# Arc tempos: cyclicity of intra-arc deformation, crustal thickening and strain rates of the Mesozoic Sierra Nevada Arc, California

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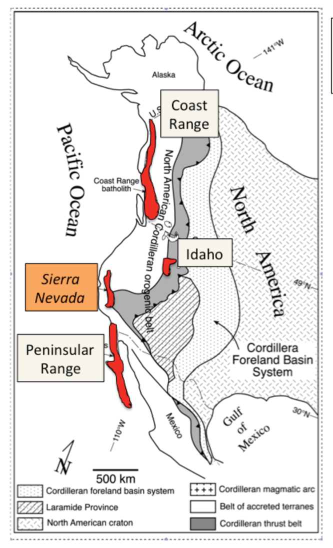
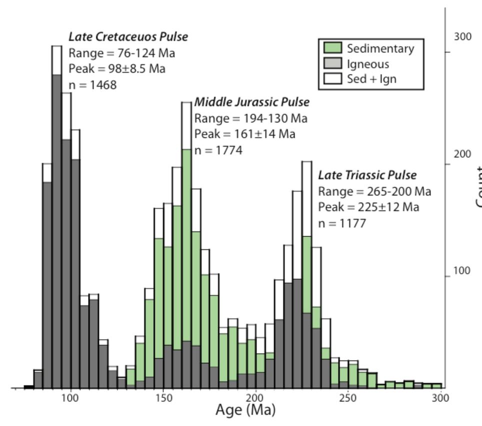



Tectonic regimes of Western North America (DeCelles, 2004)

**Sierra Nevada: Three prominent Mesozoic Magmatic flare-up events**




nature geoscience — REVIEW ARTICLE

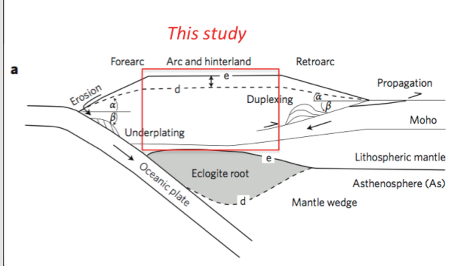
**Cyclicity in Cordilleran orogenic systems**

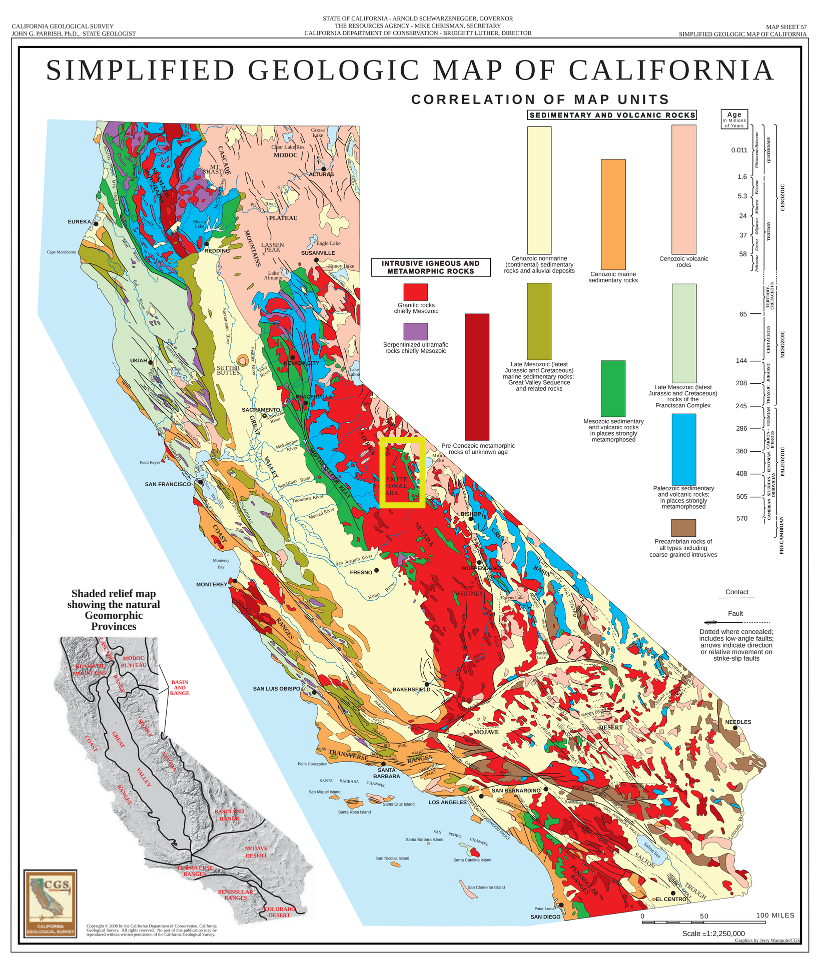
Peter G. DeCelles*, Mihai N. Ducea, Paul Kapp and George Zandt

