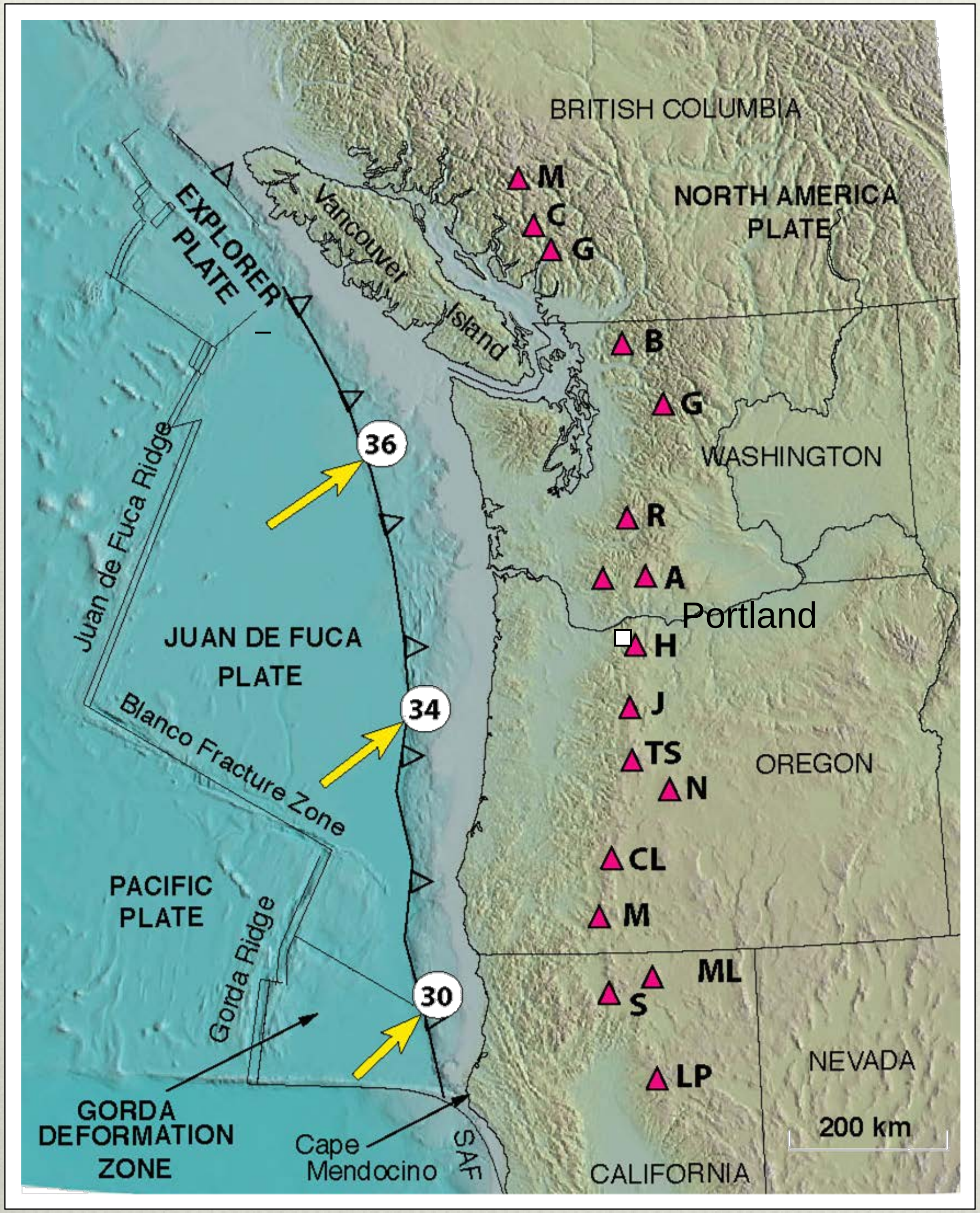
Evolution of the Cascadia Convergent Margin

Ray Wells, USGS

Contributors of data and ideas:

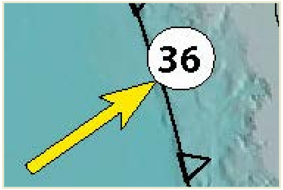
Doug Pyle, Bob Duncan, Rob McCaffrey, Rick Blakely, Joe Wooden, David Bukry, Richard Friedman, and Peter Haeussler, Gene Humphreys, Bob Stern, Becky Dorsey, Katie Keranen, Megan Anderson



Modified from Haugerud, 2000

- How was the Cascadia margin built?
- How does its history affect modern deformation, seismicity, and magmatism?
- Is the margin tectonically segmented? How?
- *Is tectonic segmentation reflected in seismogenesis?*

Convergence velocity mm/yr



(McCaffrey et al., 2007)

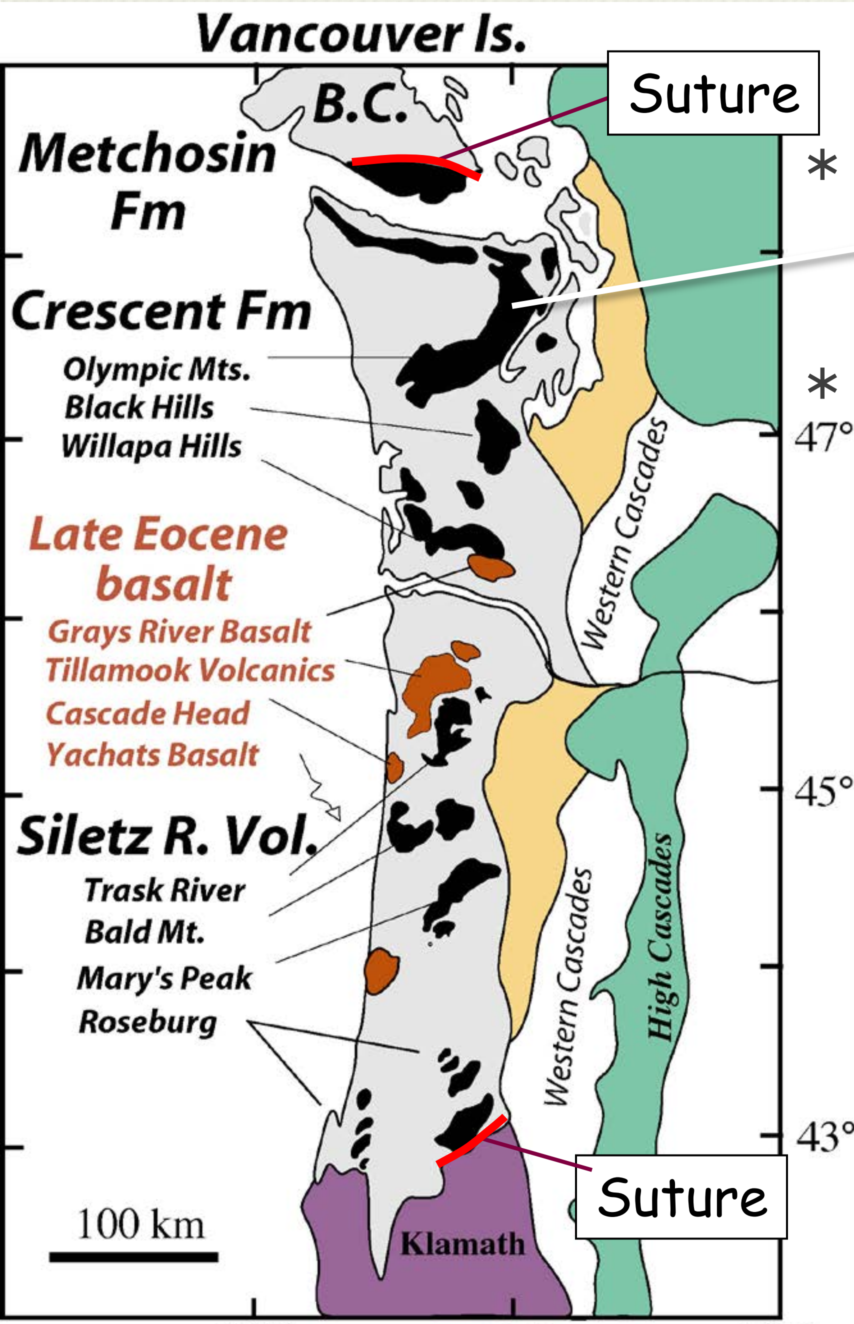
A story in three parts

- I. Origin and Collision of the Siletz terrane forming basement of Cascadia forearc
- II. Post collision reorganization, magmatism, and establishment of Cascade magmatic arc
- III. Rotation/shear overprint on modern subduction regime
- *(summarized in two posters in the poster session)*

Part One:

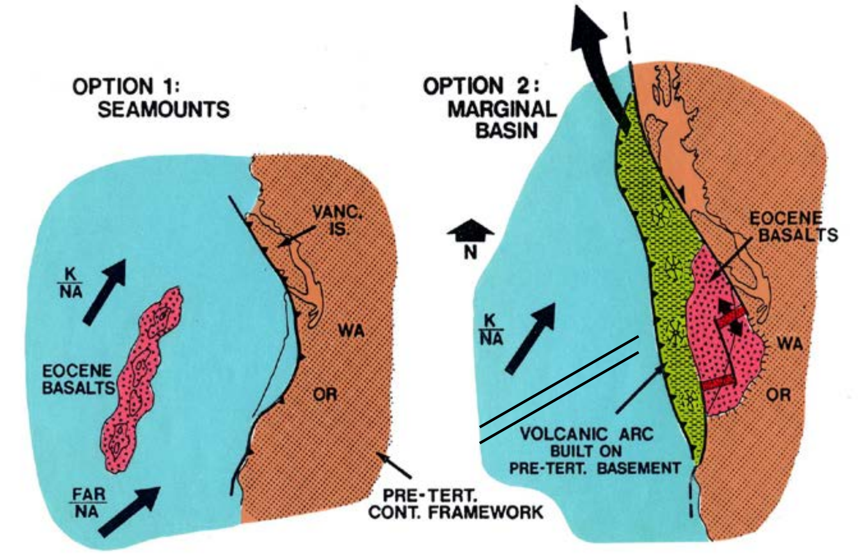
Origin and Accretion of Siletzia

“Siletzia”

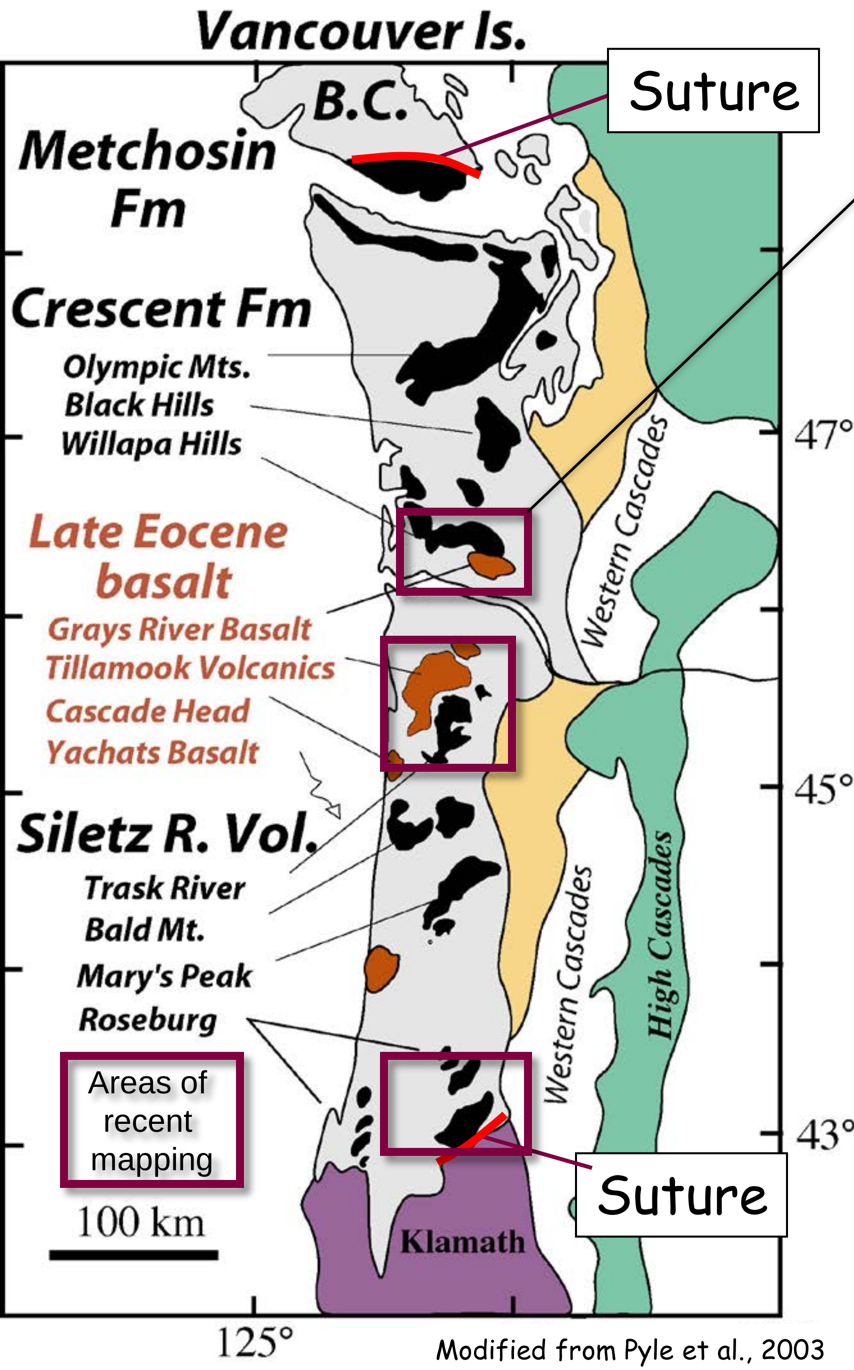


Modified from Pyle et al., 2003

* **Paleocene to Eocene basalt** – Metchosin Fm., Crescent Fm., Siletz R.Vol. forms Coast Range basement (Irving, 1979)
* **Oceanic MORB, OIB** – Snavely et al. (*AJS*, 1968) and many others
  * **Accreted ocean island chain?** (Snavely MacLeod, 1974; Simpson and Cox, 1977; Duncan 1982)
  * **Marginal rift/slab window?** E.g., Wells et al., 1984; Babcock et al., 1992; Haeussler et al, 2003; Madsen et al., 2006)



Clowes et al., 1987



New data synthesis

Geologic mapping (Wells et al, 1981, 1989, 1995; 2000; 2010, in prep.)

Ar/Ar ages (Pyle, Duncan)

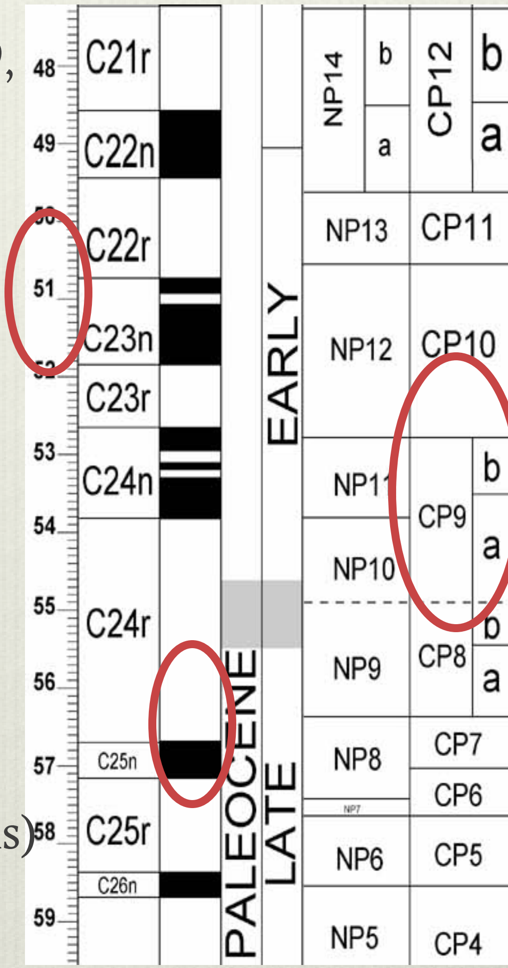
U/Pb ages (Wooden, Friedman)

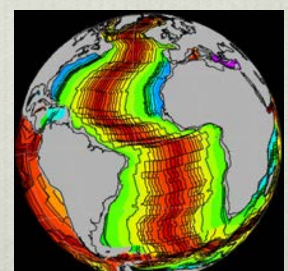
Global nannoplankton zones (Bukry)

Magnetic polarity (Simpson, Magill, Wells)

Geomagnetic Polarity Time Scale (Gradstein et al, 2004)

GPlates – open source Plate Model, 2010



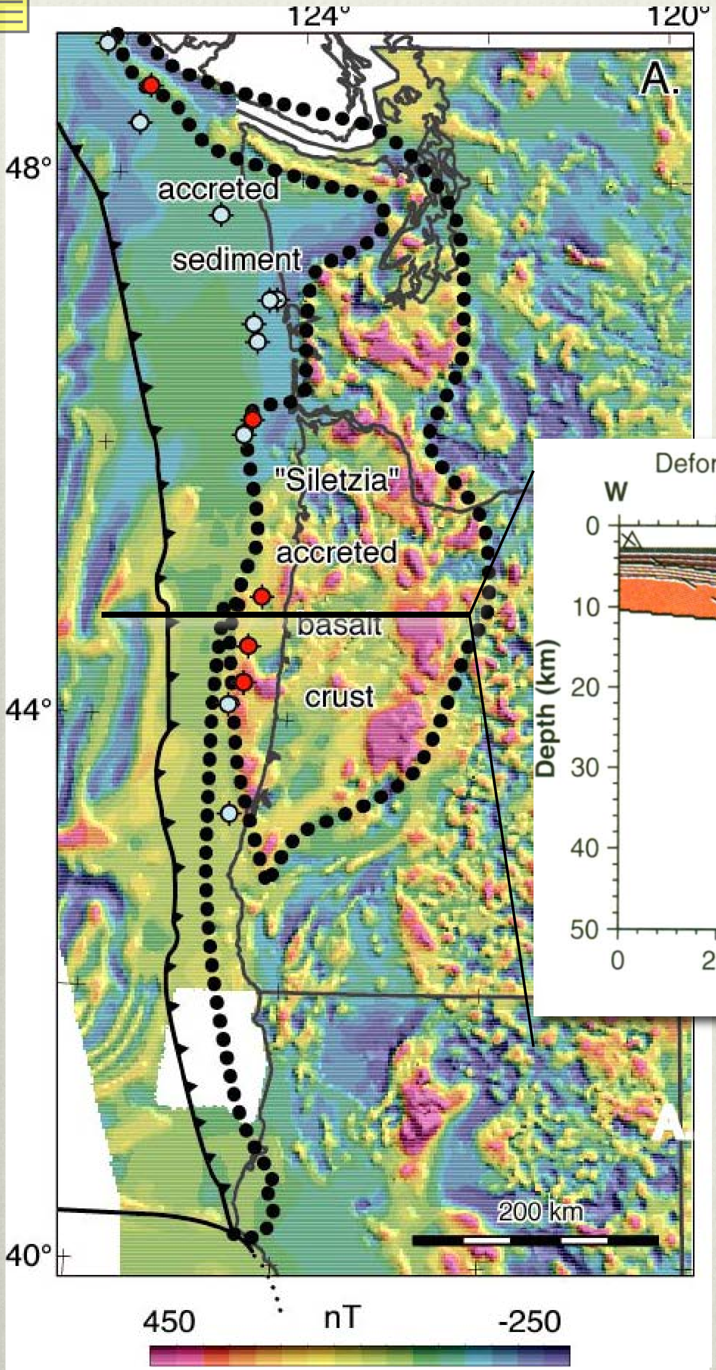


New data constrains:

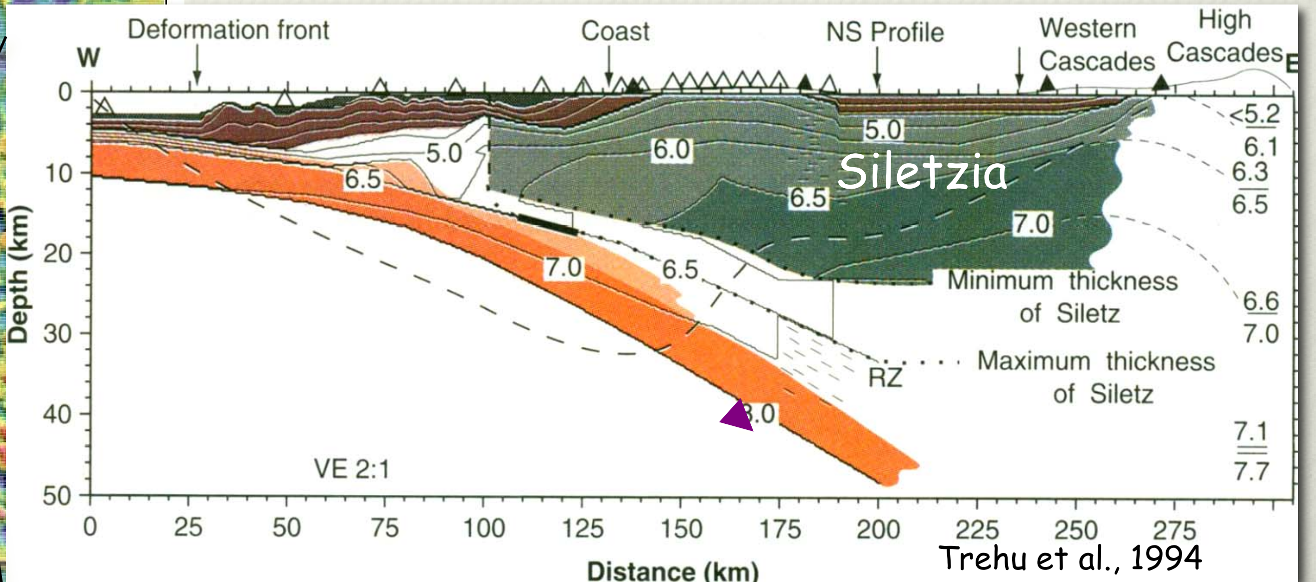
* Origin of Siletzia in OR *(ocean island/plateau)*
* Age of accretion *(51 Ma)*
* Deformation *(fold and thrust belt due to collision)*
* Post-collision extension and renewed magmatism *(late marginal rifting)*
* Plate models *(role of long-lived Yellowstone Hot Spot)*

Siletzia LIP: 1.7- 2.4 x 10^6 km^3
10-14 times volume of CRB.

