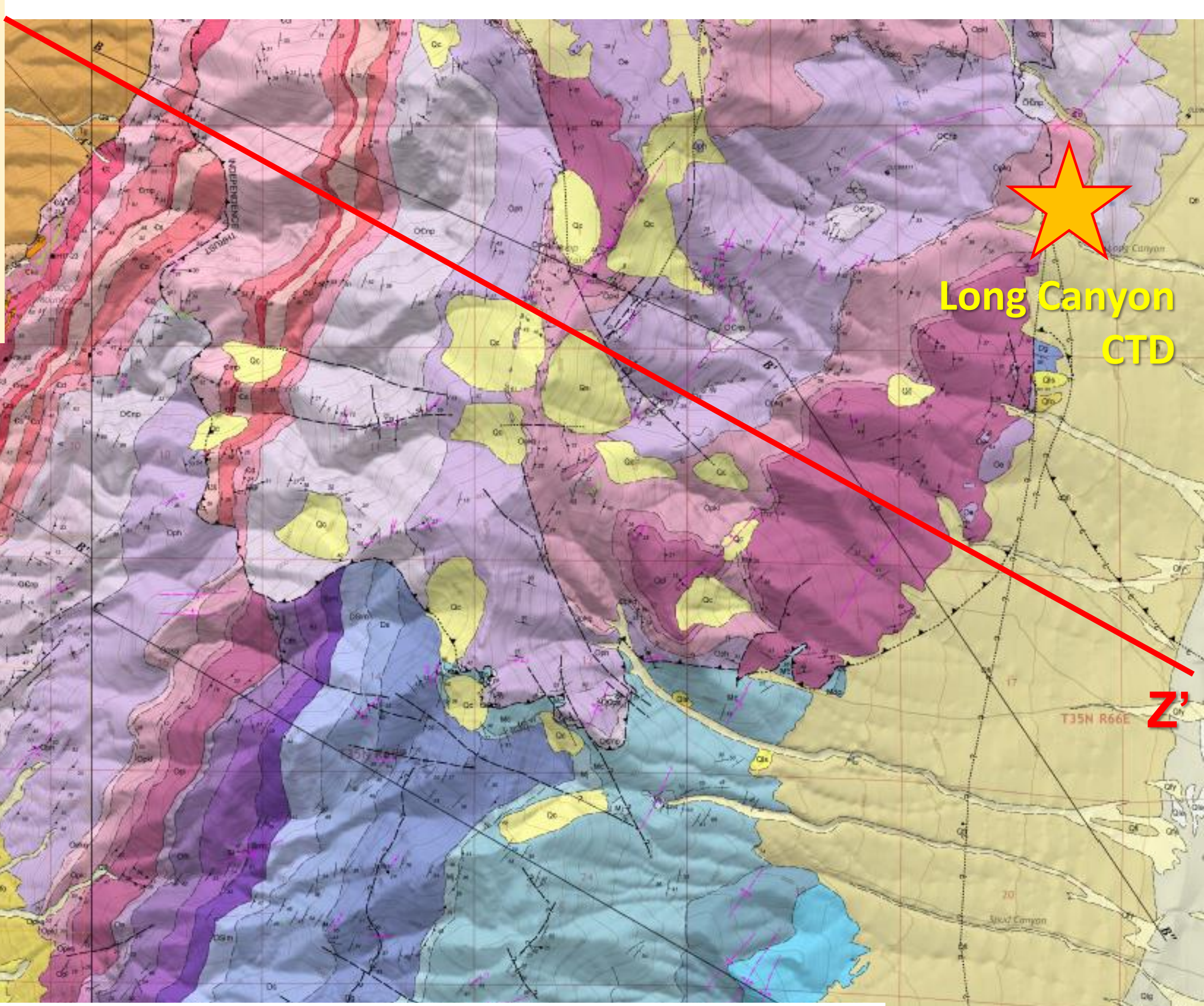


Field relationships at odds with deep burial Maps from Henry and Thorman (2015) and Zuza et al. (2018, 2019)