**This study complements the arc tempo model**

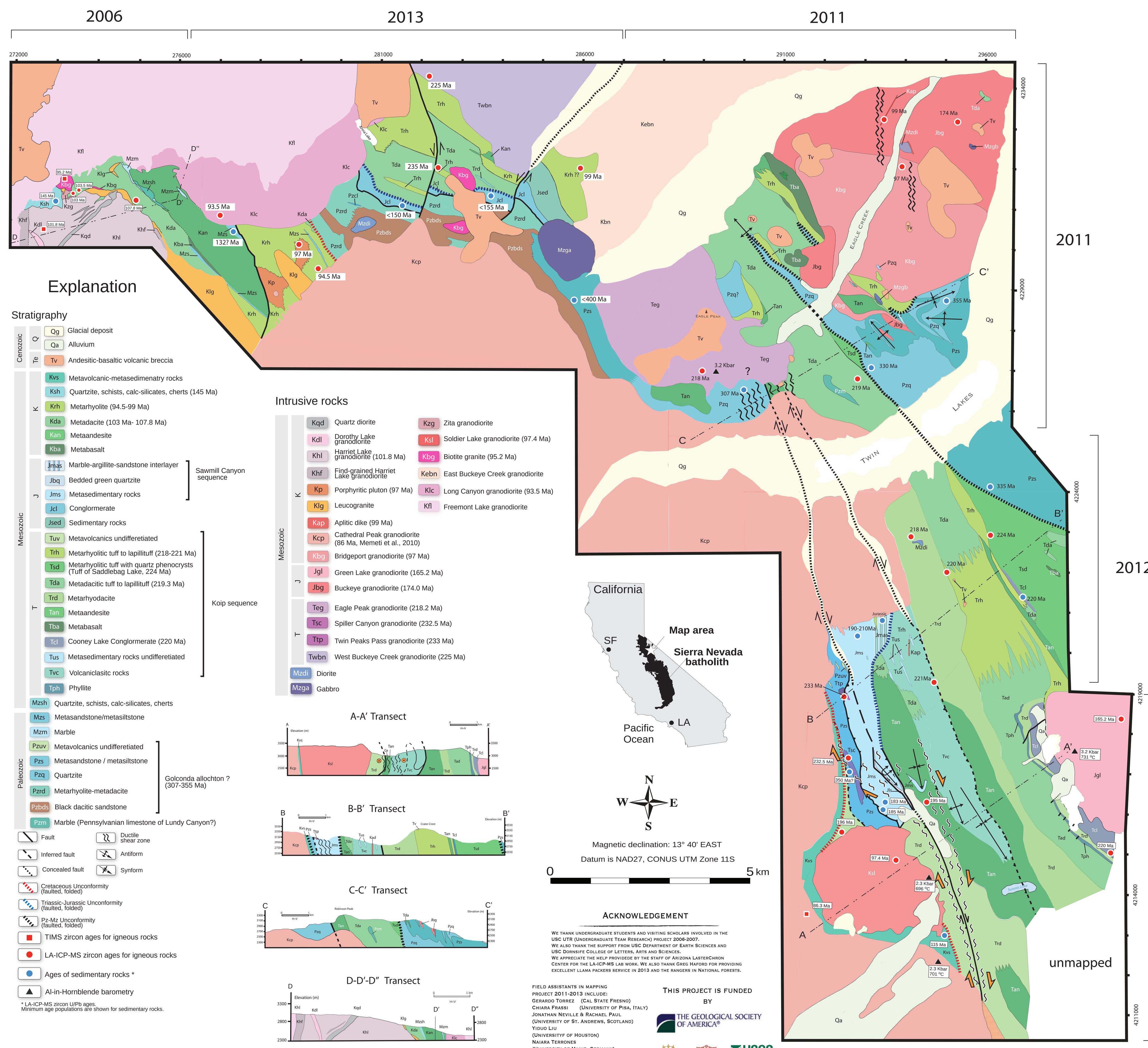
*A unifying model*

1. Retroarc underthrusting
+
2. Propagation of wedges
+
3. Foundering of arc root
+
4. Arc magmatism
+
(5. Subduction erosion)