Aeromagnetic surveys and exploration wells outline extent of Siletzia's basaltic crust



Wells, Weaver, and Blakely, 1998



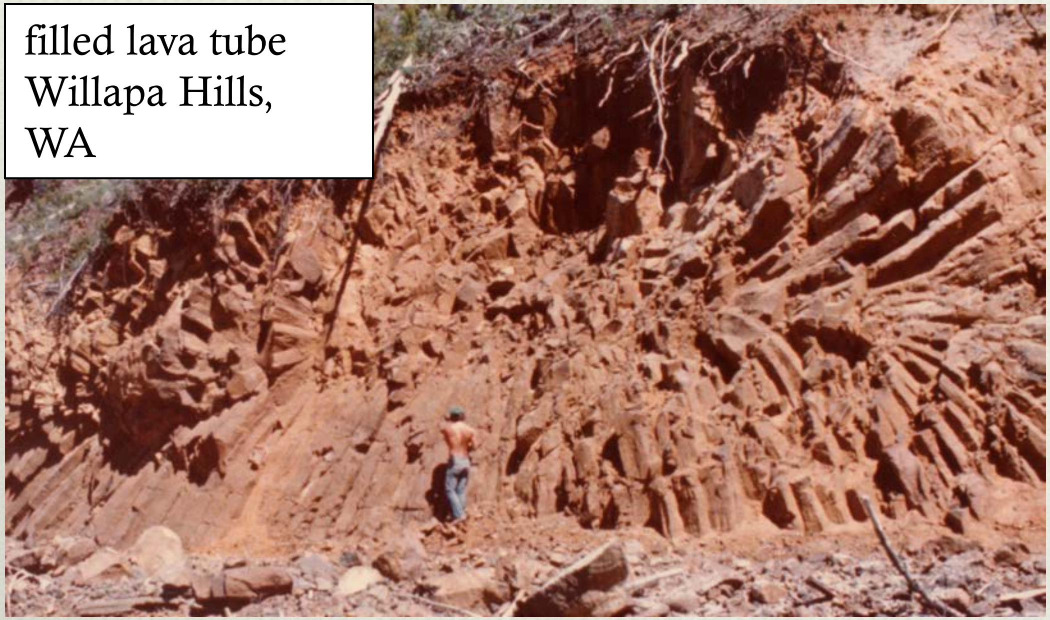
Trehu et al., 1994

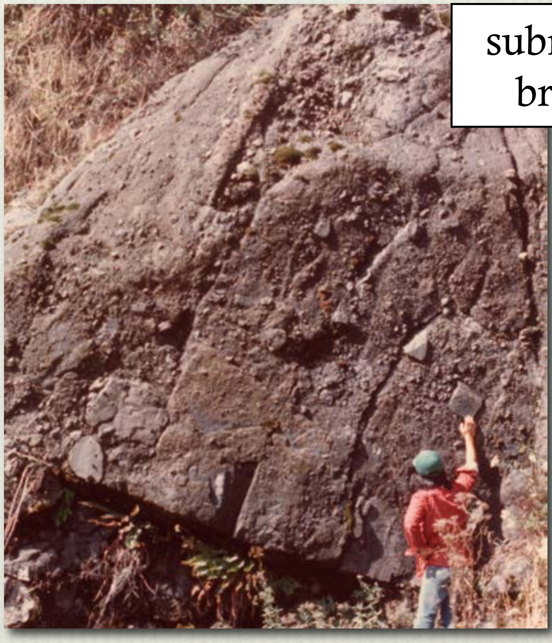
- Thickness from seismic profiles

22-32 km/OR; 20 km/WA; 10 km/V.I.

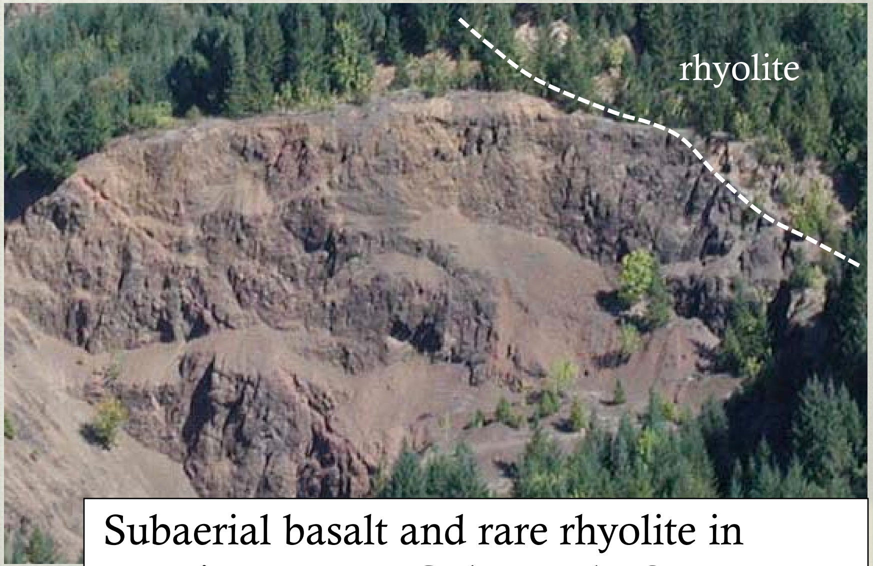
16.5 km measured in outcrop in Olympics (Tabor and Cady, 1978; Babcock et al 1992)

Siletzia is a coherent terrane, mostly submarine basalt.

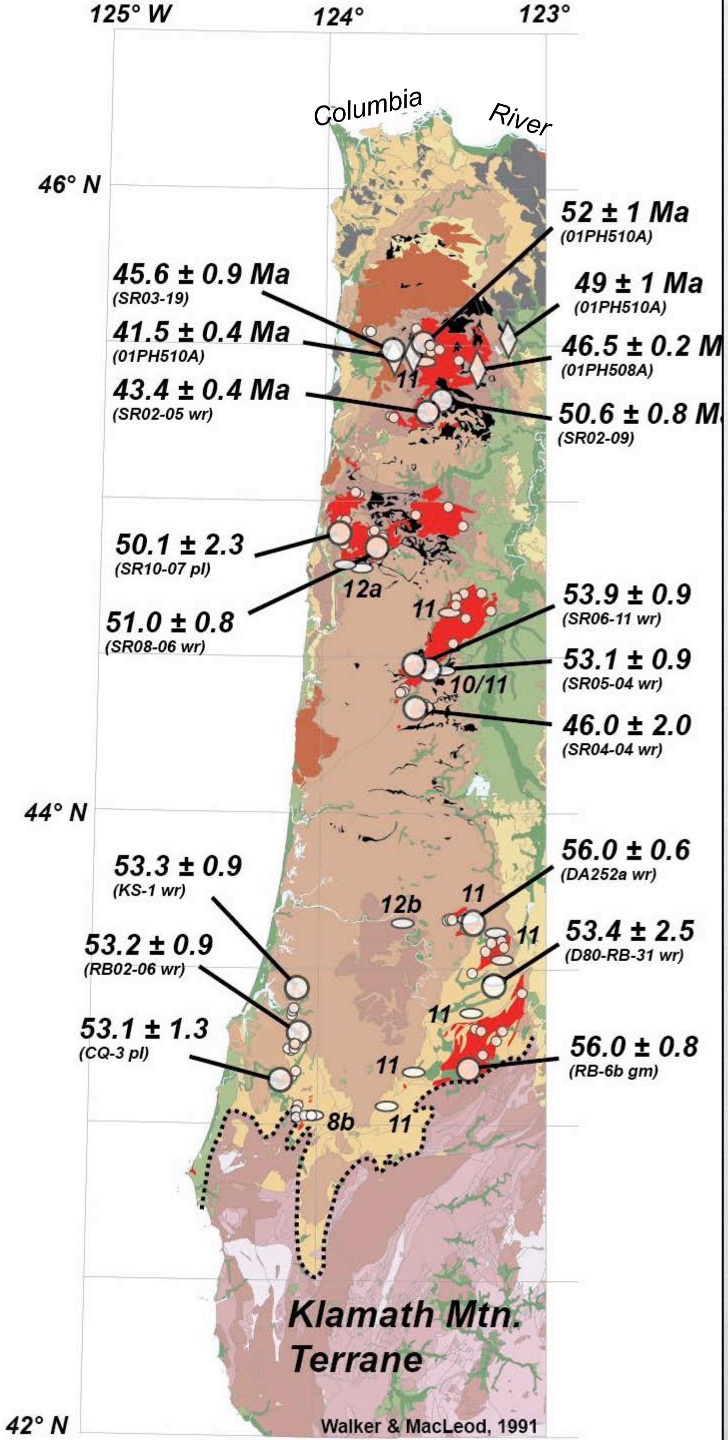

filled lava tube
Willapa Hills,
WA


submarine
breccia


Pillow basalt
Trask River, OR



Subaerial basalt and rare rhyolite in
eruptive centers; Gales Peak, OR



Siletzia
(SRV basement in OR, red):
56 Ma in south
49 Ma in north

- 15 Ar/Ar step heating ages on basalt (Pyle et al., 2003)
- 14 U/Pb ages on tuff interbeds and Si flows (Wooden, Stanford; Friedman, UBC)
- Scores of coccolith ages (Bukry)
  - E.g., CP 11, 12b, etc. on map
- Coincident with reorganization of NE Pacific spreading Chron 24-21

How and when did Siletzia accrete to NAM?

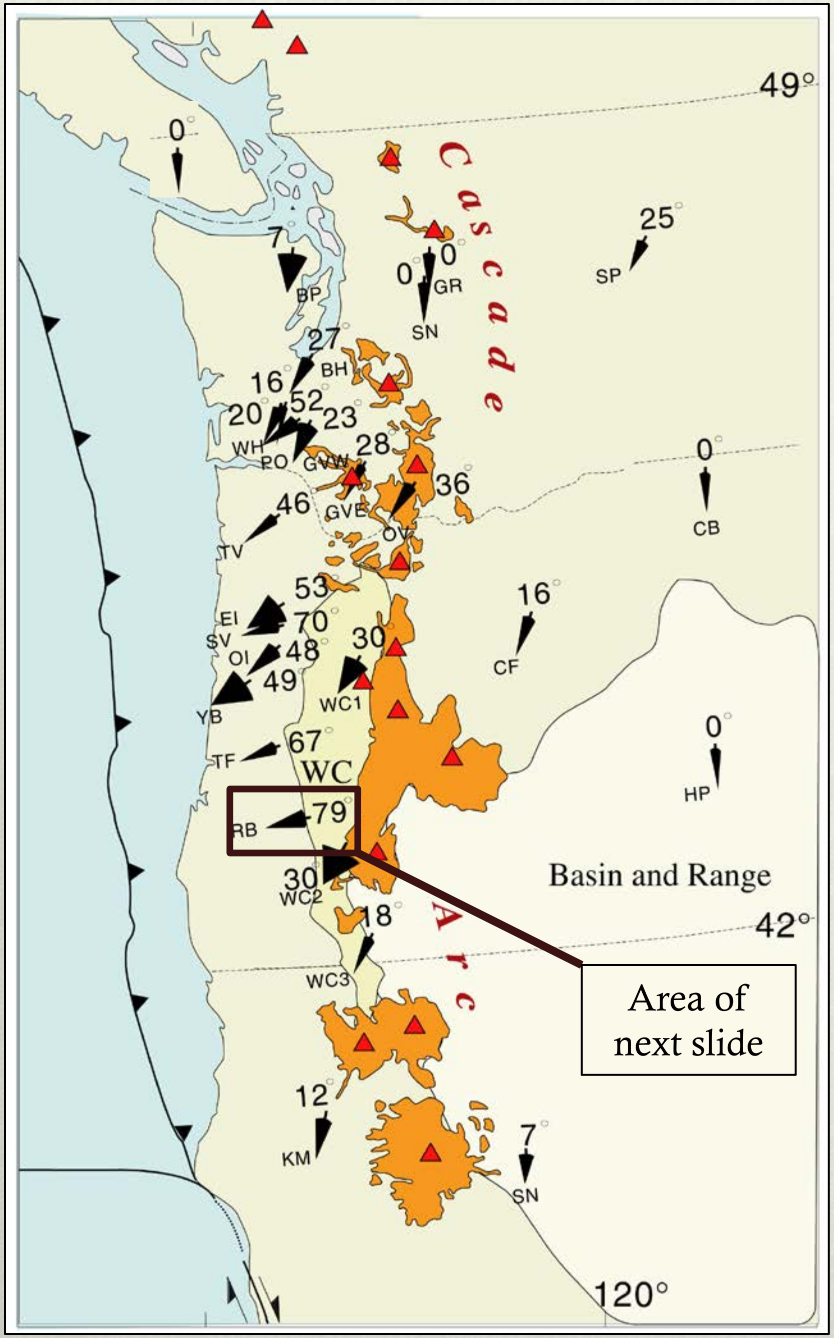
Look at:

1) Paleomagnetic rotation

2) Analysis of accretion-related folding

3) Fault slip data from terrane boundary fault

4) Age of fluvial and shallow marine sediments deposited on Siletzia

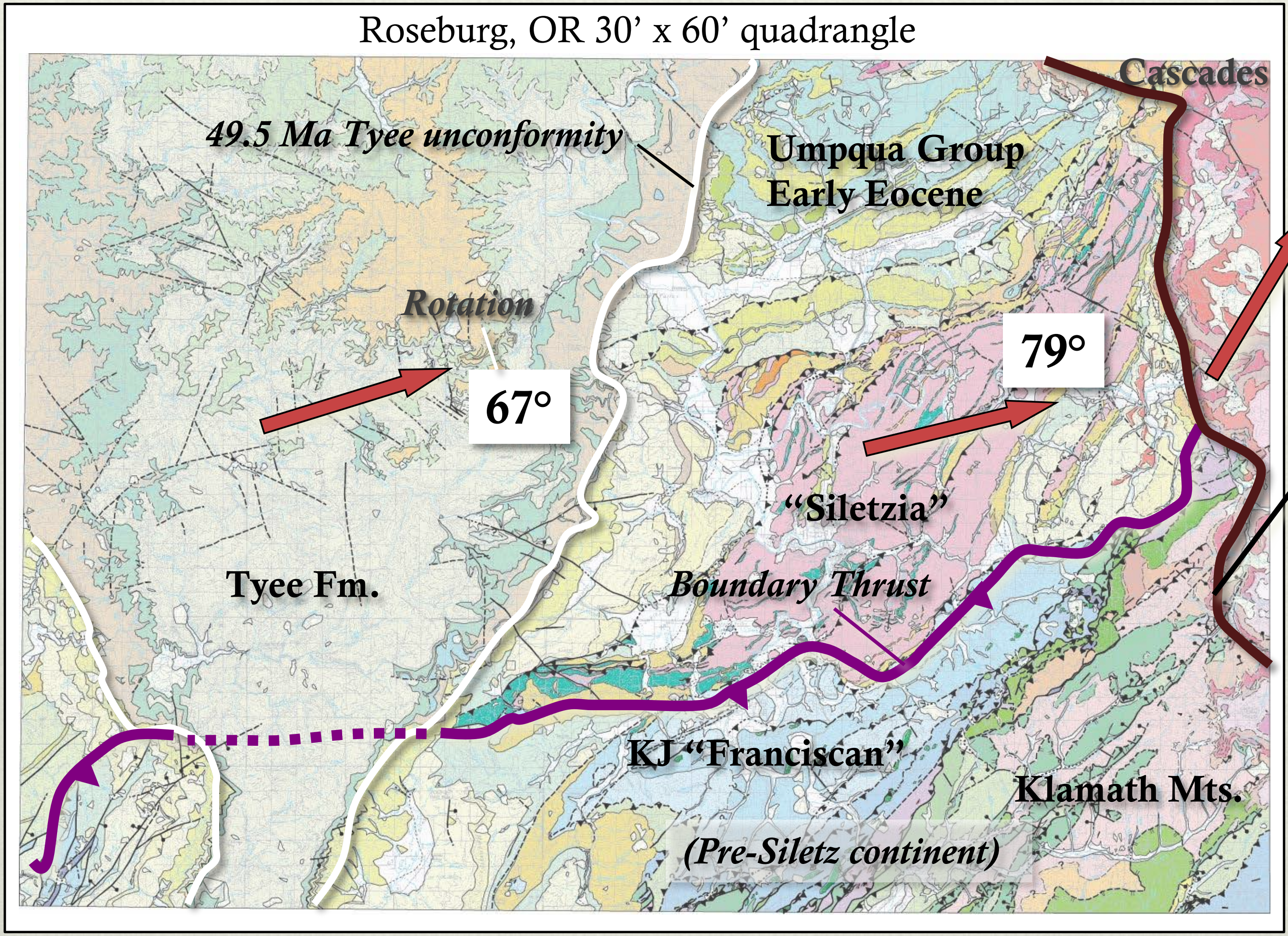


Large rotation of Oregon Coast Range and Siletz basement

- Clockwise paleomagnetic rotation, 70-79° in Siletzia; 46-67° in Eocene onlap.
- Rate: 1.19°/Ma since 50 Ma
- Rot. decreases to N, E, and S.
- Inclination flattening small; modest (<300 km) northward motion possible (Beck, 1983).

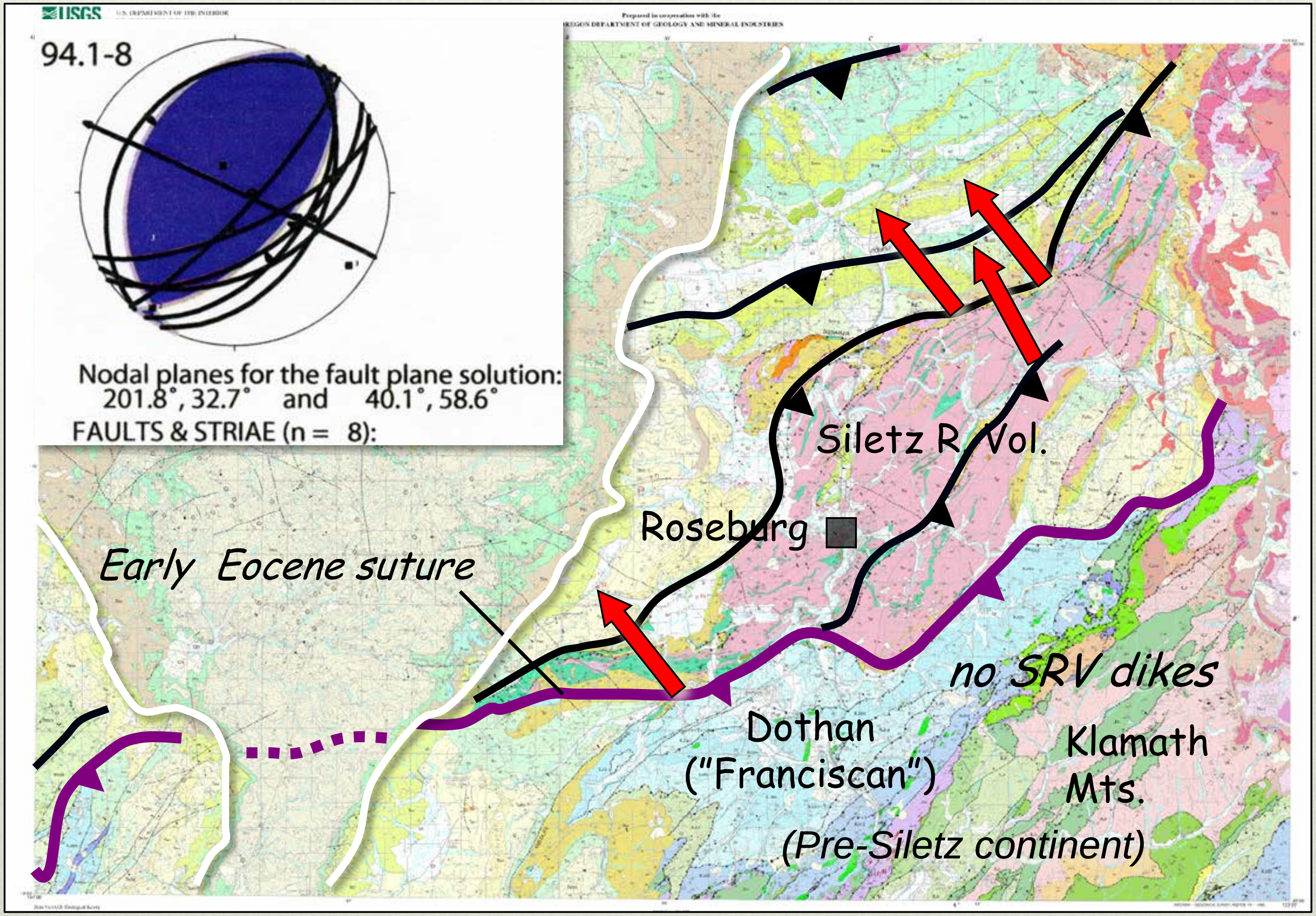
directions with 2 sigma uncertainties about mean; Gromme et al. (1986)

But most rotation postdates accretion



Rotated 48 Ma Tyee turbidites onlap boundary thrust and accretion-related fold and thrust belt. (Simpson and Cox, 1977; Wells, Jayko, Niem, et al., 2000).