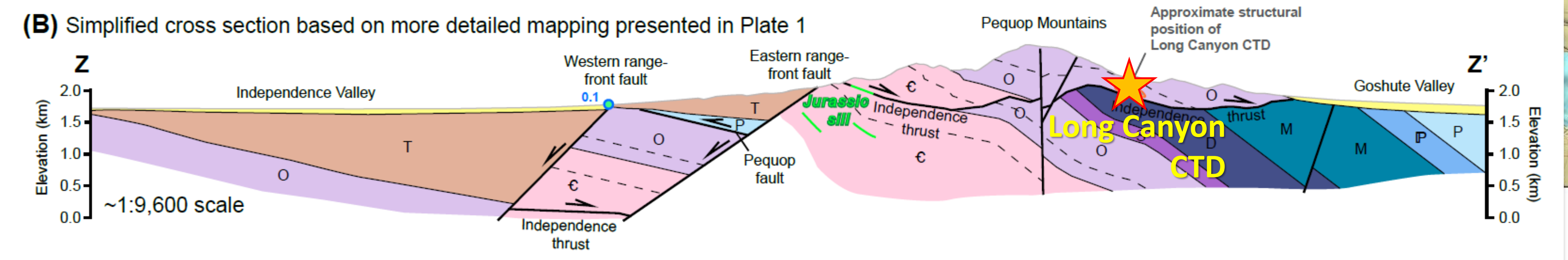


Carlin-type gold deposit (CTD) at Long Canyon probably mineralized in the Eocene at depths of < 5km

Available evidence suggests range exhumation started in late Oligocene-Miocene—after Eocene mineralization—so deep burial models would require mineralization at depths >15 km, atypical of CTDs in Nevada



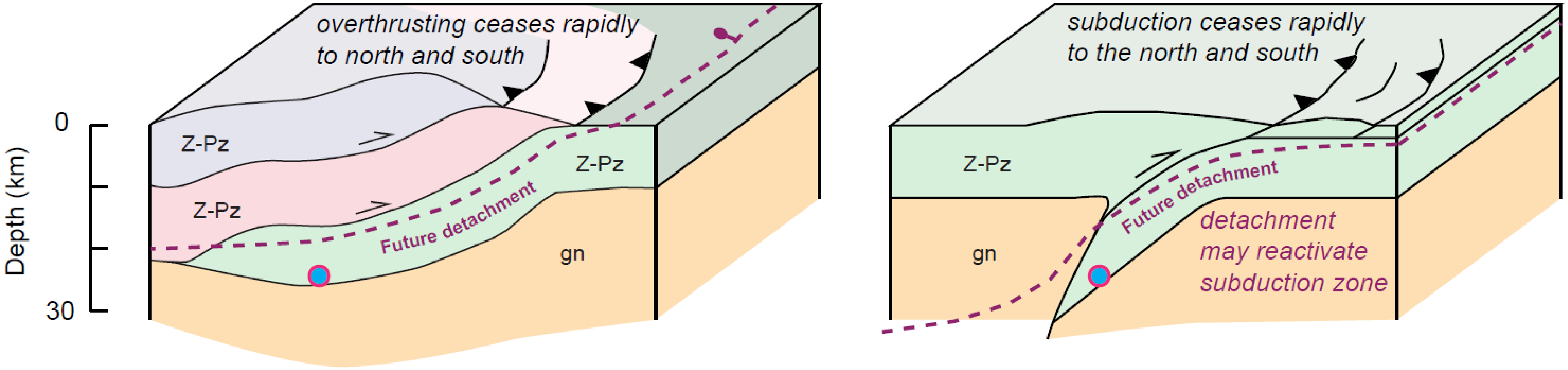
Estimated gold is 1.23 million ounces (https://www.mining-technology.com/projects/long-canyon-gold-mine-nevada/)



Models to account for deep burial

Overthrusting model
(Camilleri and Chamberlin, 1997)

Intracontinental subduction
(Lewis et al., 1999; McGrew et al., 2019)

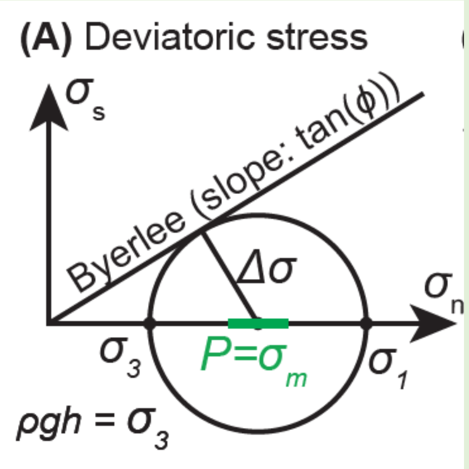


Issues with these models include:

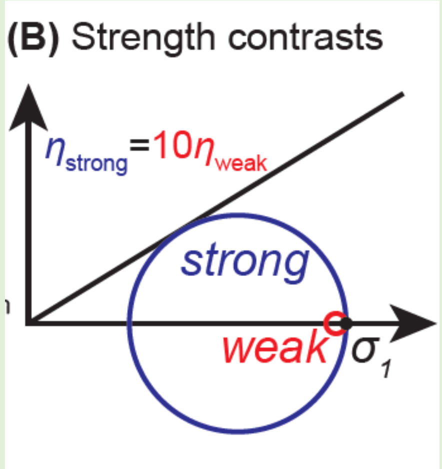
(1**) spatially isolated high strain** localization that is not observed elsewhere in NV geologic record; (2) relatively **cold burial**; (3) not recorded in regional erosion/unconformity compilations (e.g., Van Buer et al., 2009; Long, 2012); (4) requires **perfect detachment reactivation** to leave no trace (i.e., structures tend to variably plunge/dip and it is hard to believe there is no record); and (5) analogous structures imaged via seismic reflection profiels in other orogenic plateau hinterlands do not exhibit these geometries (e.g., Sinoprobe profiles in China, Wang et al., 2011 EPSL or Li et al., 2018 EPSL).

In summary, we attribute this disconnect between recorded peak pressures and field relationships to reflect non-lithostatic pressure conditions

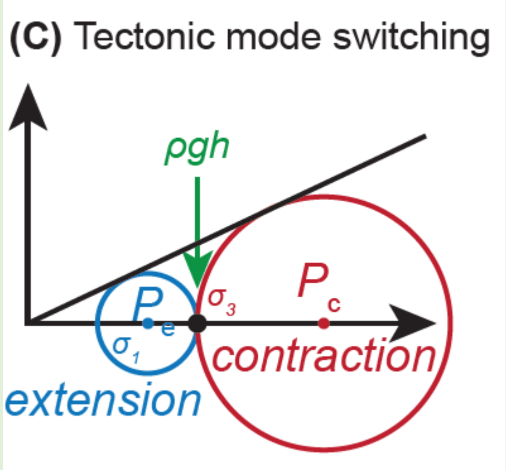
Almost all published overpressure models apply in the Cordillera core complexes (there was no time to go into all details of the geology so here is a summary) and may be additive in their effects



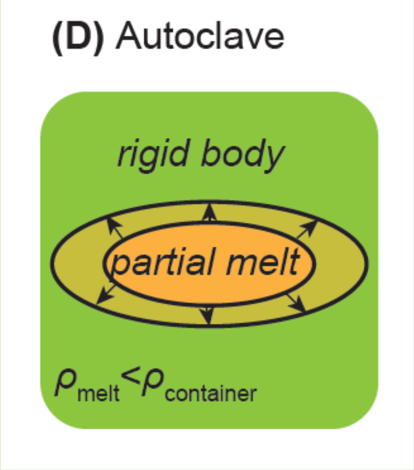
Rock strength (differential stress) from piezometry is >150 Mpa, and was likely higher during thrust-mode contractional deformation, so pressure variations of >100 MPa may be expected within the constraints of rock strength (e.g., Petrini and Podladchikov 2000)



Weak limestone marbles and shales commonly flow around strong quartzite/dolomite; the strength contrast leads to outcrop-to range-scale unit boudinage. Weaker phases may experience higher mean stress (e.g., Schmalholz and Podladchikov, 2013; Moulas et al., 2014, 2019)

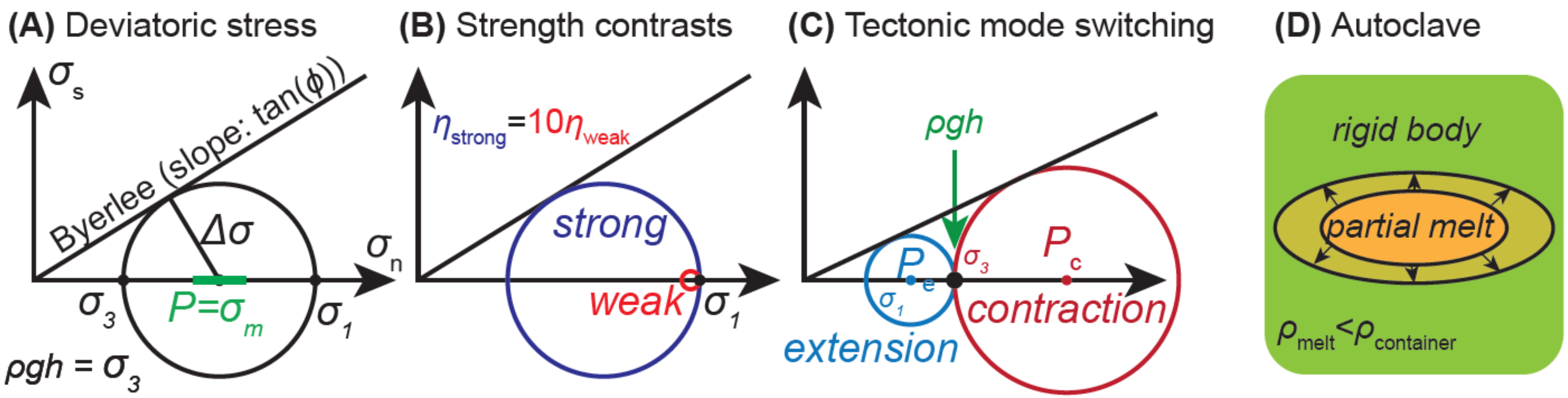


Region switched from **contractional** deformation during plateau buildup to **extension** during collapse, and thus contraction-mode pressure may be higher than extensional mean stress (Yamato and Brun, 2016)