## Bedrock geological map of host rock pendants in central Sierra Nevada, California (2006-2013, preliminary version)

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Field assistants in mapping project 2011-2013 include: Gerardo Torrez (Cal State Fresno), Chiara Frassi (University of Pisa, Italy), Jonathan Neville & Rachael Paul (University of St. Andrews, Scotland), Yiduo Liu (University of Houston), Naiara Terrones (University of Mainz, Germany), Pengwei Jiao (China University of Geosciences, Beijing), Yi-Jiun Chen & Chih-Chieh Chien (National Cheng Kung University, Taiwan), Sean Zalunardo, Sean Hartman & Pangxu Zhang (University of Southern California)

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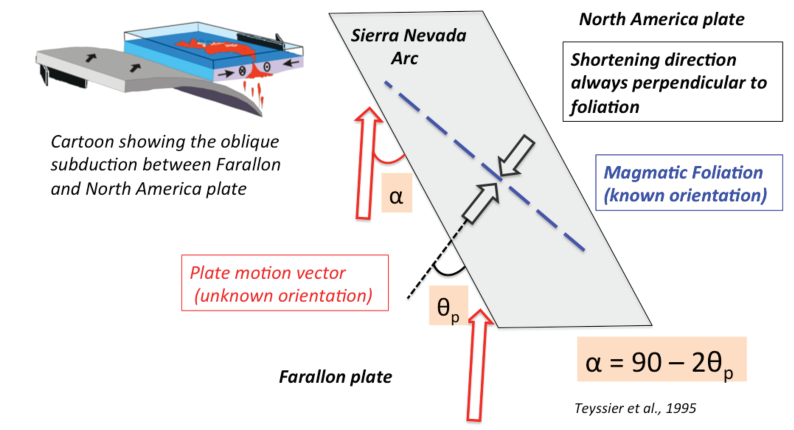
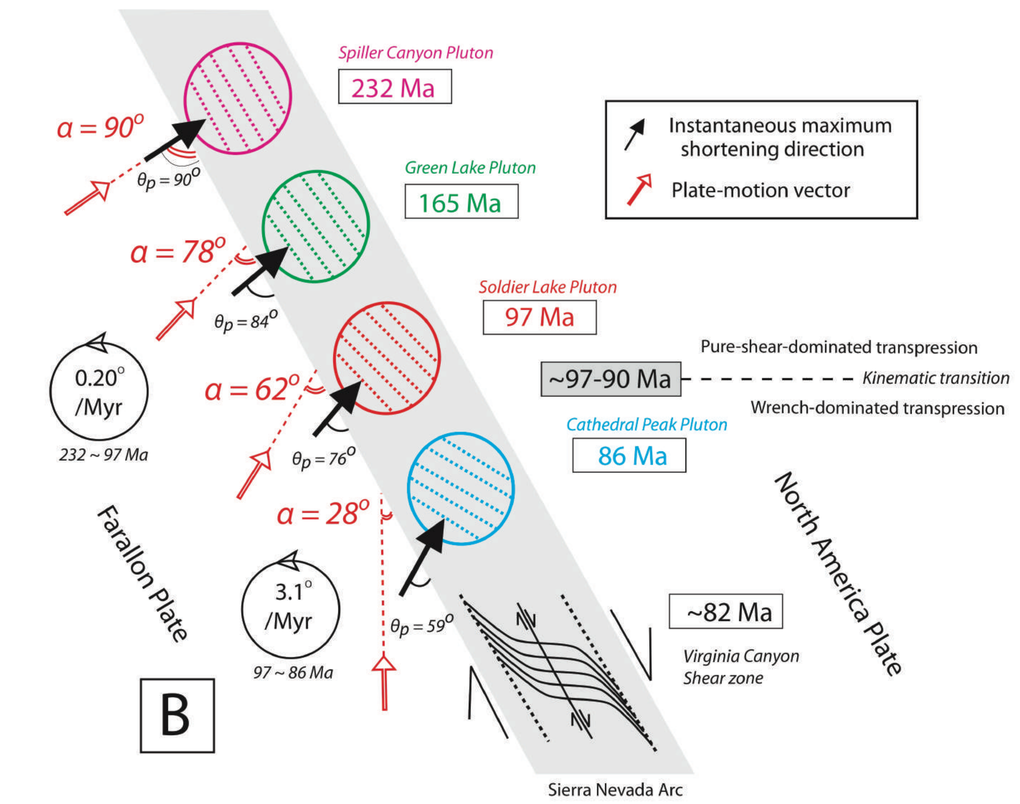
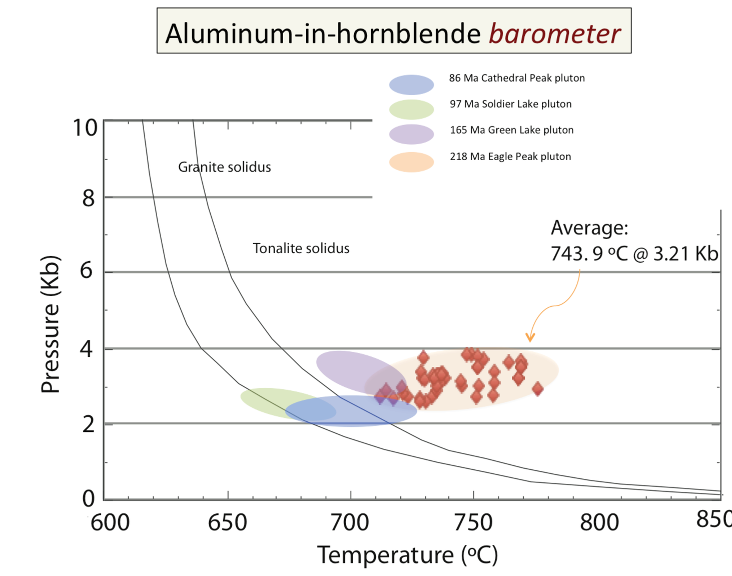