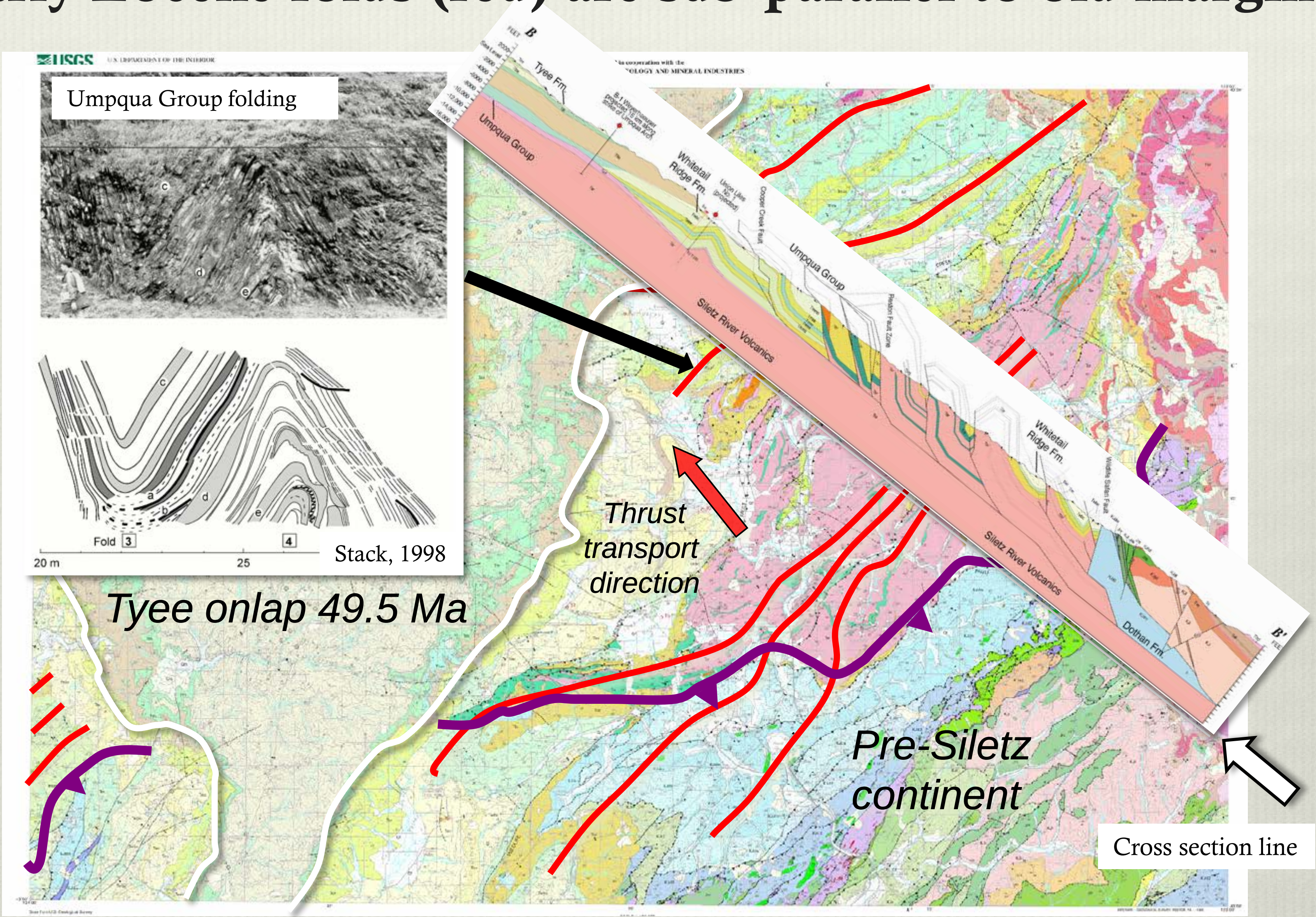
Siletzia is thrust beneath the old margin.



Wells, Jayko, Niem et al., 2000

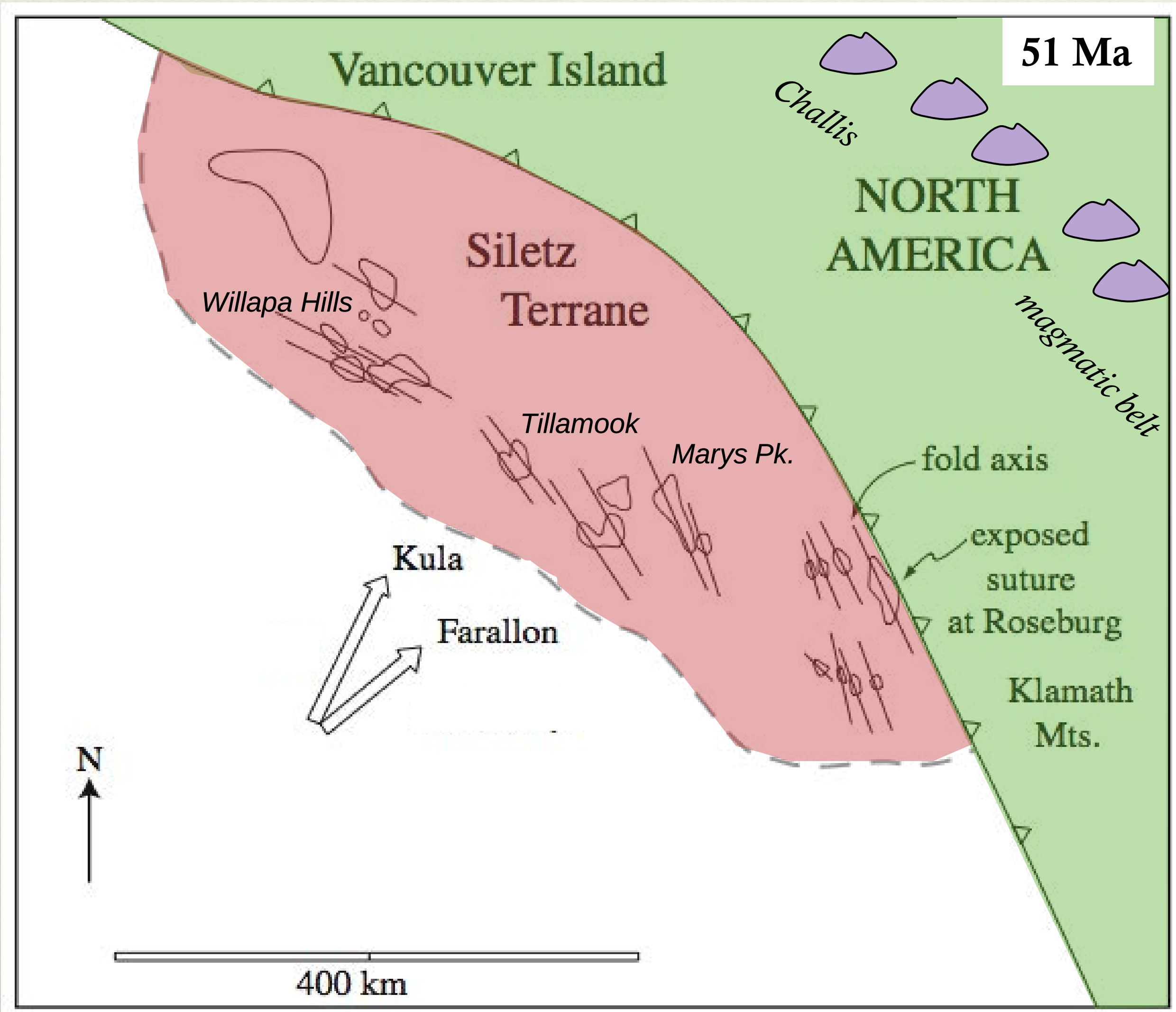
- Thrust slip vectors from slickenlines (red arrows) are ~ normal to margin.
- Strike slip is small during accretion.

Early Eocene folds (red) are sub-parallel to old margin.



Folding and thrusting was caused by accretion of Siletzia to continent.

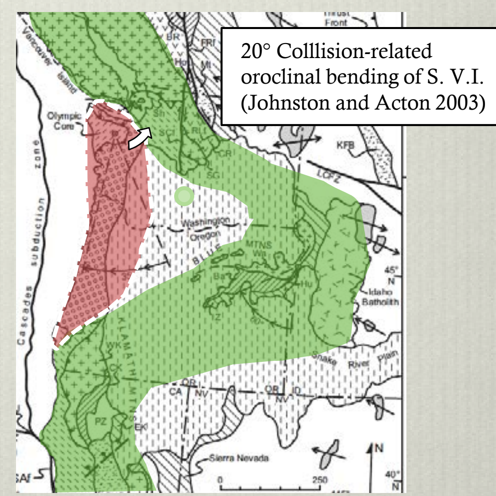
North America margin inferred from early fold trends



(Wells et al., 2000)

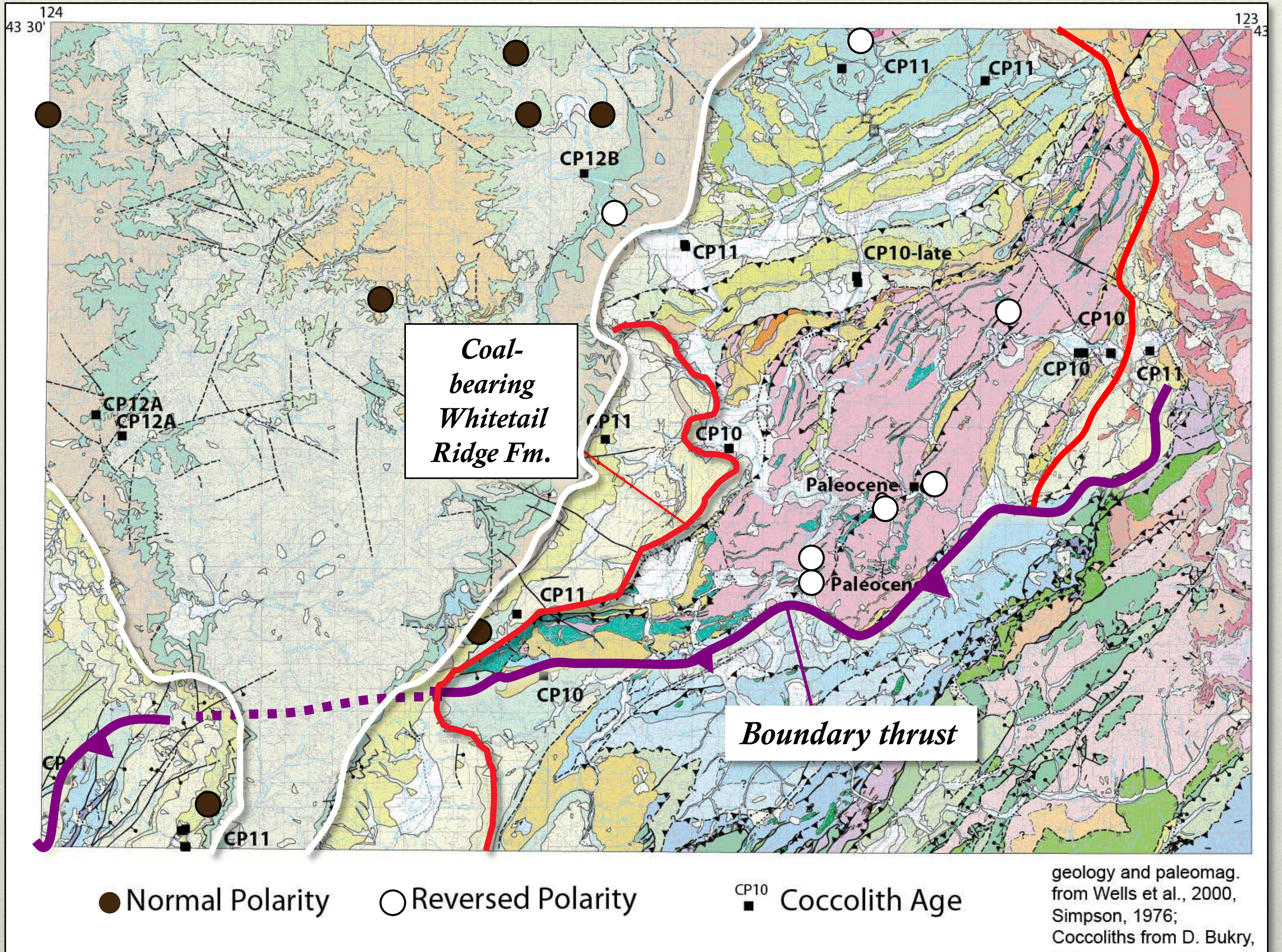
- Early Eocene collision fold axes in Siletzia, rotated back to original orientation.
- Collision of Siletzia indenter may have produced 12-20° of the oroclinal bend in Mesozoic orogenic belt

Present-day orocline

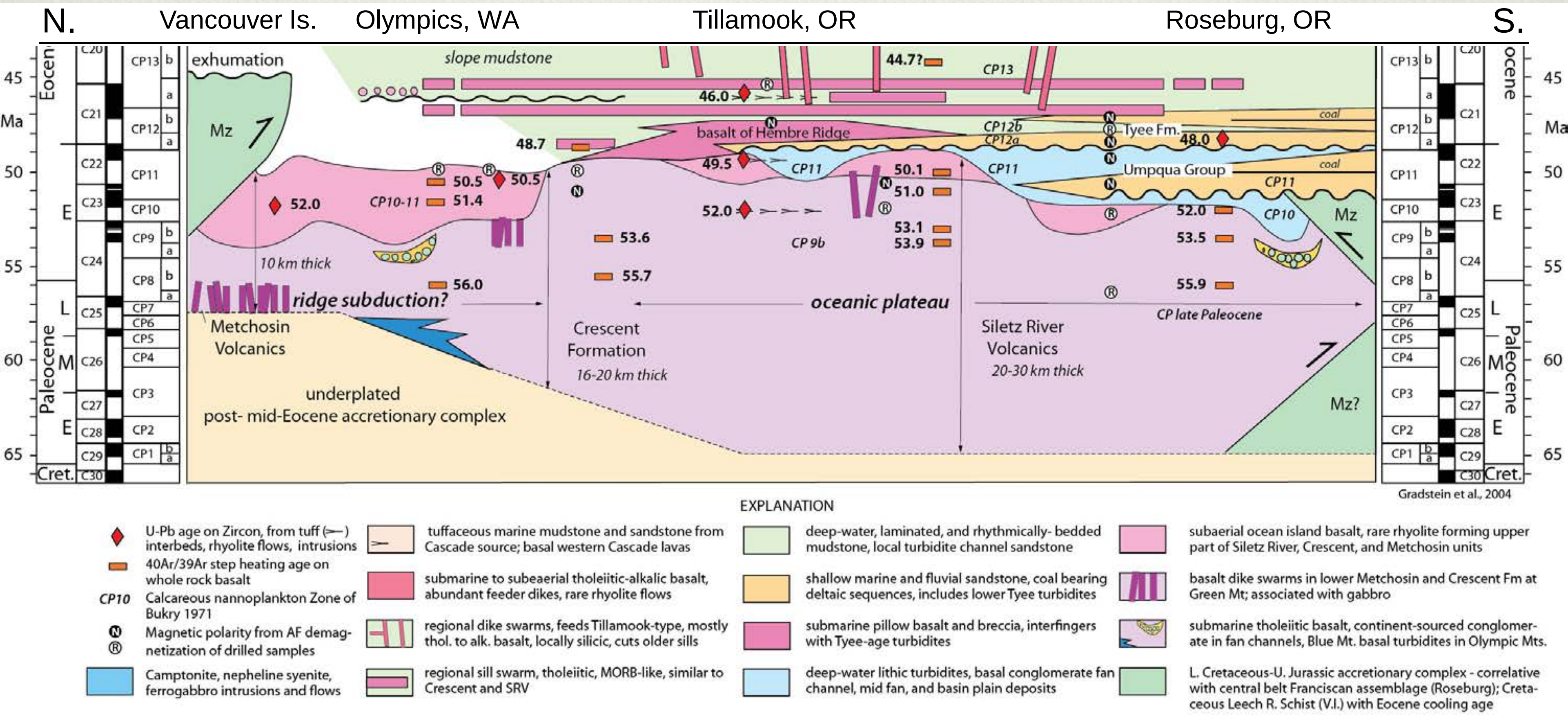


(Dickinson, 2009)

Continental onlap 51 Ma - base of coal-bearing Whitetail Ridge (red unconformity, CP 10-11 boundary)



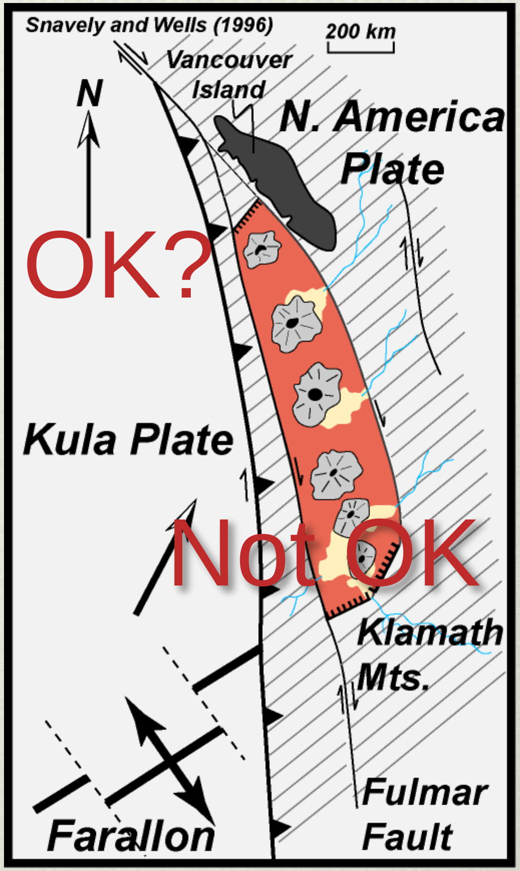
Siletzia: volcanism – 56-52 Ma in S, 49-52 Ma in N
docking – 51 Ma in S, >35 Ma in N
thickness – 20-30 km in S; 10-20 km in N.

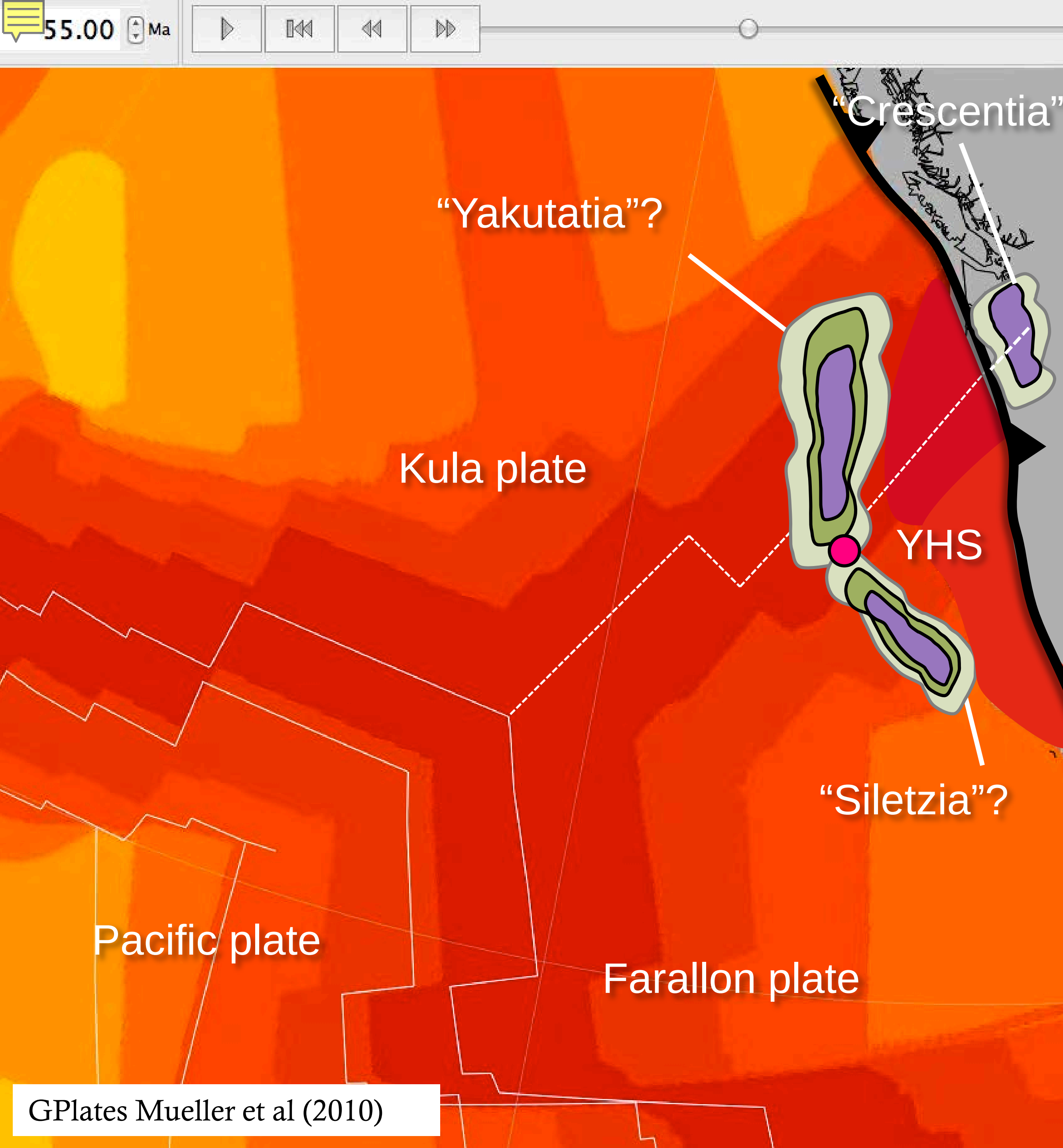


Sheeted dikes in N., not in south
Oceanic Plateau in South, ridge subduction in N?