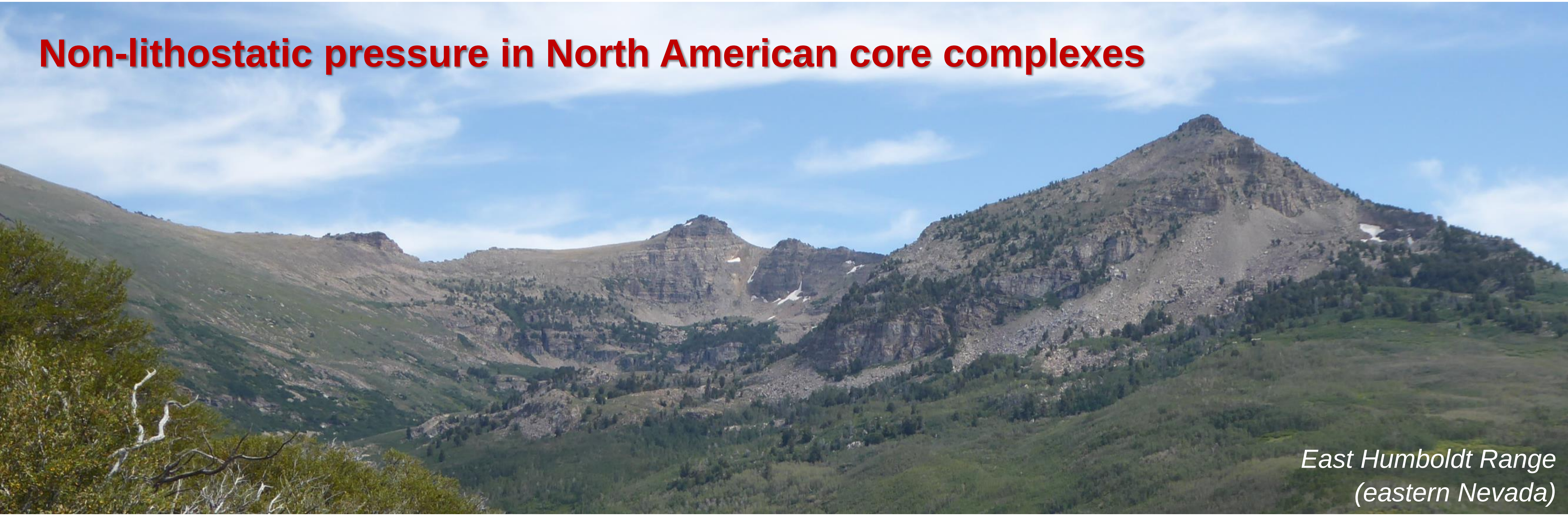
The core complex is pervasively intruded by **partial melts**, sometimes comprising **>66%** of the rock (e.g., Howard et al., 2011); this density shift can increase pressure rather significantly (e.g., Vrijmoed et al., 2009; Chu et al., 2017)

Non-lithostatic pressures may arise from a variety of published or unrealized mechanisms. Here, we conclude by suggesting this as a possibility, rather than continuing the argument that either (1) field geologists are missing major structures, or (2) petrologists are botching calculations.



A final consideration is that this region was adjacent to a thickening orogenic plateau in the Mesozoic (i.e., during peak *P*):
There is growing literature of discussing the differential stress (strength) and non-lithostatic stress state adjacent to thickened crust with GPE variations (e.g., Lechmann et al., 2014; Schmalholz et al., 2014, 2018)

Non-lithostatic pressure in North American core complexes



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Sources for *P-T* constraints

- Ruby Mountain-East Humboldt Range
  - Hurlow et al. (1991), Hodges et al. (1992), Hudec (1992), Jones (1999), McGrew et al. (2000), Hallett and Spear (2014, 2015), Wills (2014), unpublished QuiG data
- Northern Snake Range
  - Lewis et al. (1999) (L99 boxes)
  - Cooper et al. (2010) (F10 boxes)