## Tracking plate kinematics

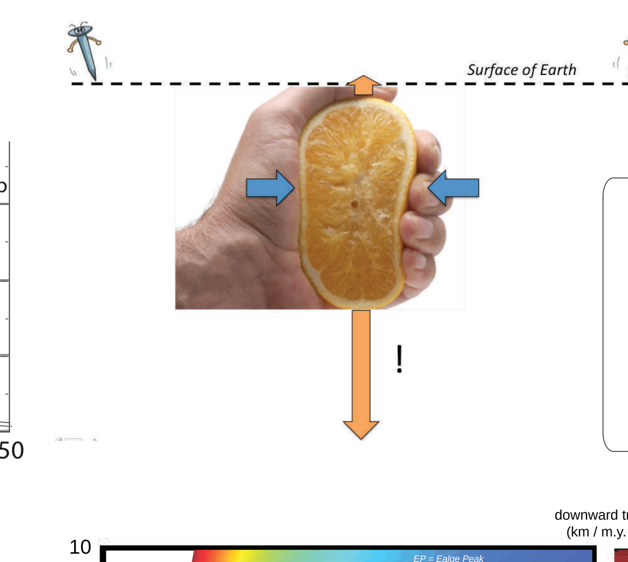
*We used magmatic fabrics as "snapshots" of incremantal strain and associated the change of direction with the kinematics transition of the subducting plate.*