Oregon geologic history fits accreted oceanic plateau rather than slab window/rift origin for Siletzia

* Coast Range basalt 22-32 km thick - too thick for rift crust
* No dike swarms in SRV or adjacent continent in Oregon
* Lack of early normal faulting - Thrusting is followed by rifting, not the reverse
* Basalt sequence is submarine to subaerial, not the reverse
* Sedimentary basin fill progresses from bathyal to subaerial.
* Sediments lack thermal maturity.
* No chemical evidence of continental source beneath Siletzia.





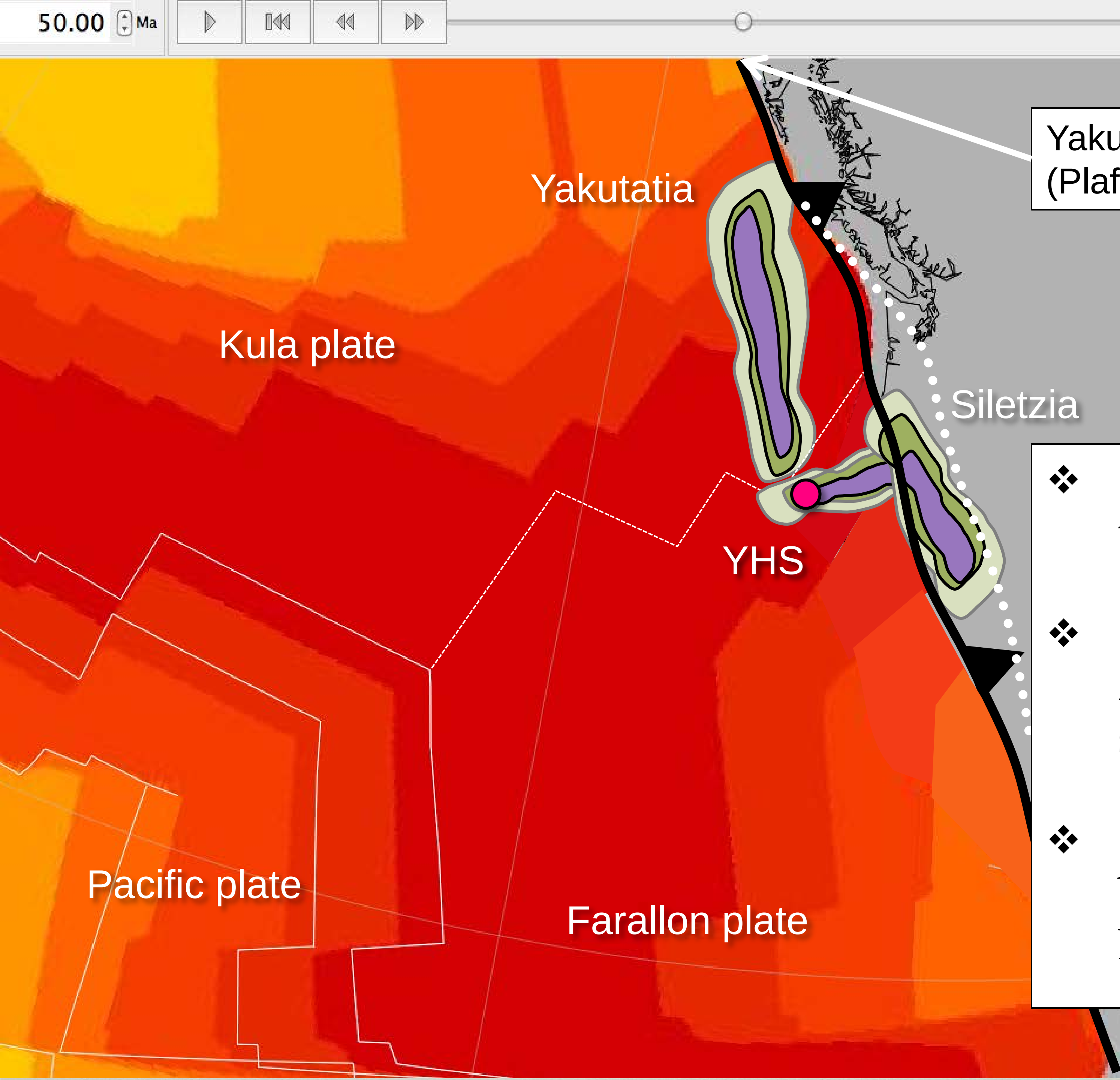
55 Ma

- K-F Ridge azimuth passes near fixed Yellowstone Hot Spot
- Resurrection-Farallon Ridge also a possibility

Siletzia source options:

- 1. Hot spot source
- 2. Ridge source
- Hot spot preferred to explain flood basalt volumes and thickness

51 Ma



Yakutat terrane source (Plafker, 1994)

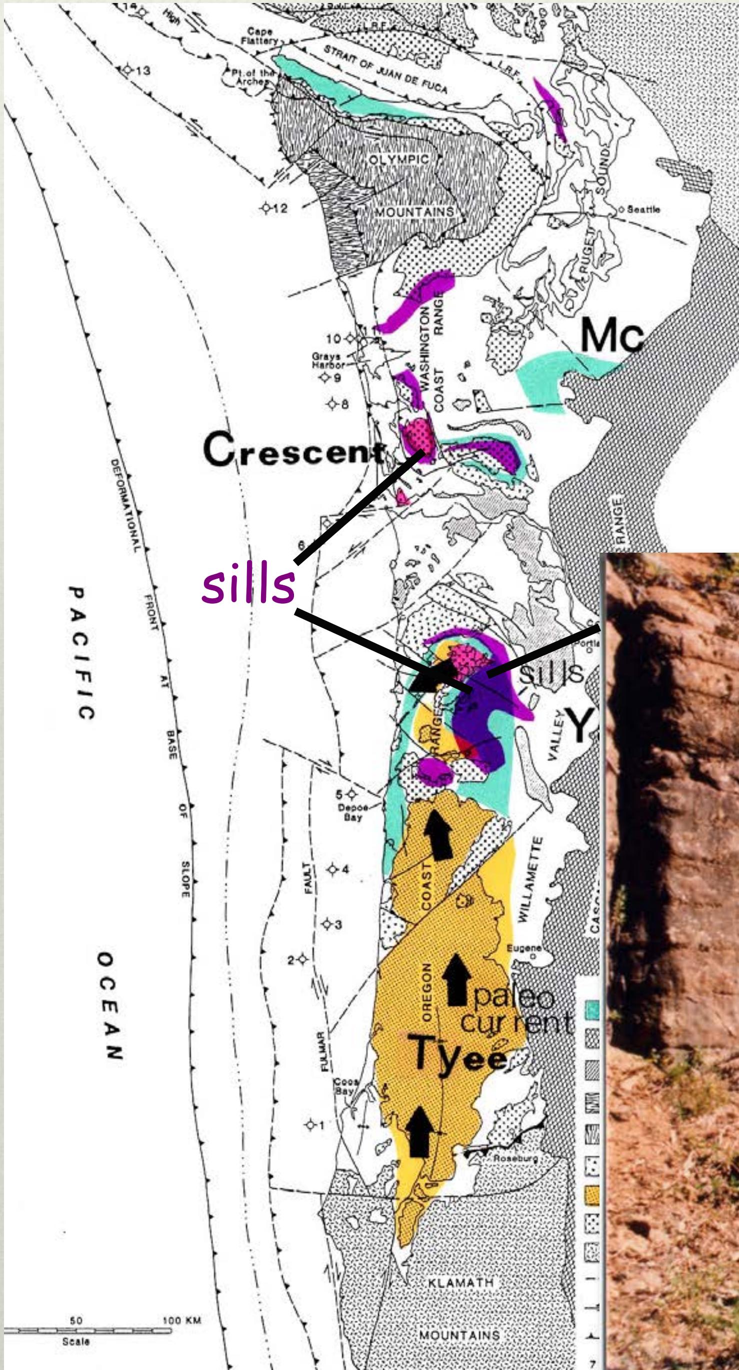
- Siletzia accreted to margin
- Subduction zone steps seaward
- Siletzia becomes part of NAM

Part Two:

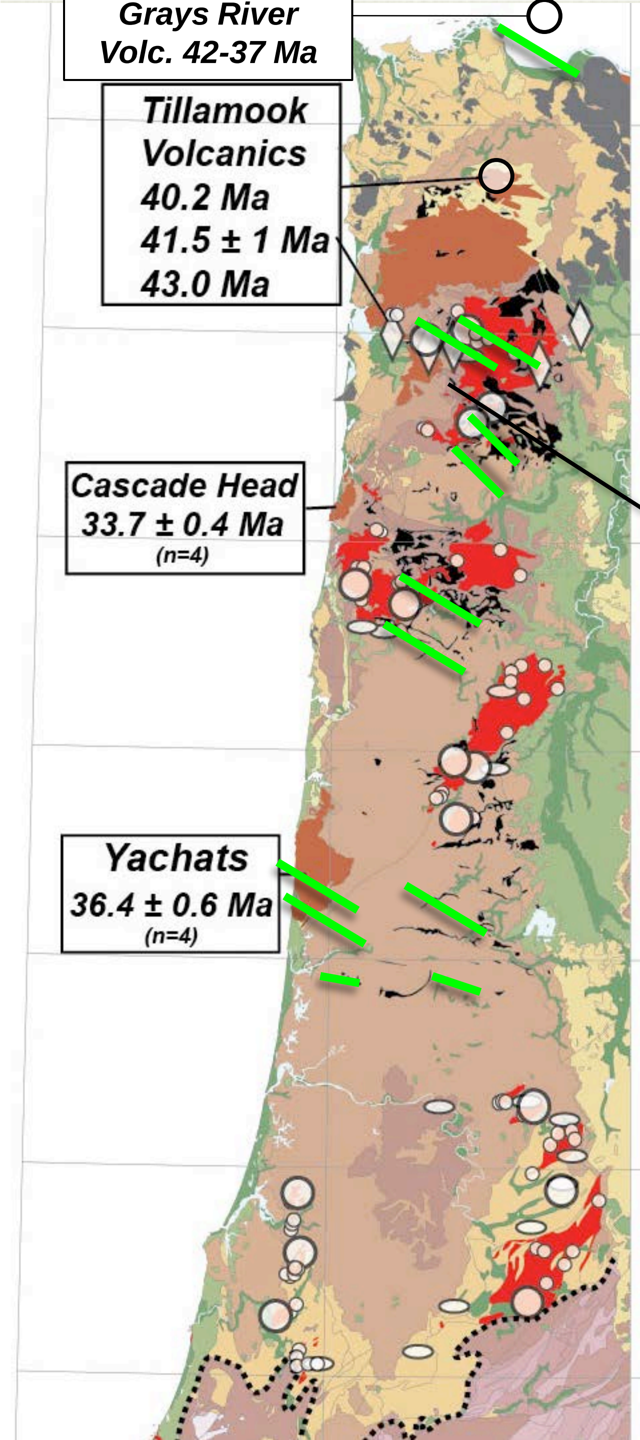
Post-accretion Reorganization and Magmatism

48-45 (?) Ma regional sills

* MORB-like major elements TiO2 1.5%, K20 < 0.2%
* subduction initiation, ridge interaction?

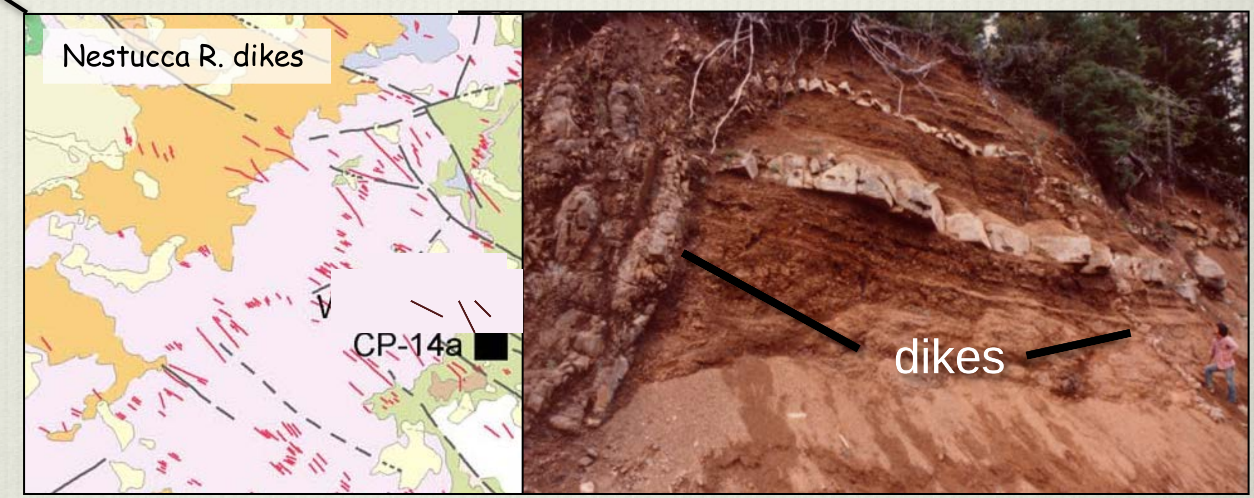


Tholeiitic and alkalic basaltic shields built after collision, 44-33 Ma (red-brown color)



Tillamook, Yachats, Cascade Head, Grays R.

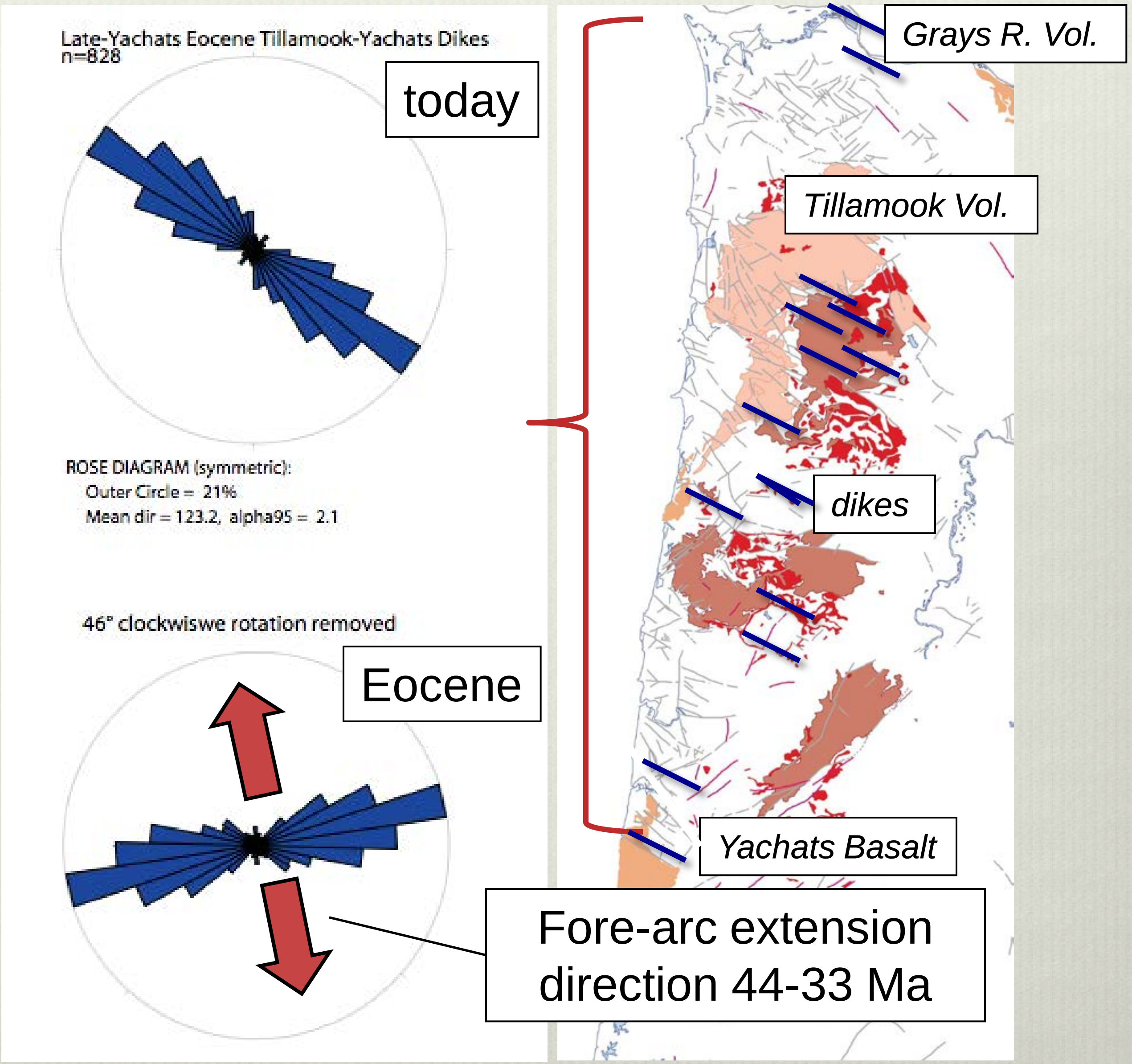
High TiO_2 basalt, 2.5 to 3.5%, bimodal



- E-MORB, OIB, Macleod and Snavely, 1974; Davis et al, 1995, Barnes, etc.
- Yellowstone He isotopic signature, Pyle et al., 2003.

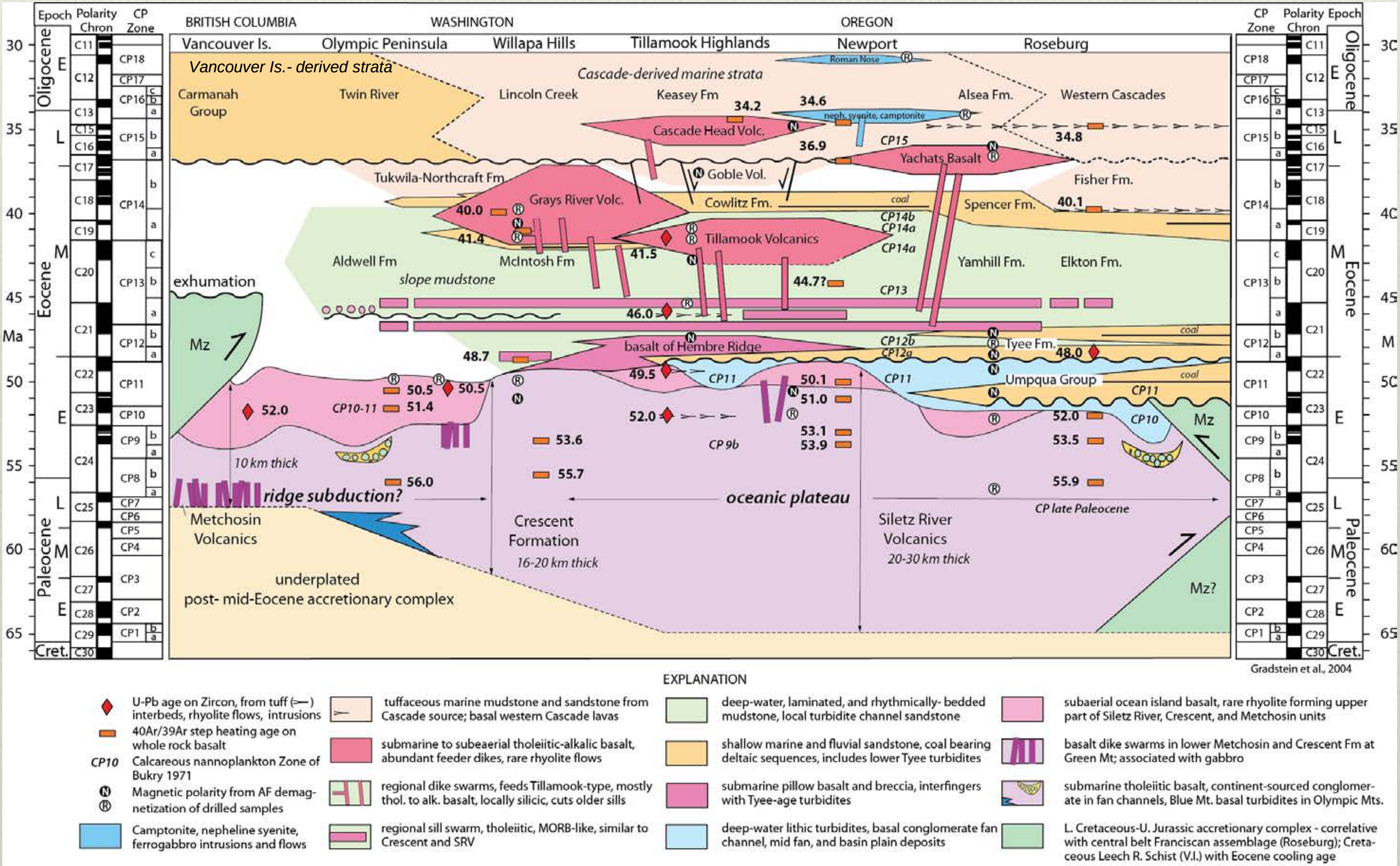
Post-accretion basaltic/alkalic volcanism was fed by regional dike swarm - margin-parallel extension.

- 828 dikes
- 303° av. Trend
- 257° after removing 46° Tillamook CW rotation.
- NNW-SSE margin-parallel extension
- Eugene to Chehalis, WA

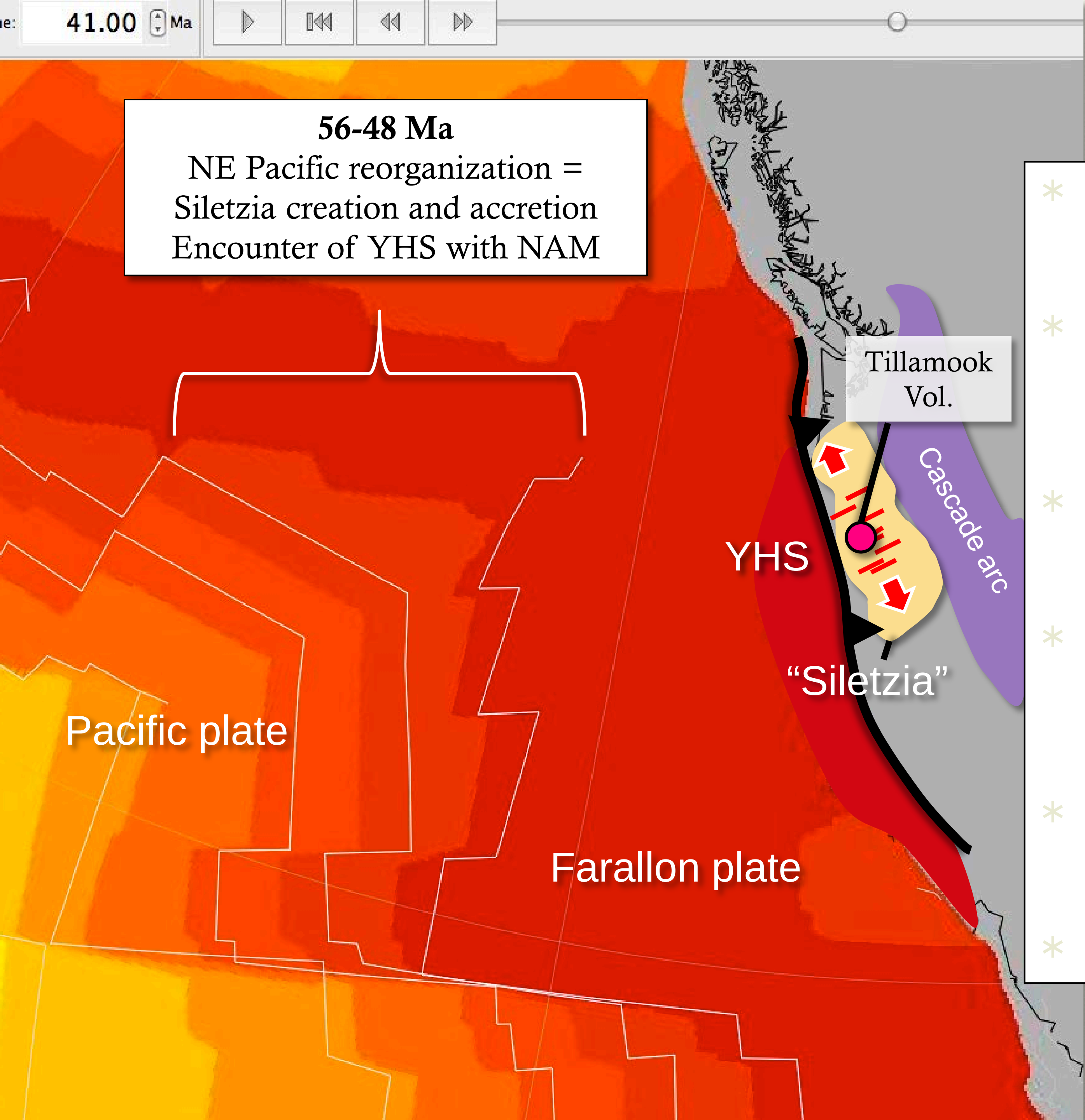


R. Wells and Z. Venera in prep.

Post-accretion – Coastal basaltic and alkalic magmatism 43-30 Ma
Cascade arc volcanism 40 Ma in Oregon



41 Ma



* NAM (Siletzia) is over YHS near Cape Blanco
* Margin parallel forearc extension and normal faulting
* Coastal dike swarm Eugene to Centralia
* Tillamook-Yachats tholeiitic and alkalic volcanism in fore-arc
* Magmatism youngs to N and S away from TV
* Arc magmatism

after Duncan,1982

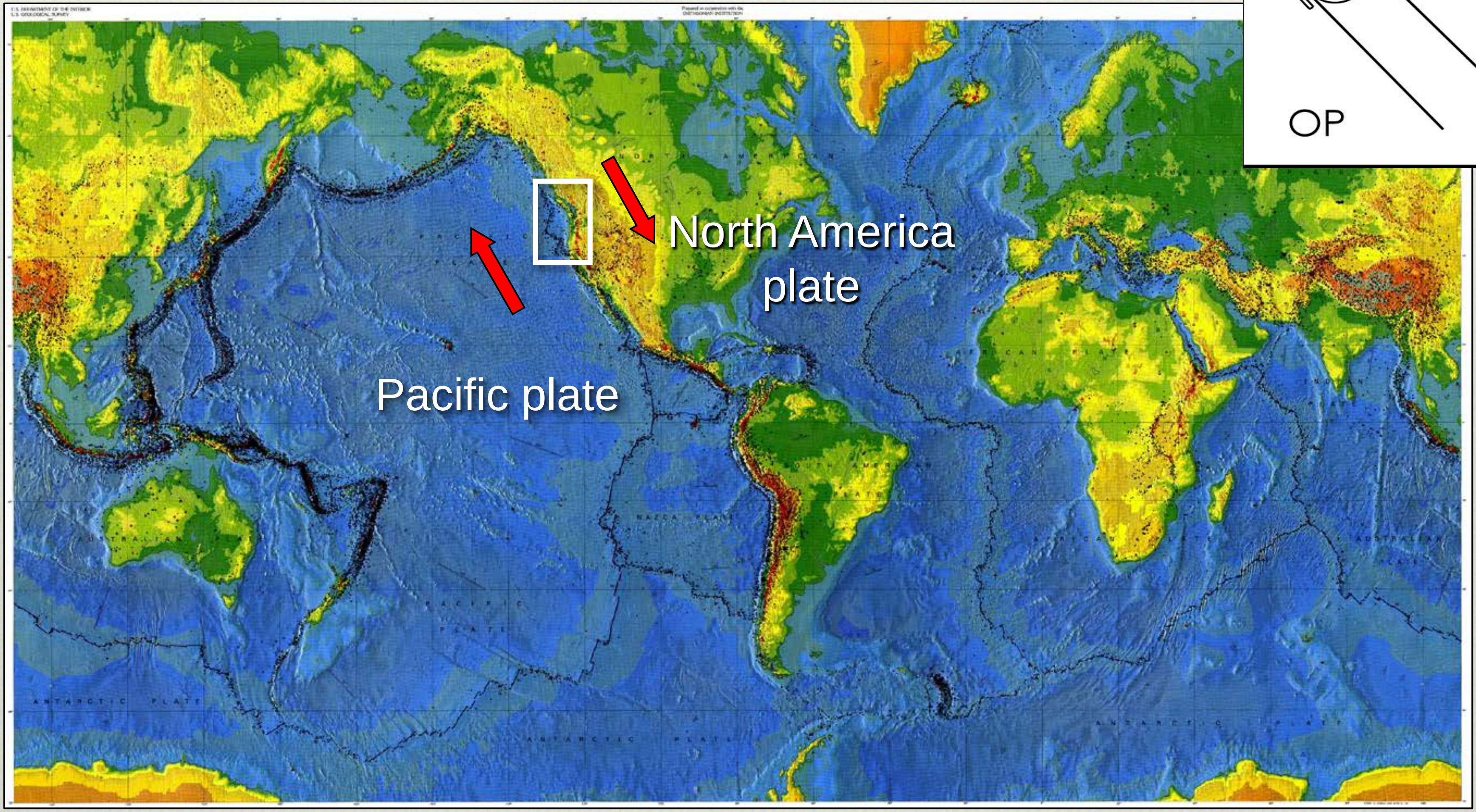
Siletzia Summary

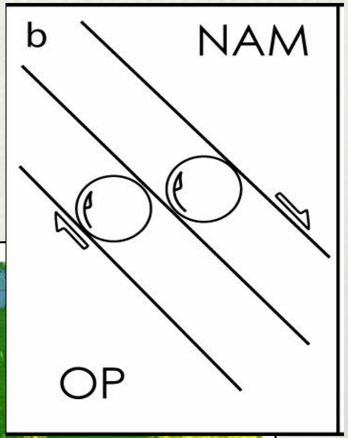
* Oceanic LIP; 14 times CRB volume.
* Age: 56-49 Ma - Chron 24-21 during NE Pacific reorganization.
* Accreted by 51 Ma.
* Post-accretion marginal rifting and magmatism 44-30 Ma contemporaneous with start-up of Cascade Arc.
* Long lived YHS could provide:
  * Nearshore source of Siletzia 56-49 Ma
  * LIP magma volumes
  * Renewed fore-arc magmatism as NAM overrode the hot spot at 43 Ma.

Part Three:

Rotation/shear overprint on the modern subduction regime

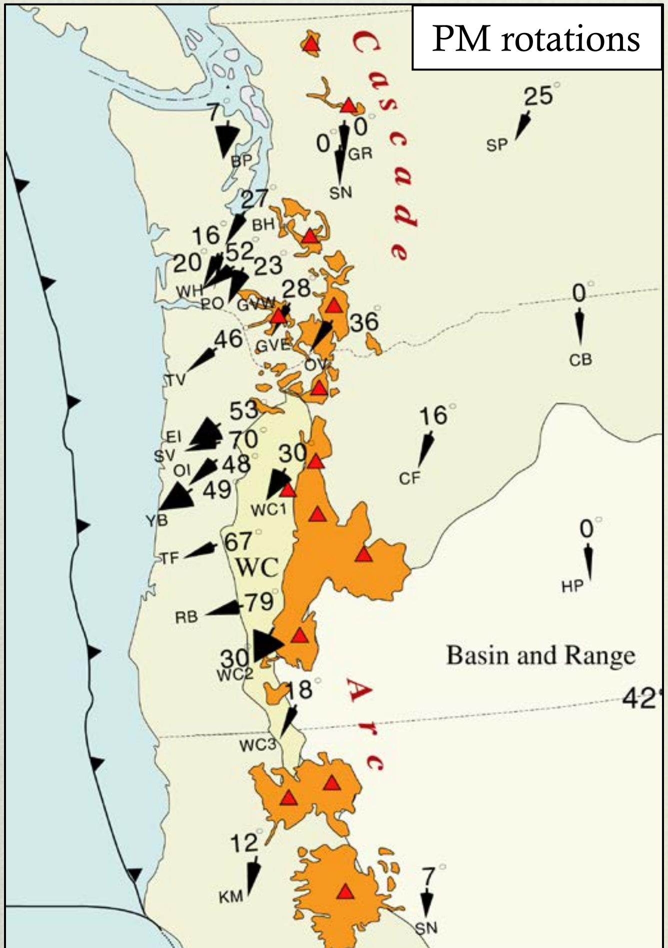
Rotation/shear overprint on modern subduction regime is significant.



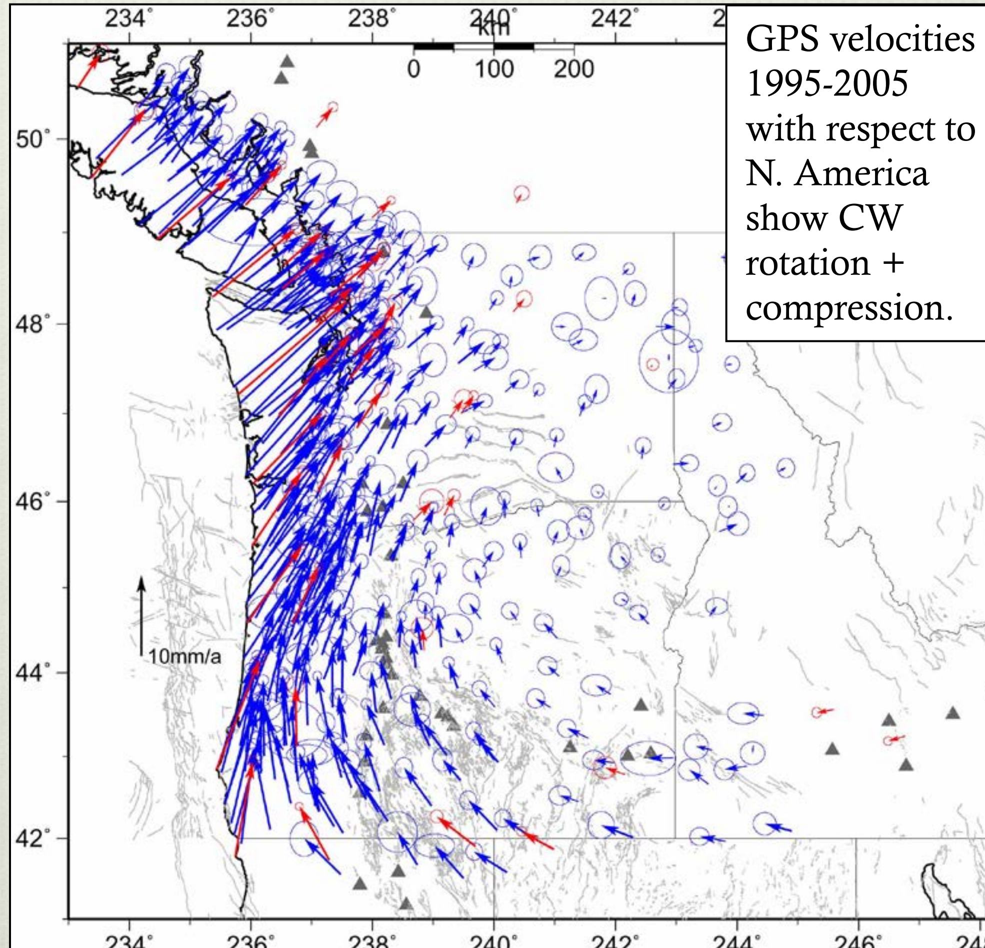


Cascadia SZ is caught in right lateral shear between two large plates.

Paleomagnetic data indicate clockwise rotation of the PNW with respect to stable NAM at about 1° /Ma since accretion of Siletzia at 51 Ma. GPS shows rotation is still occurring today.

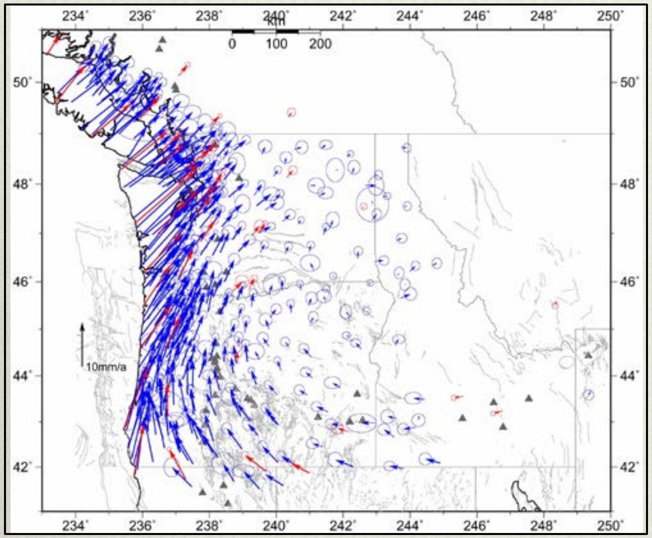


21 paleomagnetic studies, 1977-1988
summarized by Wells and Heller, 1988



Blue are campaign sites, red are continuous sites, Many institutions: RPI, UW, GSC, USGS, OSU, NGS, PANGA (McCaffrey et al., 2007).

GPS contains long term block motion + elastic deformation adjacent to big faults (McCaffrey al., 2007)



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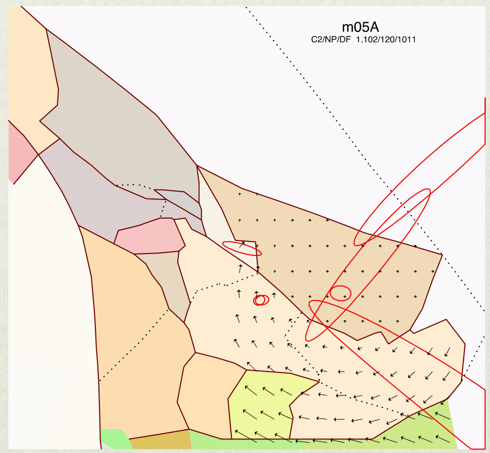

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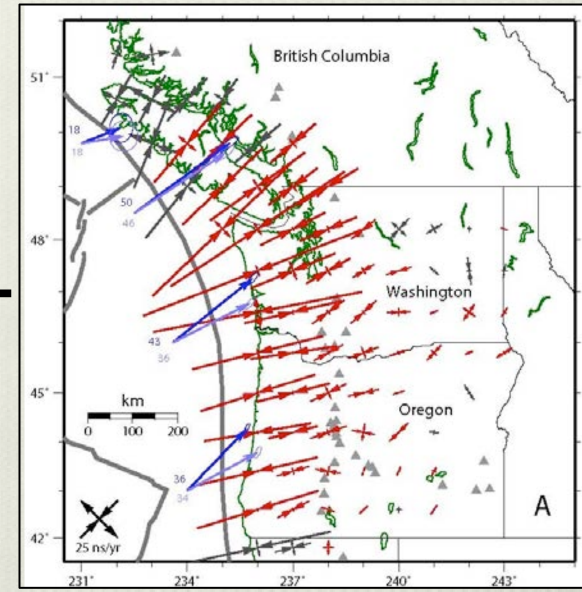
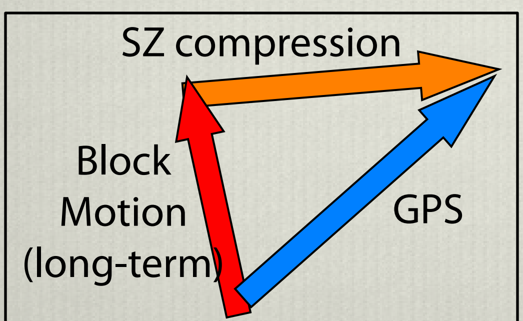
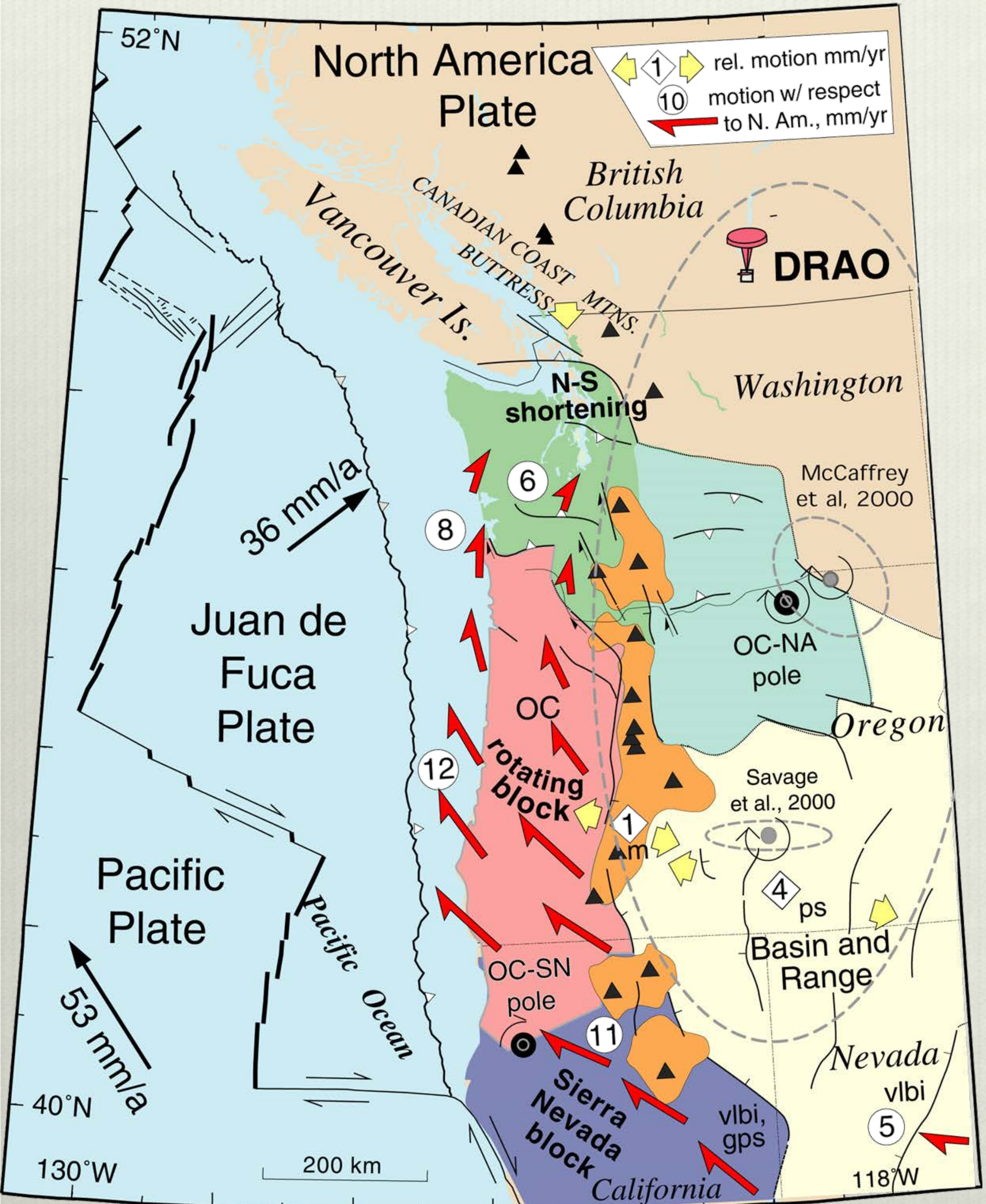