**Aluminum-in-hornblende *barometer***

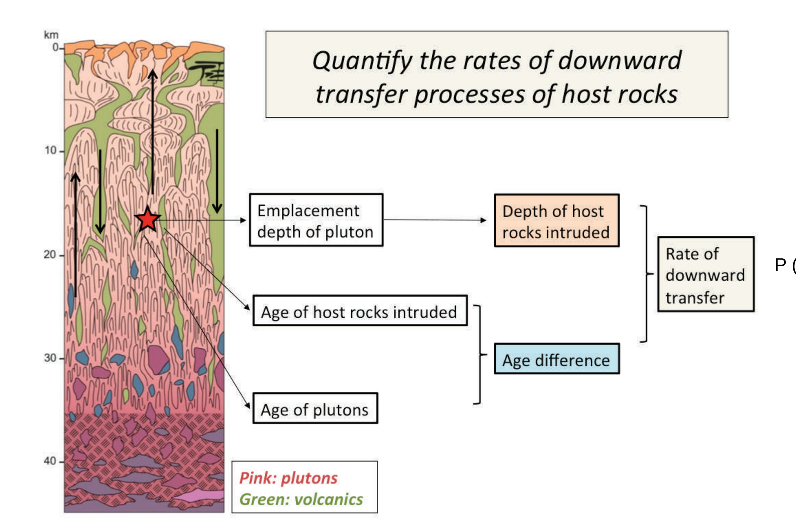


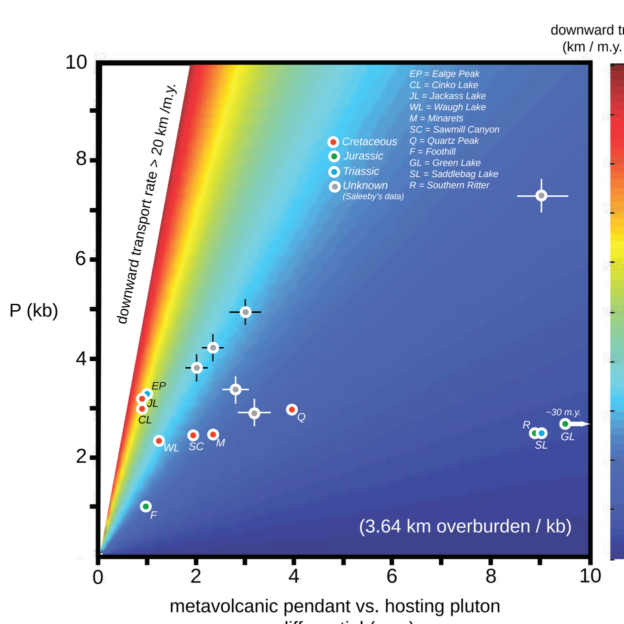

*Now you are squeezing an orange like this…*




## Mesozoic exhumation

*We calculated that the exhumation of the central Sierra Nevada was only about 5 km in Mesozoic and thus it requires significant amount of materials to be transported downwards.*

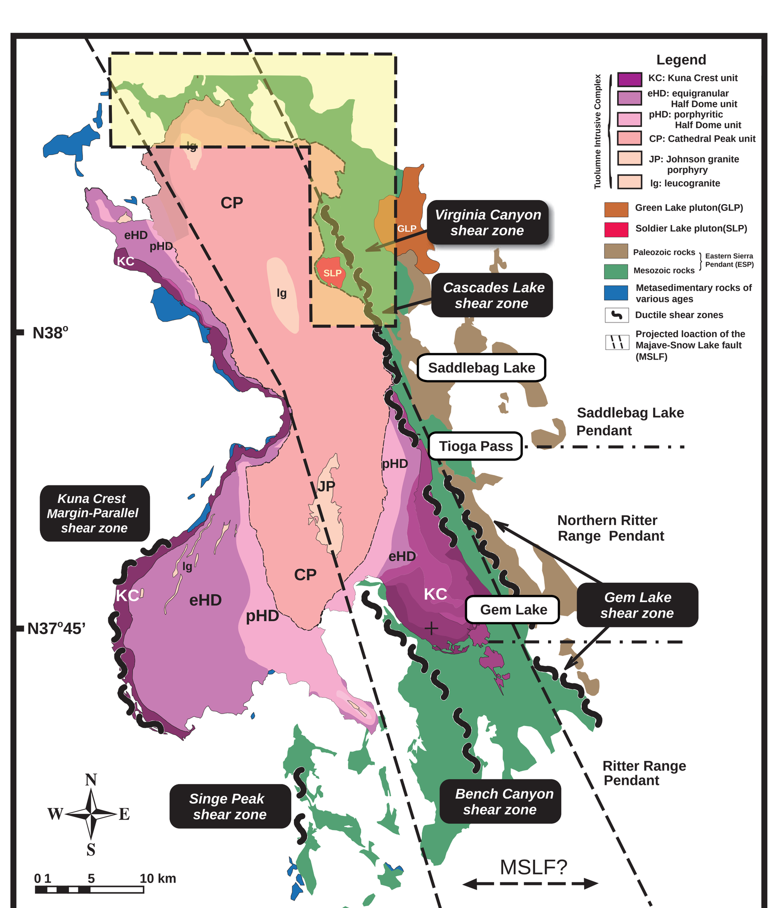



## Rates of downward transfer of materials

*Calculated rates of downward transfer of materials range from 2-13 km/Myr or 2-13mm/yr.*

*Strain rates associated with this process is estimated to 6.7x10^-15 ~ 4.3x10^-14 1/s.*