Present GPS velocity = Block motion (long-term geologic) + compression from NE moving Juan de Fuca plate along locked megathrust



(Red arrows show direction of shortening)

Block motions cause margin-parallel shortening

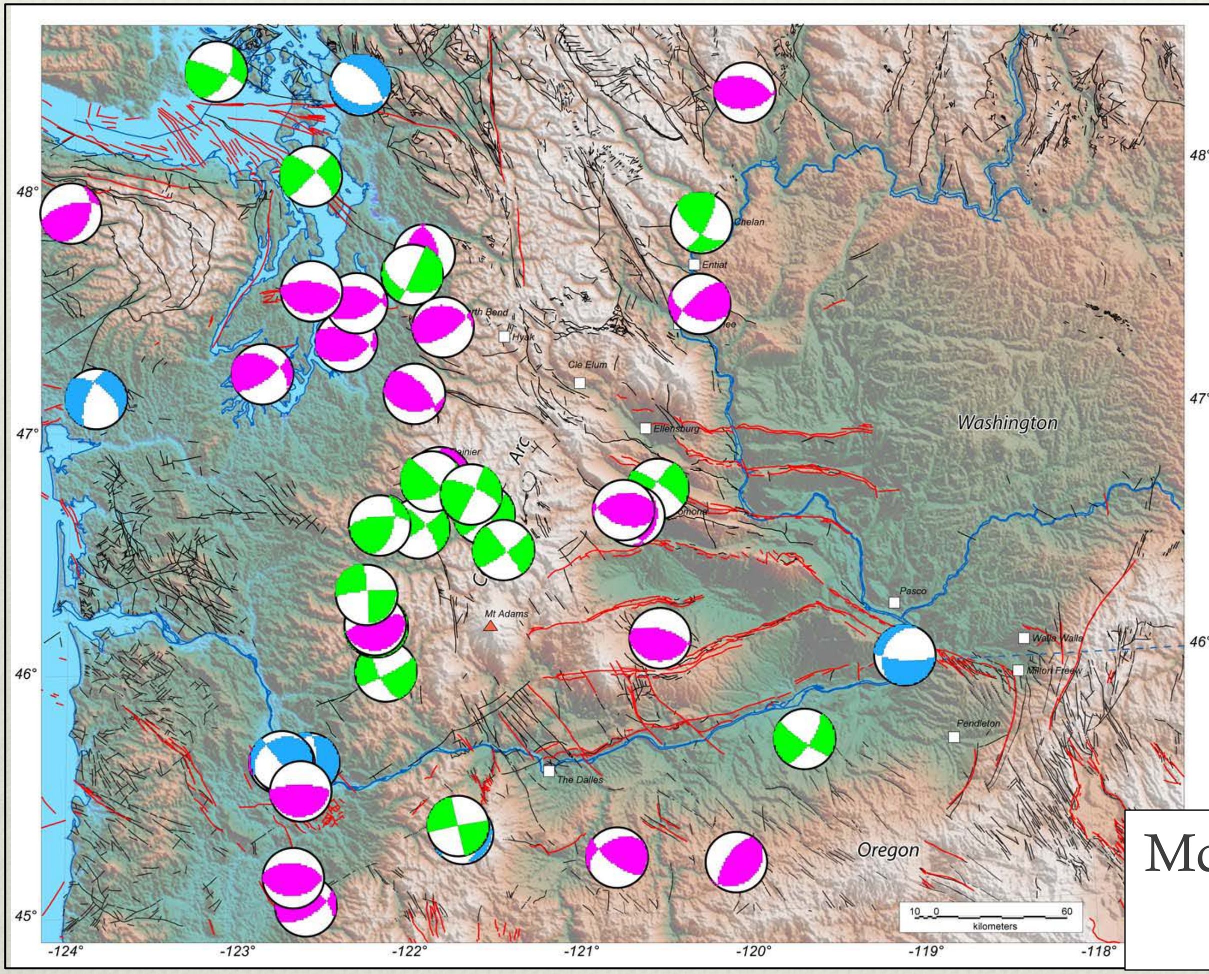


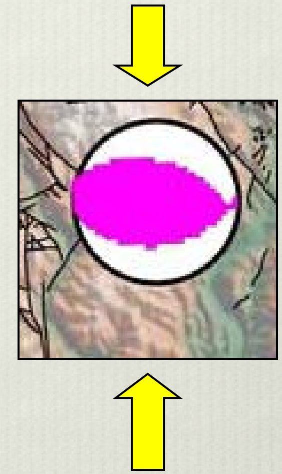
- Sierra Nevada dragged northward by Pacific Plate
- Oregon (pink) pivots clockwise to get out of the way
- Washington (green) gets squeezed against Canada, producing earthquakes and faults.
- SE Oregon and Nevada stretch to fill in the gap behind rotating block

after Wells et al., 1998; Wells and Simpson, 2001; Wang et al., 2003

USGS science for a changing world

Thrust earthquakes accommodate northward motion of Oregon



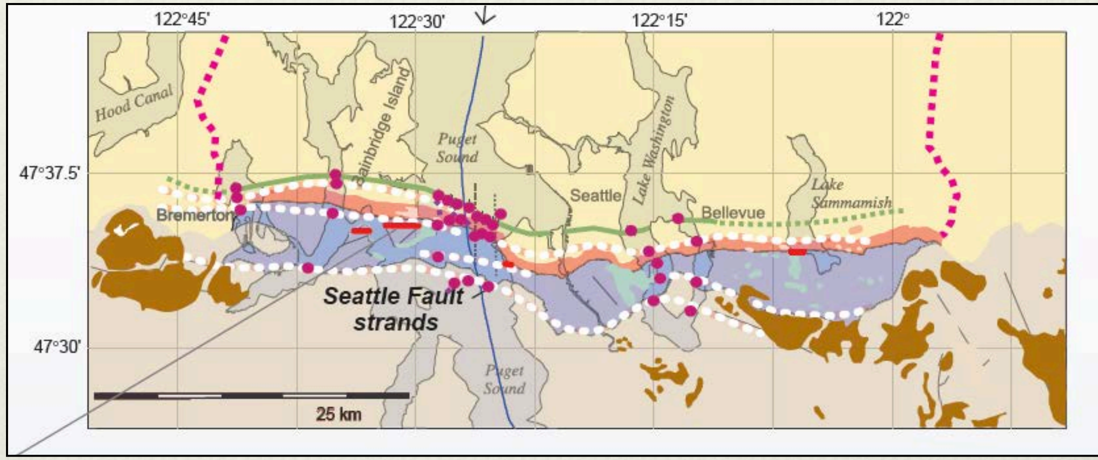


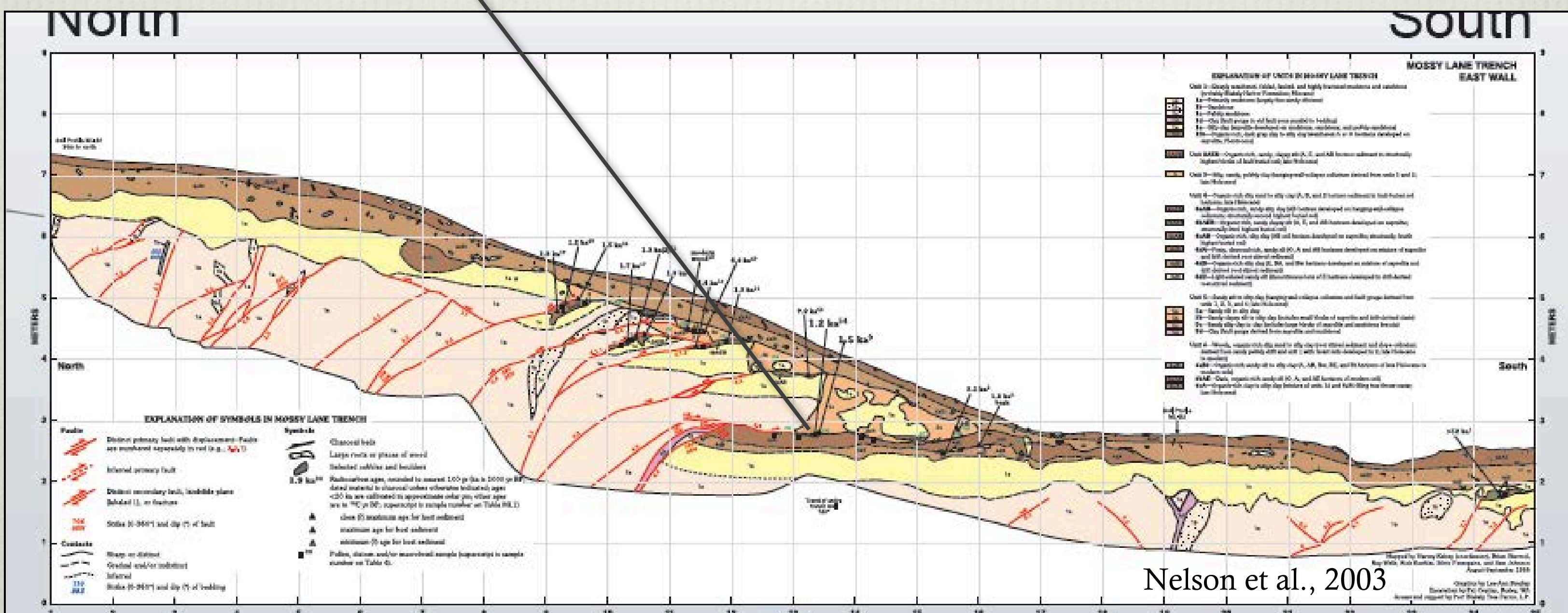
Thrust earthquake
Focal mechanism

McCaffrey et al 2007;
PNSN, OSU

Surface rupturing earthquakes on Seattle thrust have occurred repeatedly in the past 2500 years.

- Trench wall shows 13 million-year-old bedrock thrust over young forest soil containing 1,200 yr-old log.



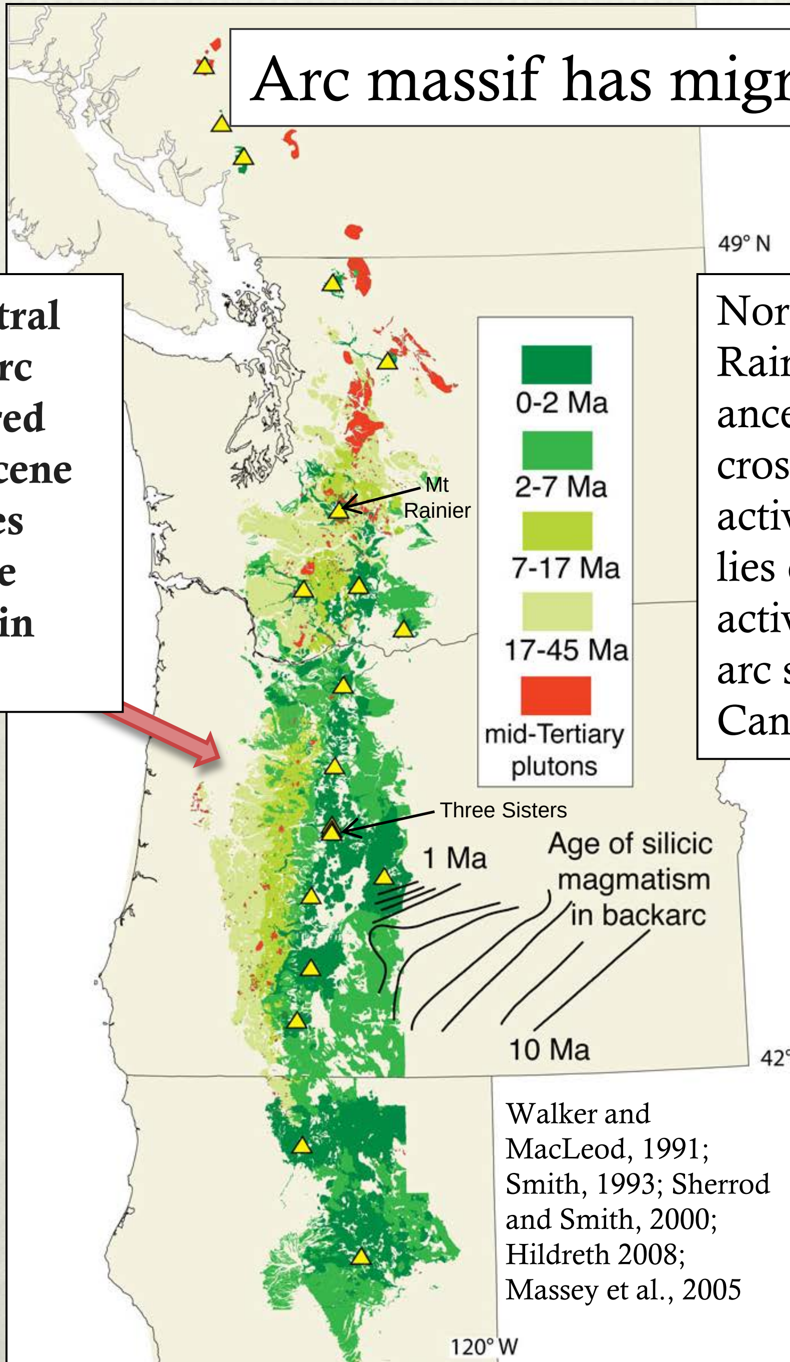


Nelson et al., 2003

How does Cascade arc respond to block motions?

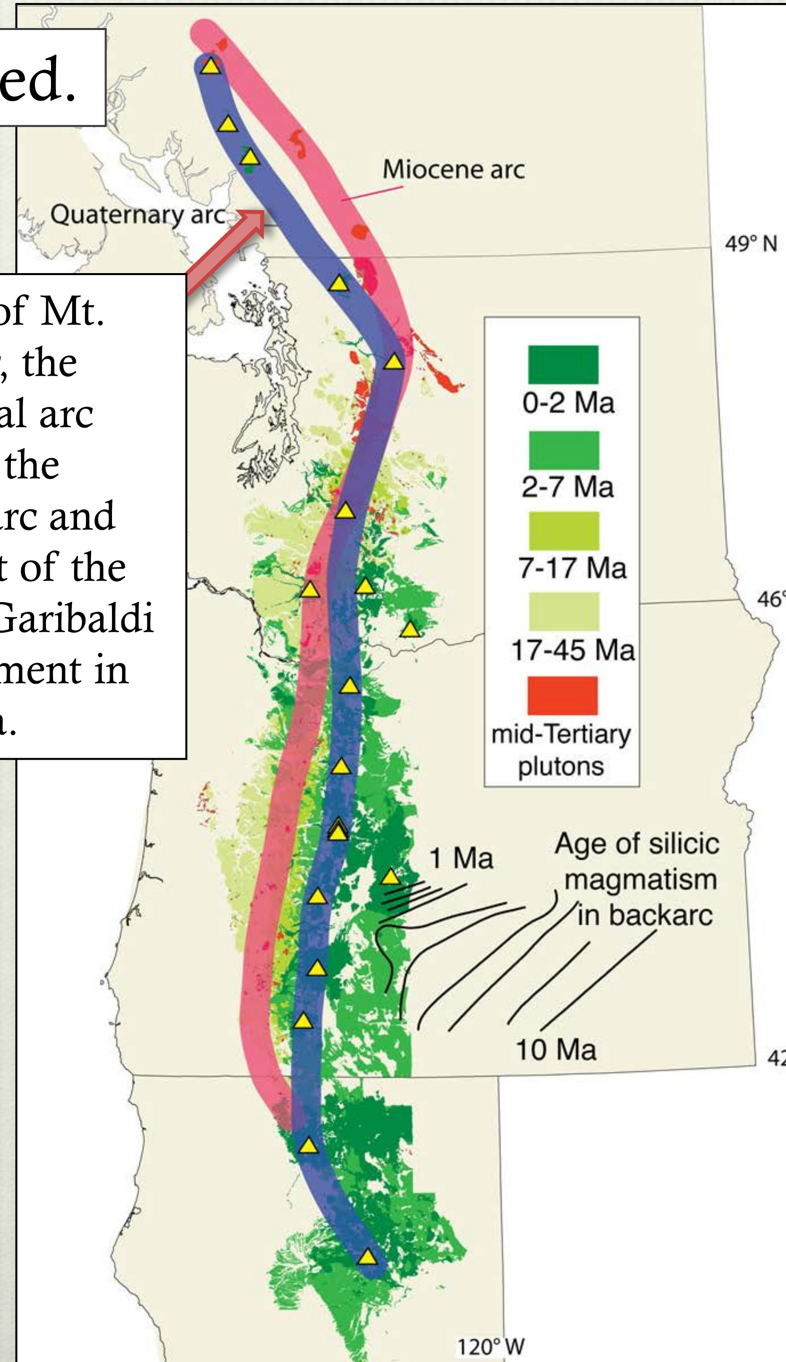
Arc massif has migrated.

The ancestral Cascade arc axis inferred from Miocene plutons lies west of the active arc in Oregon.

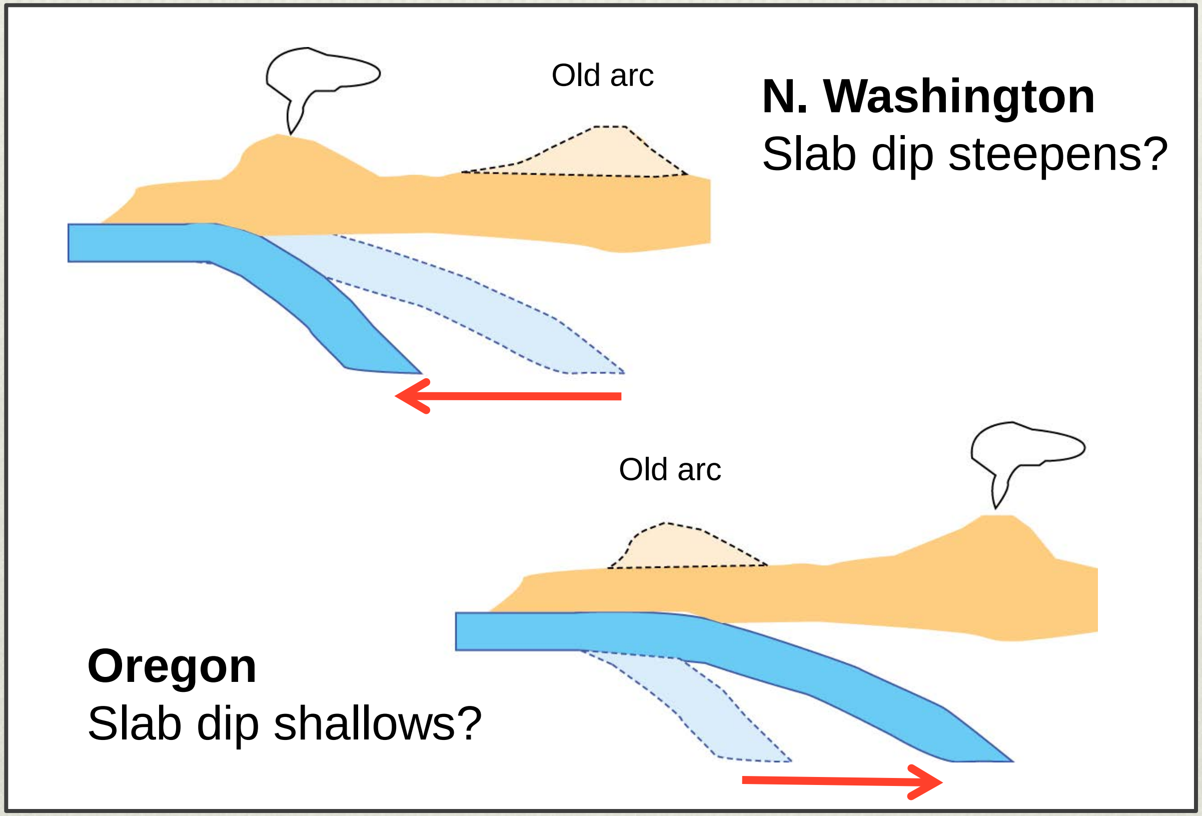


Walker and MacLeod, 1991; Smith, 1993; Sherrod and Smith, 2000; Hildreth 2008; Massey et al., 2005

North of Mt. Rainier, the ancestral arc crosses the active arc and lies east of the active Garibaldi arc segment in Canada.