## Geological map of study area

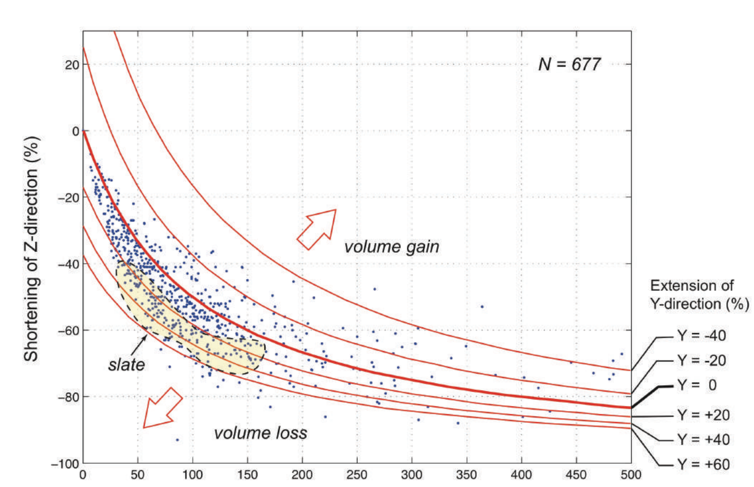
| | Timing | Area | References |
|---|---|---|---|
| Pz-Mz unconformity | 220-330 Ma | Twin Lakes | This study |
| | 240 Ma- Permian | Mt. Dana | Brook et al., 1977 |
| | 220-260 Ma | Saddlebag Lake | Schweickert and Lahren, 2006 |
| Tr.-Jr. unconformity | 190-220 Ma | Twin Lakes | This study |
| | 185-195 Ma | Virginia Canyon | This study |
| | 164-203 Ma | Ritter Range | Tobisch et al., 2000 |
| K. unconformity | 97-115 Ma | Virginia Canyon | This study |
| | 113-170 Ma | Saddlebag Lake | Hartman and Paterson, 2013 |
| | 110-148 Ma | Oak Creek | Longiaru, S., 1987 |
| | 100-153 Ma | Ritter Range | Tobisch and Fiske, 1982 |

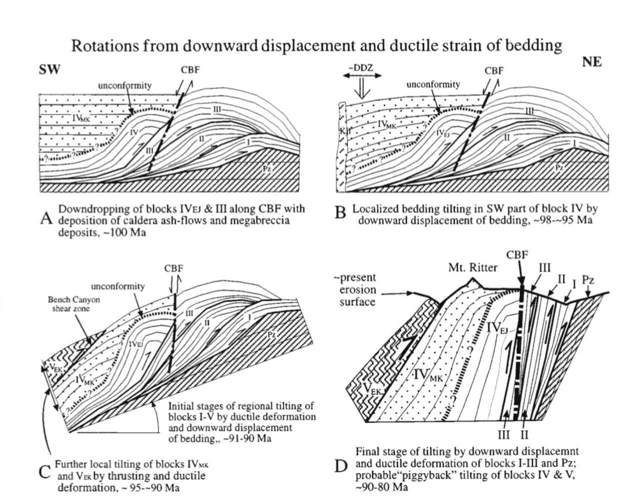
## Timing constraints on unconformities

| Time period | 245 Ma ~ 220 Ma | 180 Ma ~ 150 Ma | 110 Ma ~ 80 Ma |
|---|---|---|---|
| Virginia Canyon Area | (a) 330°-striking magmatic foliation and steep lineation in 232 Ma SCP (b) NE-or SW-vergent Triassic thrusts (~219 Ma) (c) NW-striking foliation in Golconda allochthon cut by 232 Ma SCP | (a) NW-striking foliation and steep lineation in ~220 Ma strata cut by 164 Ma GLP (b) 324°-striking magmatic foliation ($M_1$) and steep lineation in 164 GLP (c) NW-striking foliation in Early Jurassic strata cut by 97 Ma SLP (d) N40W-N30W-trending and NE-or SW- vergent thrusts of Middle Jurassic ages (GLT, EMT, ESCT, WSCT) (e) Folded unconformity with N40W-trending and steep FAP constrained to 219-174 Ma to the north of Virginia Canyon Area[††] | (a) NW-striking foliation in 115 Ma Cretaceous strata and Cretaceous thrust (CKF) cut by 97 Ma SLP (b) NW-striking and counterclockwise-rotated $M_1$ foliation in Cretaceous plutons (c) Dextral transpressional Virginia Canyon shear zone (pre-86 Ma to 80 Ma) |
| Saddlebag Lake Area | (d) N21W-and N61W-striking Fold Axial plane (FAP) in Permian-Triassic strata[*] (e) NW-striking foliation with 43% shortening in Paleozoic-Jurassic strata[†] | (f) N40W-N30W-striking, NE-or SW-vergent thrusts of Early to Middle Jurassic ages[§§] (g) NW-striking foliation with 43% shortening in Paleozoic-Jurassic Strata[†] | (d) Virginia Canyon shear zone extends to Saddlebag Lake Area (pre-86 Ma to ca. 80 Ma)[***,†††] (e) Steeply bedded and folded Late Cretaceous rhyolite (113 Ma)[§§§] |
| Ritter Range Area | (f) NNW-striking FAP in Pennsylvania to Permian strata[§] (g) NW-trending folds in Middle to Late Paleozoic strata[#] (h) NW-striking foliation in strata of Middle Triassic to Early Jurassic ages[**] | (h) NW-striking, steep foliation in Triassic-Jurassic strata formed between 150 Ma and 140 Ma[§,##] (i) NW-striking foliation in strata of Middle Triassic to Early Jurassic ages[**] | (f) NW-striking cleavage formed synchronously with emplacement of Late Cretaceous plutons (91-82 Ma)[###] (g) NW-striking foliation formed in Cretaceous volcanic rocks of 100 Ma. Deformation is about 92 Ma[§] (h) Bedding tilting is constrained to 101-90 Ma or around 90 Ma[§,****] |