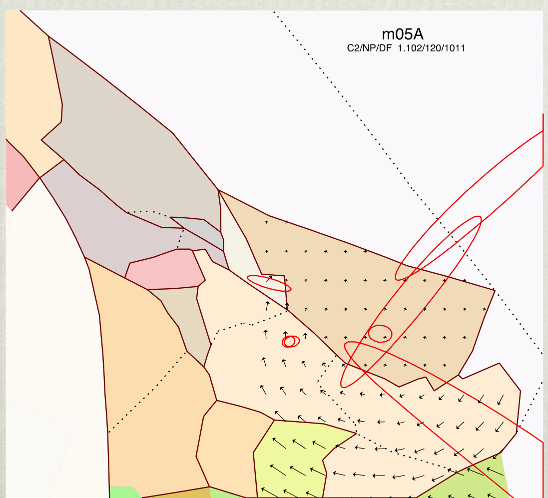
Changing slab dip might explain arc migration.

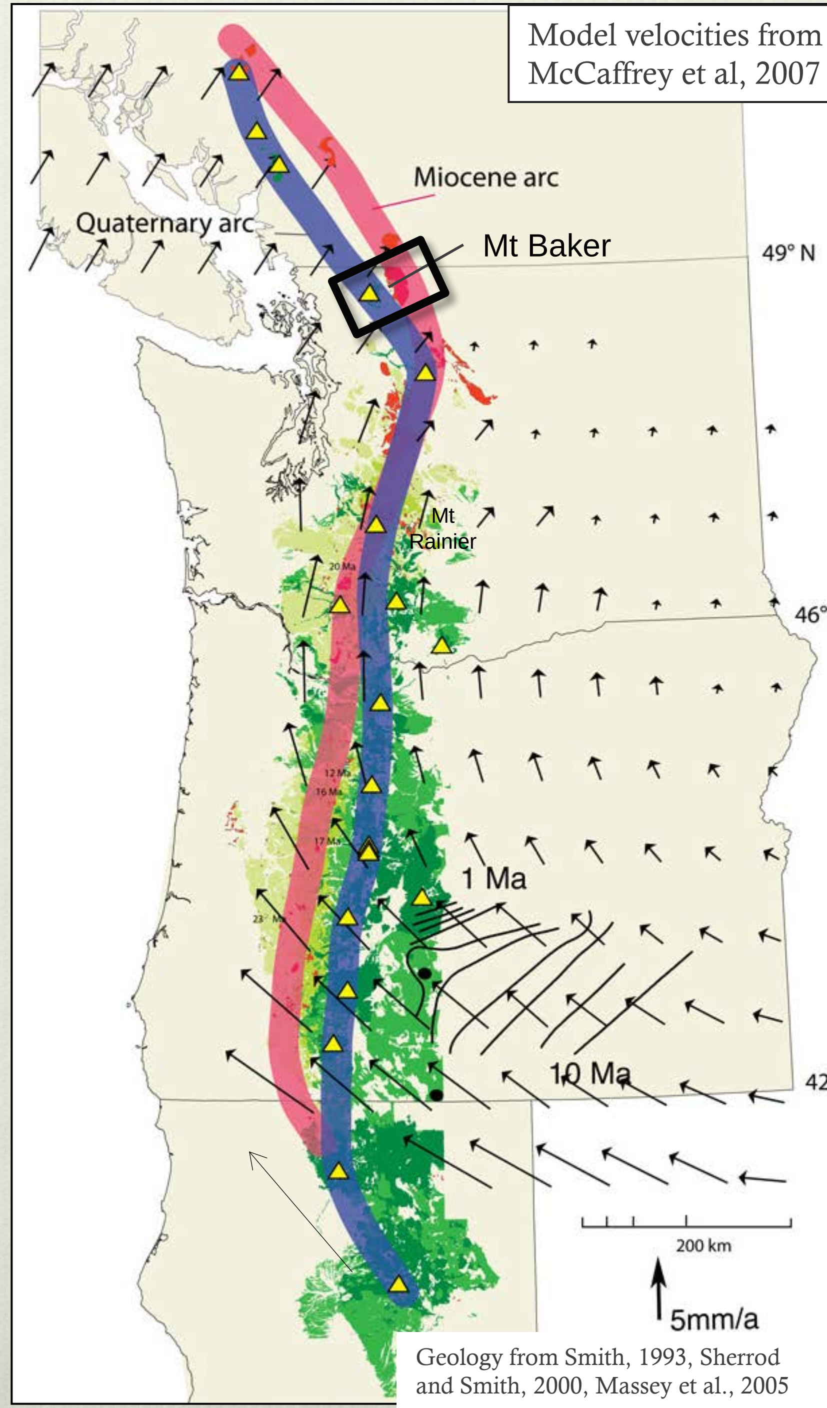


More likely, the old arc has rotated with the upper plate

- **Westward** apparent displacement of Miocene arc from modern axis in Oregon is consistent with its northwest GPS velocity with respect to North America.
- **Eastward** apparent displacement of Pemberton Belt in B.C. is consistent with its northeast GPS velocity.
- Modern and ancient arcs are nearly congruent where velocity is parallel to arc trend.

Secular microplate motions from GPS data (after removing CSZ locking; McCaffrey et al., 2007)



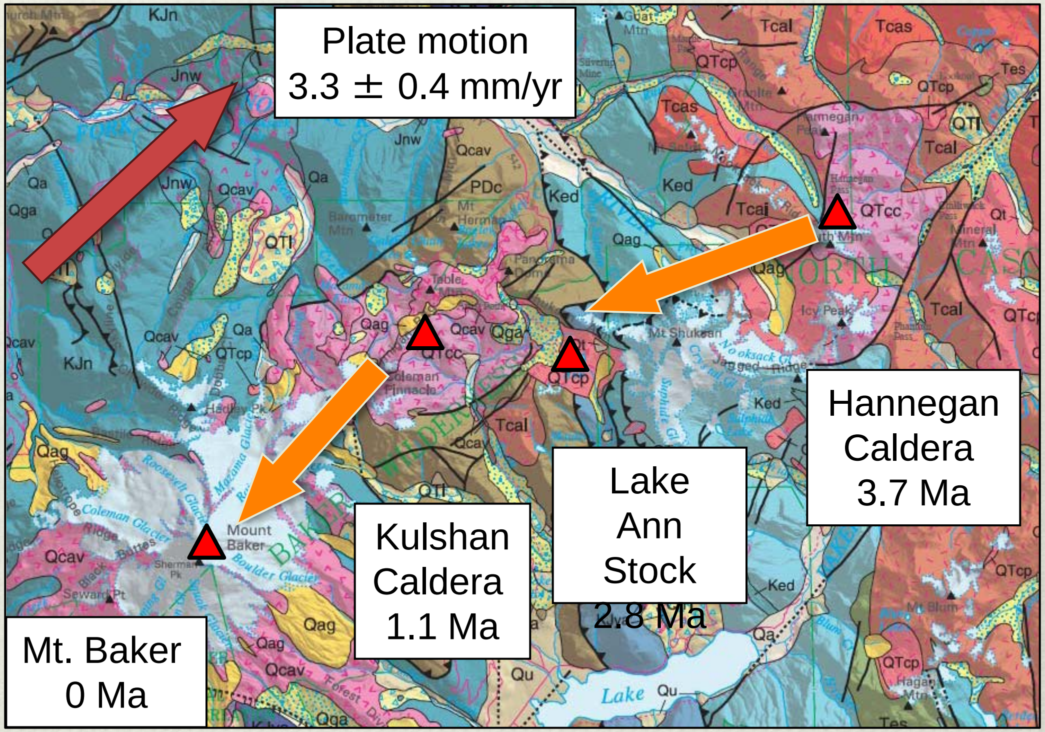


Model velocities from McCaffrey et al, 2007

Geology from Smith, 1993, Sherrod and Smith, 2000, Massey et al., 2005

At Mt. Baker, shift of magmatic focus is consistent with observed N42° E plate motion with respect to NAM.

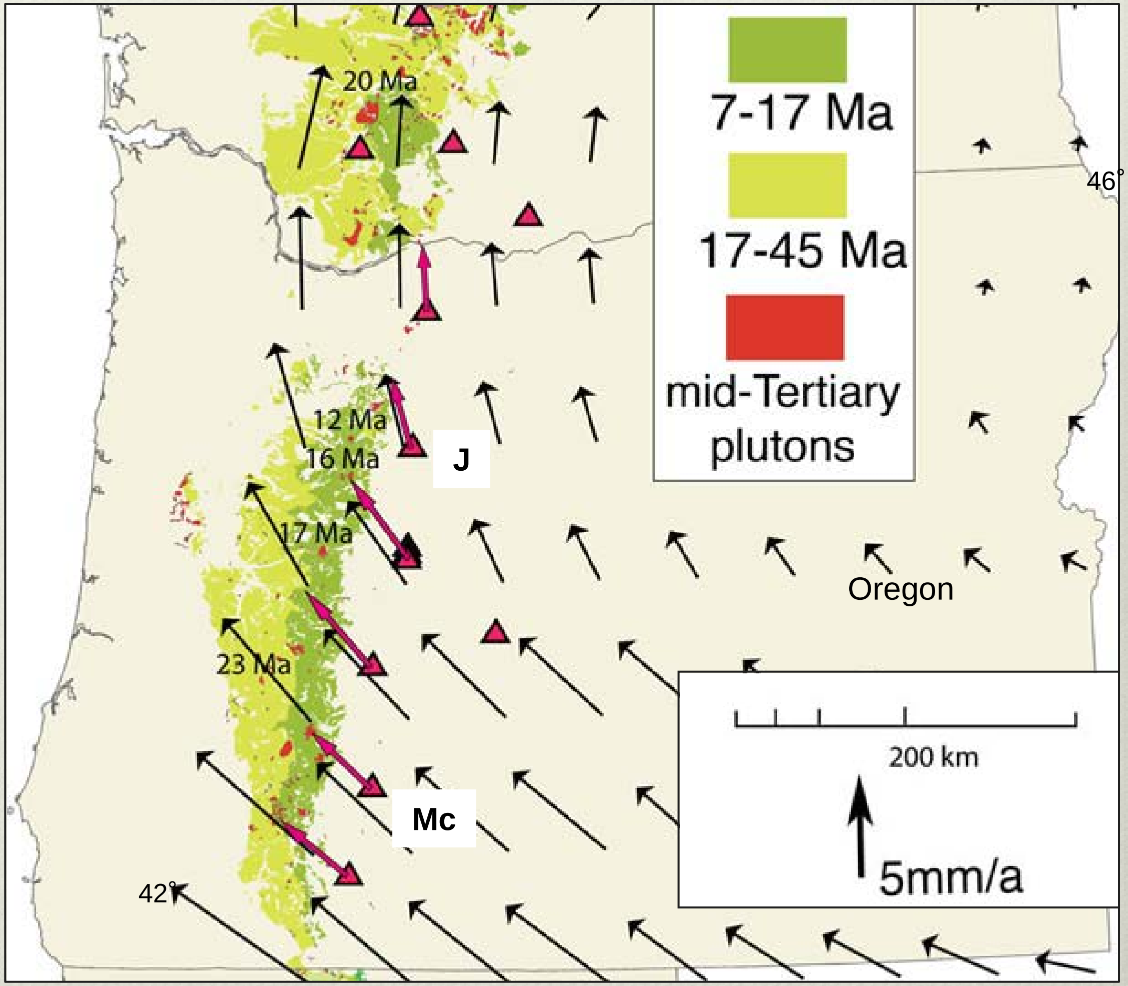
- Mt Baker mini-hot spot track
- More than half of the magmatic migration at 6.3 mm/yr can be explained by block motion.
- Is there additional slab rollback?



Modified from Tabor et al., 2003, Hildreth et al., 2003, Hildreth, 2007

In Oregon, Miocene plutons lie 75-110 km NW of the High Cascade axis in the direction of current plate motion.

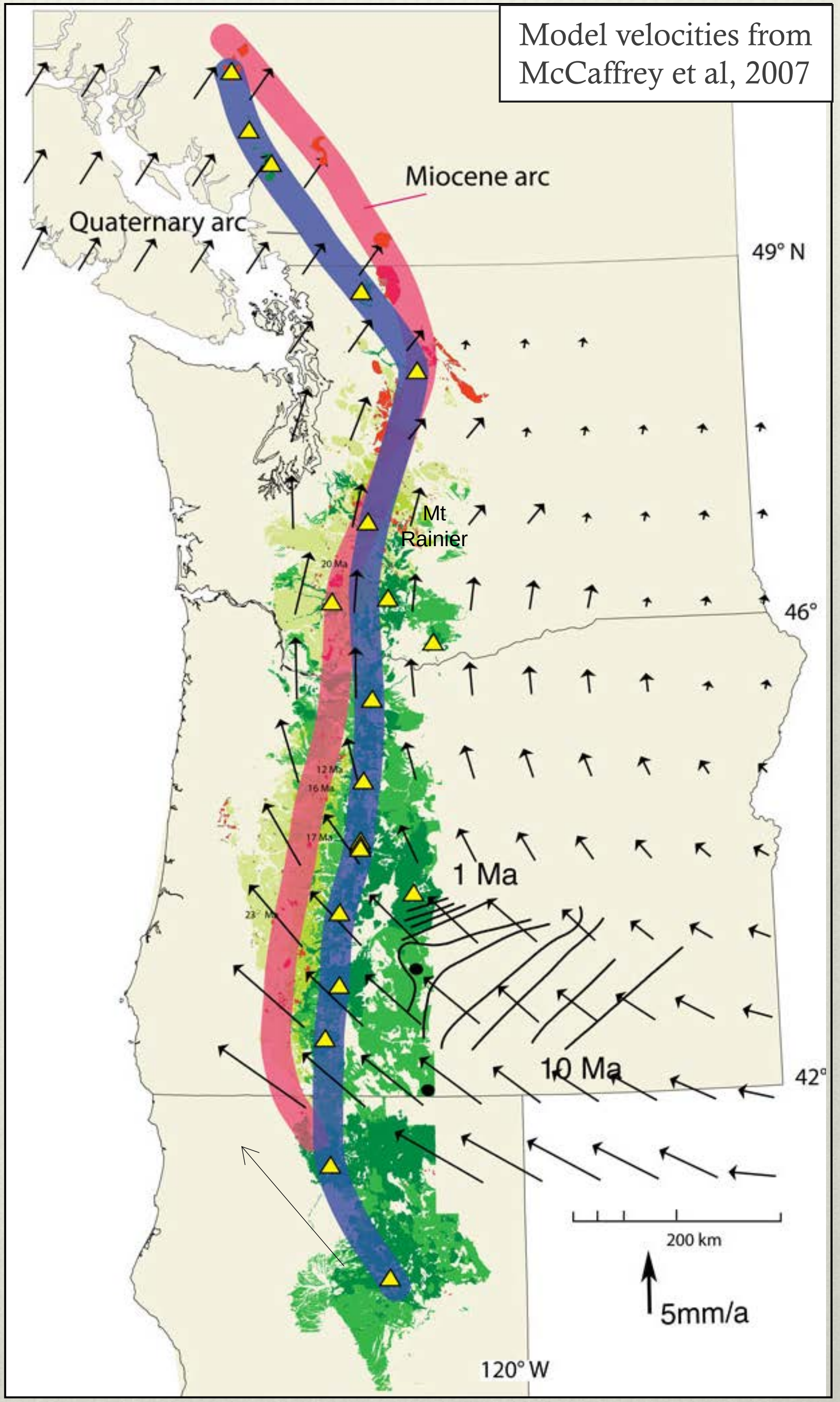
- Geologic rates inferred since 16 Ma:
  - 4 mm/yr from Mt. Jefferson
  - 6.8 mm/yr from Mt. McLoughlin.
- GPS current motion:
  - 3.6 mm/yr at Mt. Jefferson
  - 7.7 mm/yr at Mt. McLoughlin
  - Nearly same as geologic rates from pluton offset
- Implication: Plutons were generated near arc axis (in NAM ref. frame) and rotated to present position at the geodetic rate.



Geology from Sherrod and Smith (2000) and Smith 1993), Dubray and John, in prep.; GPS velocity model (black arrows) from McCaffrey et al.(2007).

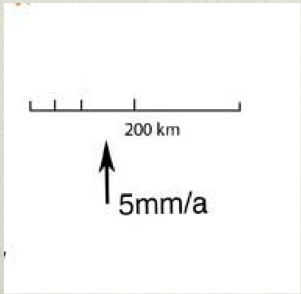
Rotation of the upper plate can explain most of the arc displacement.

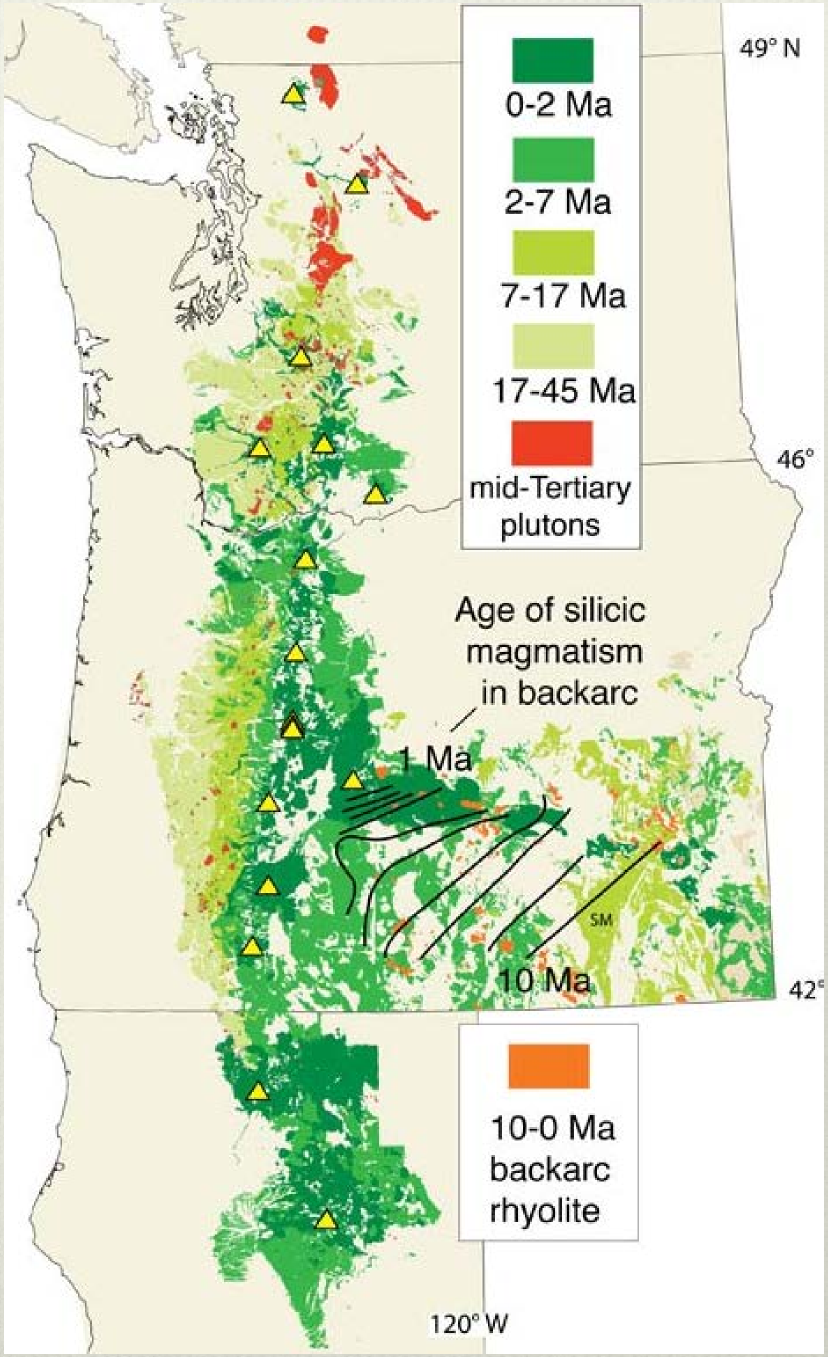
- **Old arc is rotated above an arc magma source nearly fixed in the NAM reference frame**
- That is, arc source moves with NAM as JDF plate rolls back (in HS ref frame, e.g., Zant and Humphreys, 2008)



0 Ma

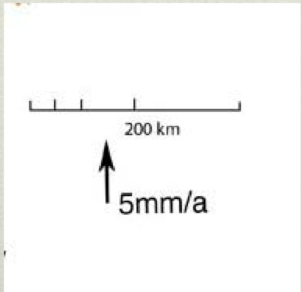
Assuming constant rotation rates 16-0 Ma, we can reconstruct past arc positions from GPS poles.

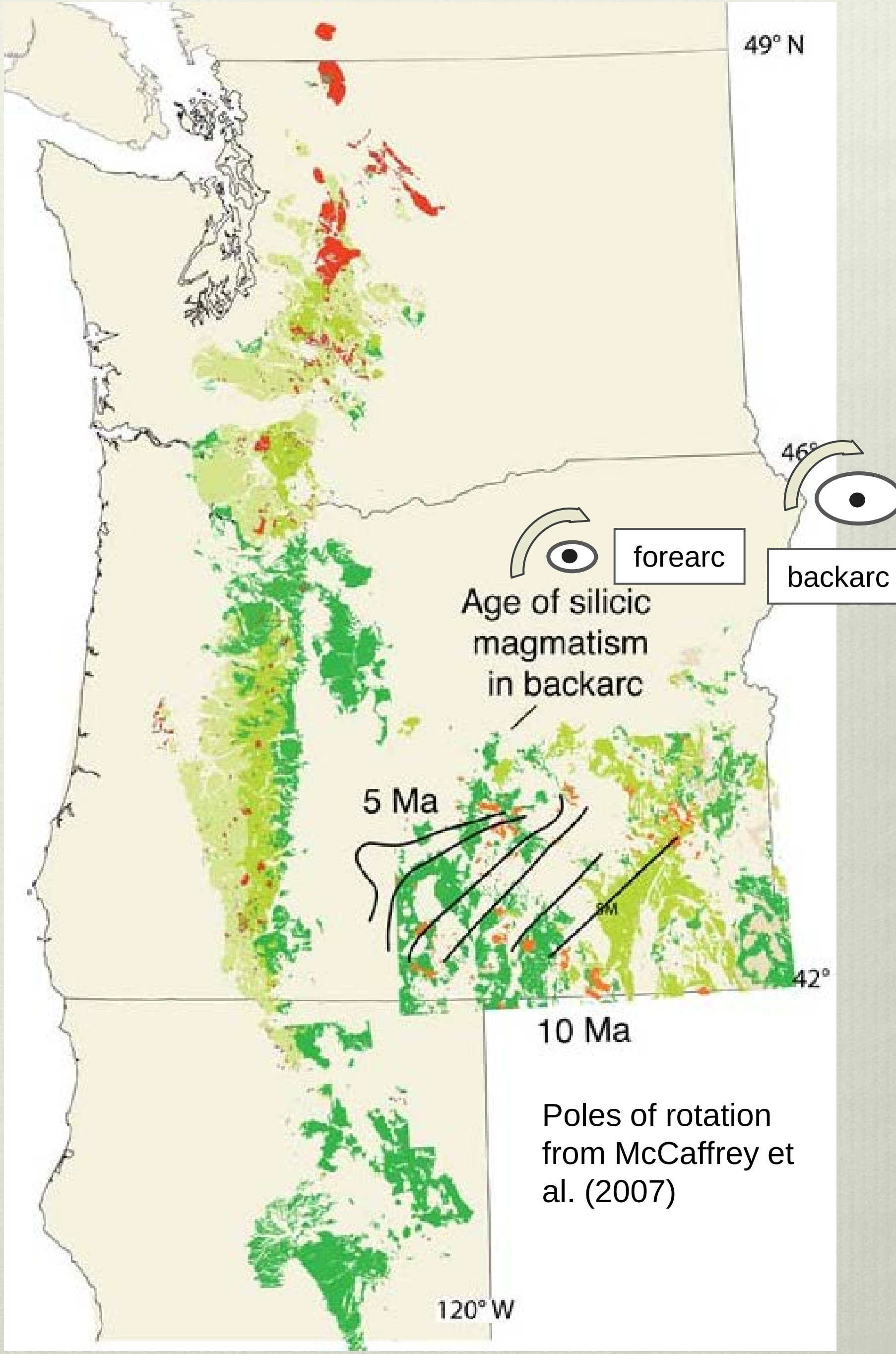




5 Ma

Assuming constant rotation rates 16-0 Ma, we can reconstruct past arc positions from GPS poles.

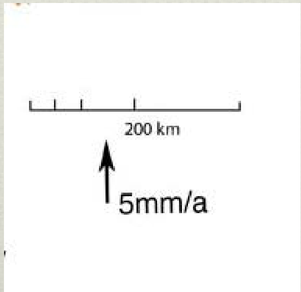


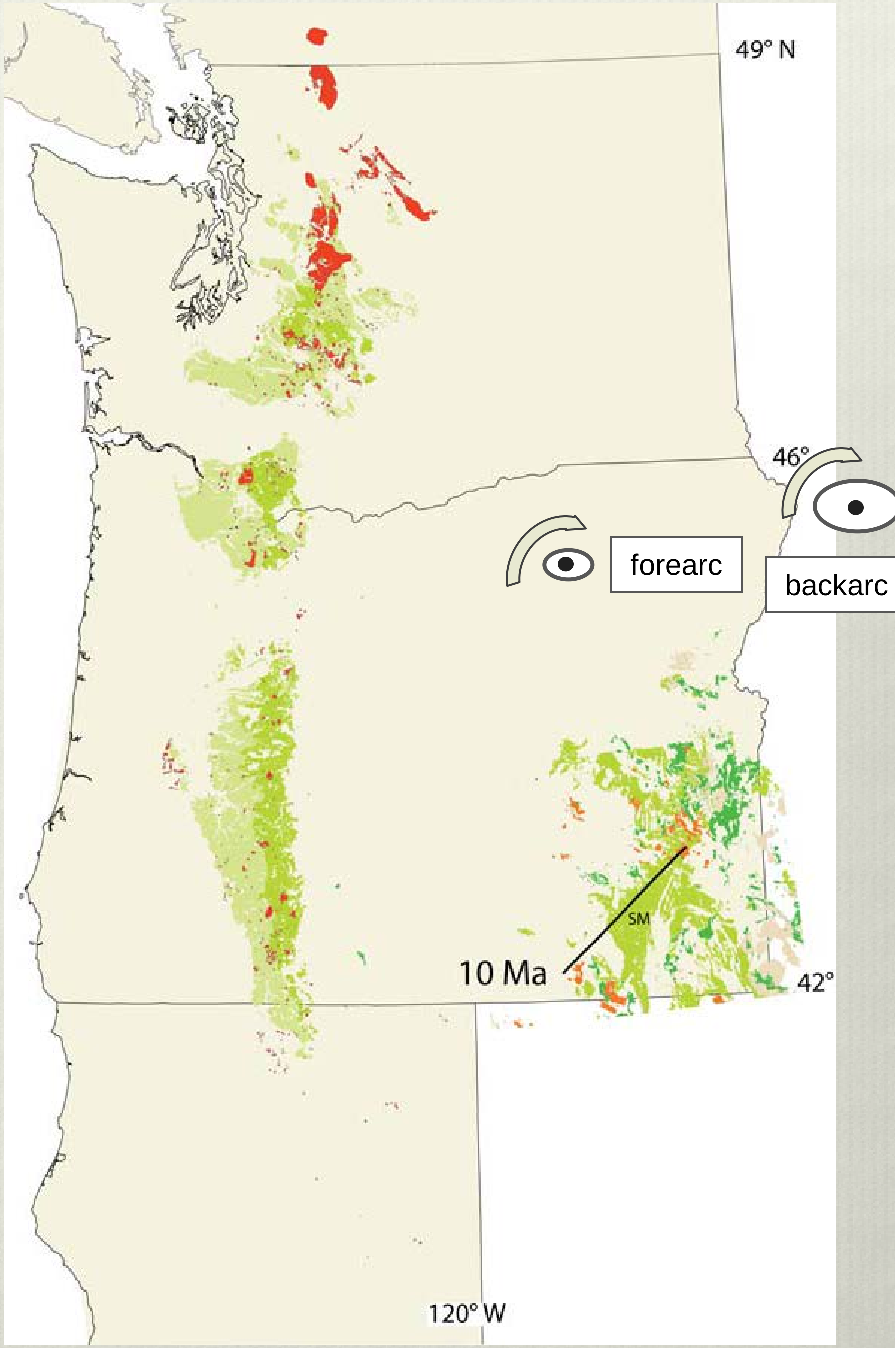


Poles of rotation from McCaffrey et al. (2007)

10 Ma

Assuming constant rotation rates 16-0 Ma, we can reconstruct past arc positions from GPS poles.

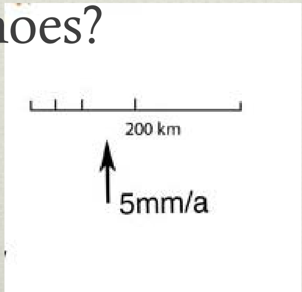


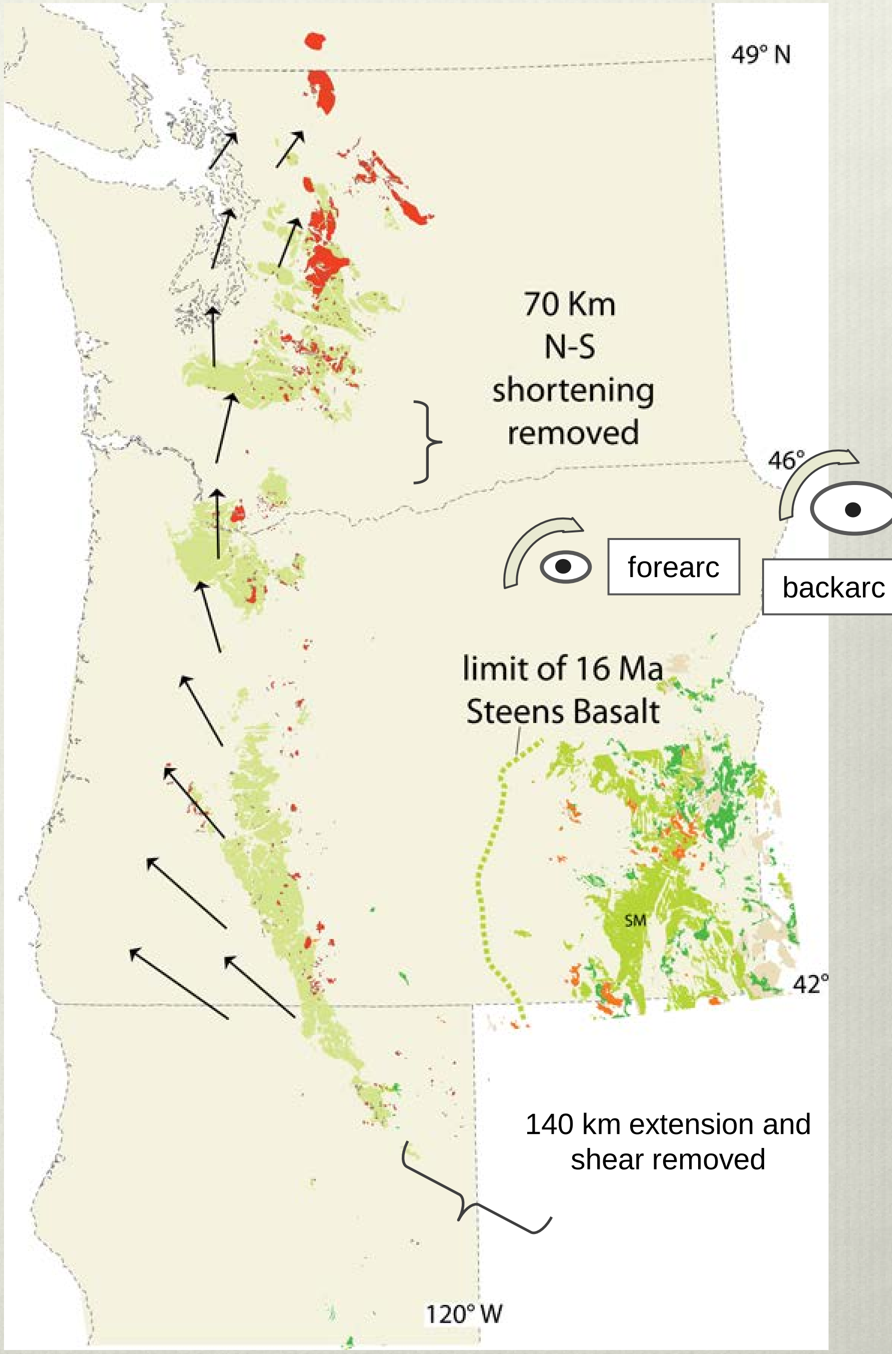


16 Ma

Assuming constant rotation rates 16-0 Ma, we can reconstruct past arc positions from GPS poles.

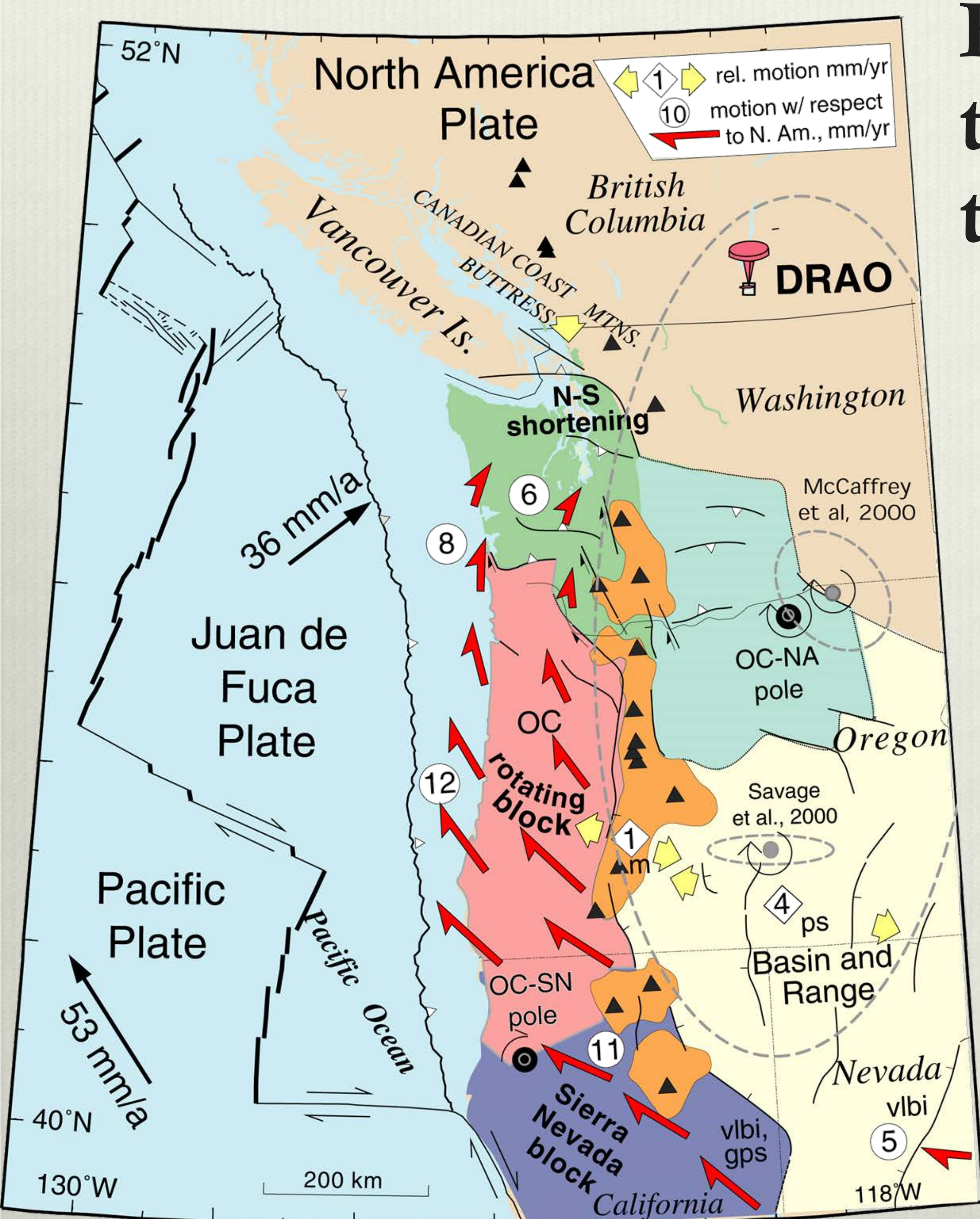
- Model implies: 70 km N-S shortening in arc
- Even more in forearc.
- Where is it?
- Affect on volcanoes?





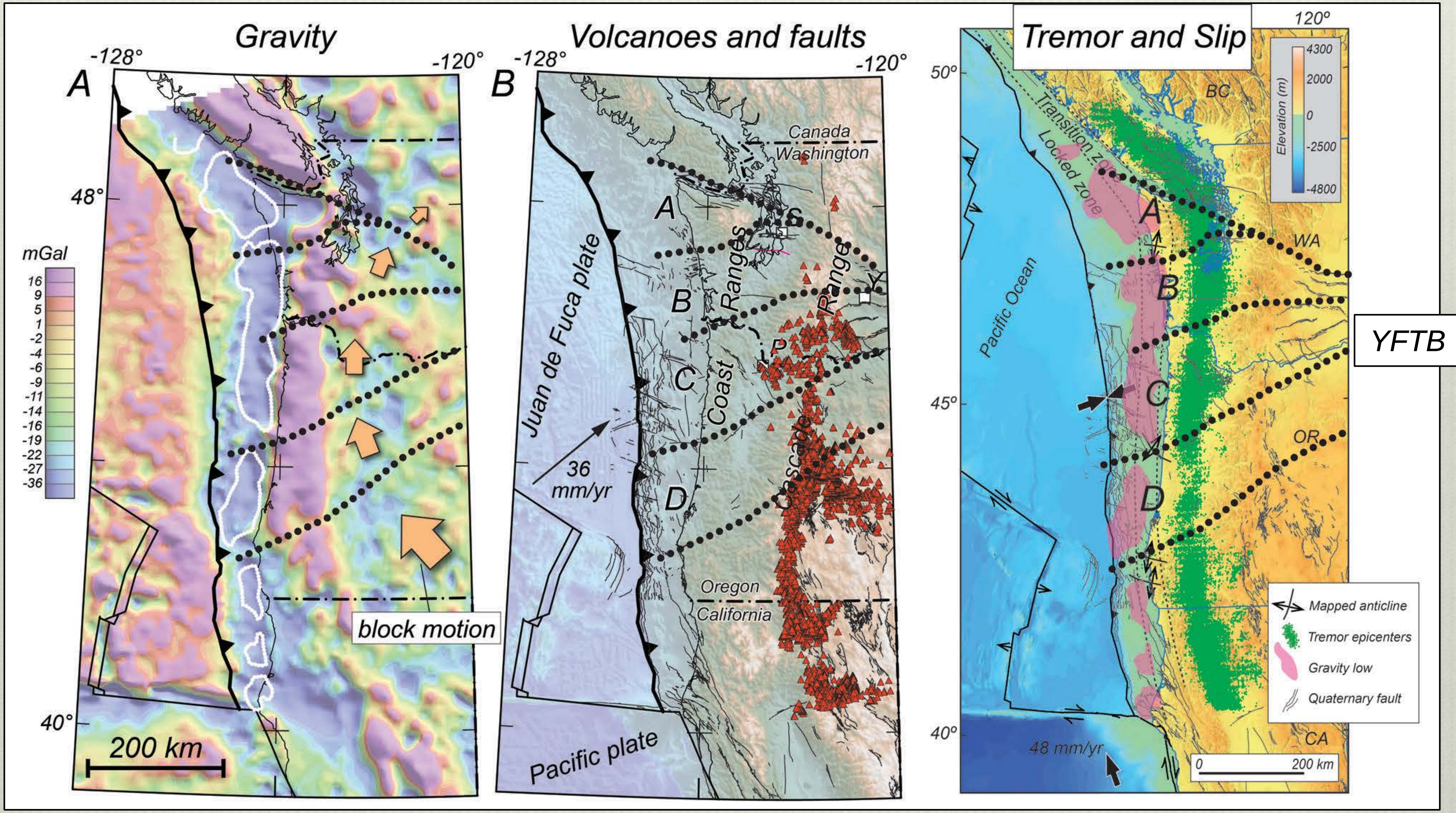
Rotation causes margin segmentation.

Block rotations tectonically segment the margin.



- Orientation of plate boundary and convergence change along strike
- Arc changes from extensional to compressional
- Transverse structures accommodate margin parallel shortening.

Hypothesis: Northward motion deforms and segments upper plate. How does this affect volcanism and seismicity?



- See poster by Anderson, Blakely, Sherrod, Bedrosian and Wells in Poster Session

Post-accretion rotation and shear - summary

* Clockwise rotation since 50 Ma at ~ 1°/Ma.
* Rotation driven by Pac-Nam dextral shear
* Clockwise block motion causes margin parallel shortening and EQ.
* Miocene Cascade arc has rotated away from the arc magma source about a pole near the present GPS pole.
* Long term clockwise block motions have tectonically segmented the margin.
* Implications for current Cascadia seismicity and magmatism?