Note: [*]Brook (1977); [†]Albertz (2006), timing not well constrained and probably time-transgressive strain; [§]Tobisch and Fiske (1982); [#]Greene and Schweickert (1997); [**]Tobisch et al., (1977), timing not well constrained and probably time-transgressive strain; [††]Cao and Paterson (2013); [§§]Schweickert and Lahren (2006); [##]Stern et al., (1981); [***]Whitesides et al., (2010); [†††]Hartman and Paterson (2013); [§§§]Memeti et al., (2014); [###]Sharp et al., (2000); [****]Tobisch et al., (1995)

## Timing constraints on deformation

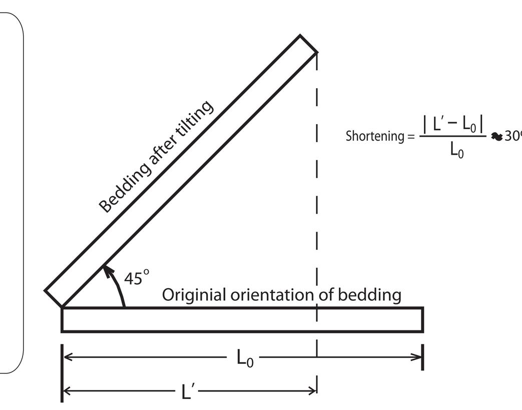


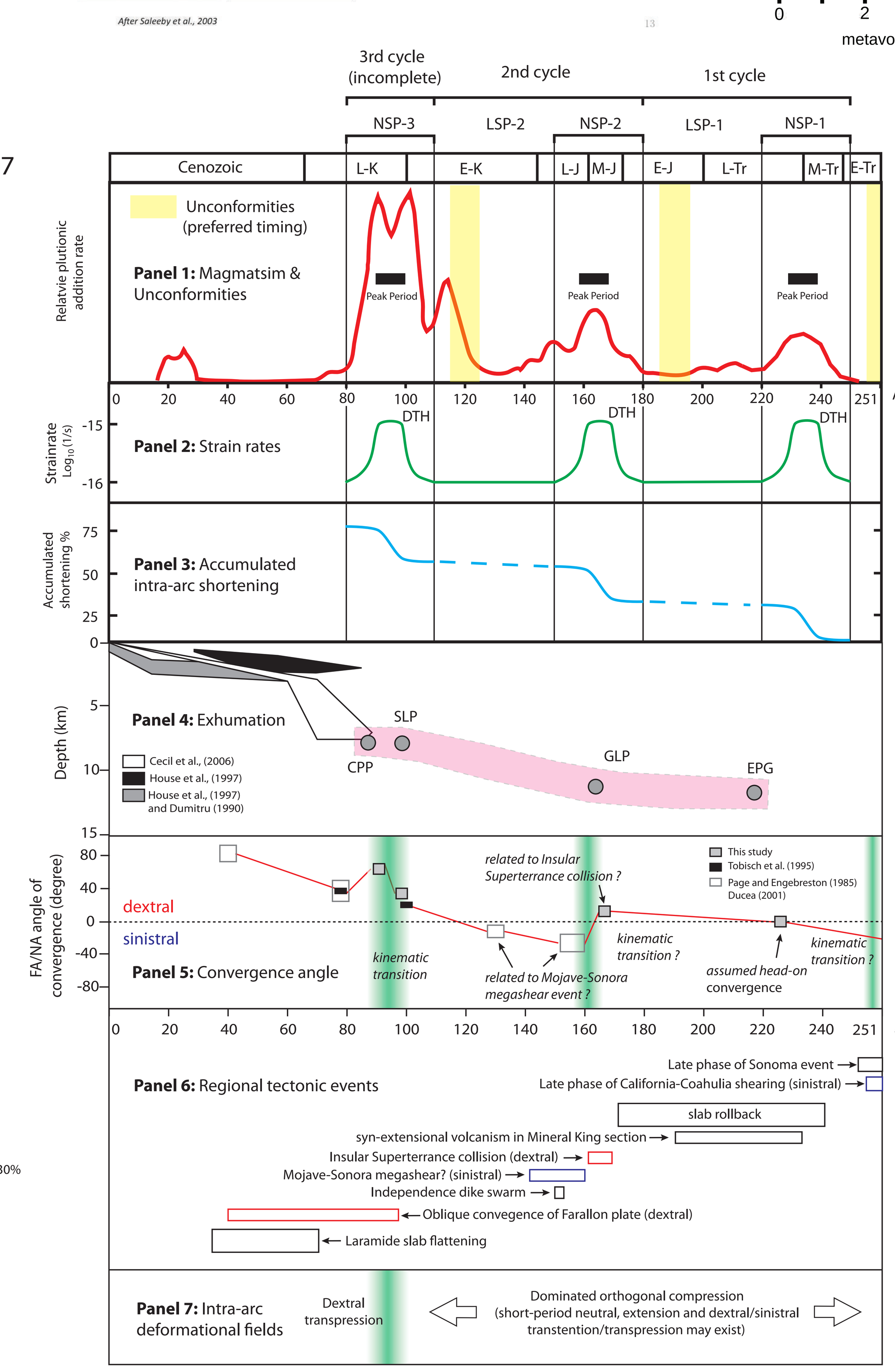

*Tobisch et al., 2000*

*We estimated ~50% shortening stain associated with foliation formation, ~30% shortening strain associated with thrusts, and 10% shortening related to bedding rotation in late stage.*

*The total bulk intra-arc shortening is about 75% shortening and >150% vertical extension with limited volume change and arc-parallel extension.*



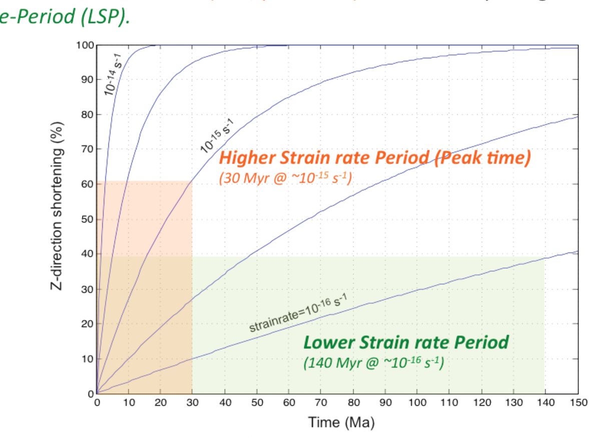

## Estimated total bulk intra-arc strain




## Summary of arc processes

**Mass balance**

The total strain of 75% intra-arc shortening can be achieved by ~30-Myr-long *Higher-Strain-rate-Period (HSP, peak time)* and ~ 140-Myr-long *Lower-Strain-rate-Period (LSP).*




*Shortening strain vs. Time*

**Strain rates**

| Geological processes (* = intra-arc) | Estimated strain rates (1/s) | |
|---|---|---|
| * Magma ascent and emplacement | $10^{-4} \sim 10^{-14}$ | Normal rates |
| * Intra-arc shortening (Normal strain rate period) | $\sim 10^{-15}$ | |
| * Host rocks downward transport | $6.7 \times 10^{-15} \sim 4.3 \times 10^{-14}$ | |
| * Sierra Crest Shear Zone (scaled to width) | $< 10^{-13.7} \sim 10^{-13.8}$ | |
| * Intra-arc shortening (Lower strain rate period) | $\sim 10^{-16}$ | Lower rates |
| Fold-and-thrust belt (Jurassic to Cretaceous) | $4.2 \times 10^{-16}$ | |

## Conclusions

*(1)The intra-arc processes are cyclic.*

*(2)Multiple feedbacks linking intra-arc processes.*

*(3)Significant crustal thickening transfers materials downwards and might fertilize the magma source.*

*(4)A unifying model of an arc should include the intra-arc processes.*