Subduction Zone Initiation

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GeoPRISMS Subduction Cycles and Deformation Workshop

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GeoPRISMS *Geodynamic Processes at Rifting and Subducting Margins*

Why is understanding Subduction Initiation (SI) important?

- Establishes initial parameters for mature subduction zones (esp. mantle wedge depletion)
- In some cases associated with massive magmatic outpourings (new type of LIP) and production of most arc crust.
- Produces forearc lithosphere – important for understanding seismogenic zone
- Origin of most ophiolites such as Oman, which provide key models of oceanic lithosphere
- Illuminates forces controlling plate motions: lithospheric strength and density vs. asthenospheric convection

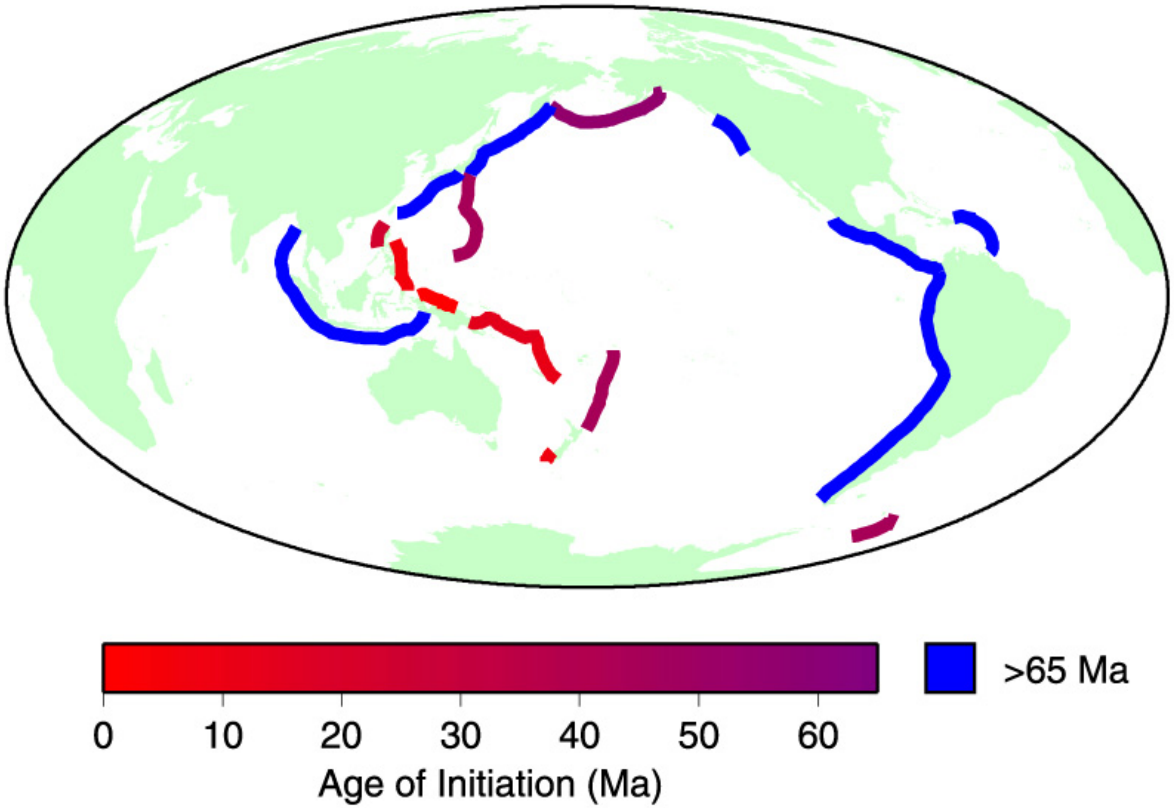
It’s 2011, >40 years after the plate tectonic revolution, why don’t we understand how subduction zones form?

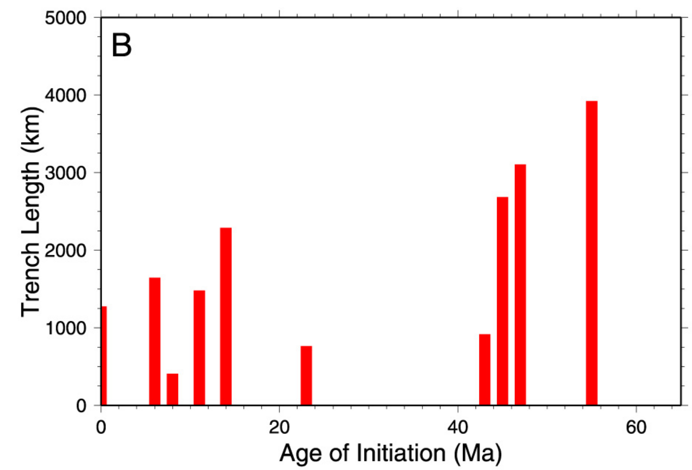
1) It’s not a steady-state process

   The present is only partly key to the past

2) Geodynamicists have been working without much geologic insight
3) Amphibious problem
4) No single way to start a new subduction zone
5) 3D problem

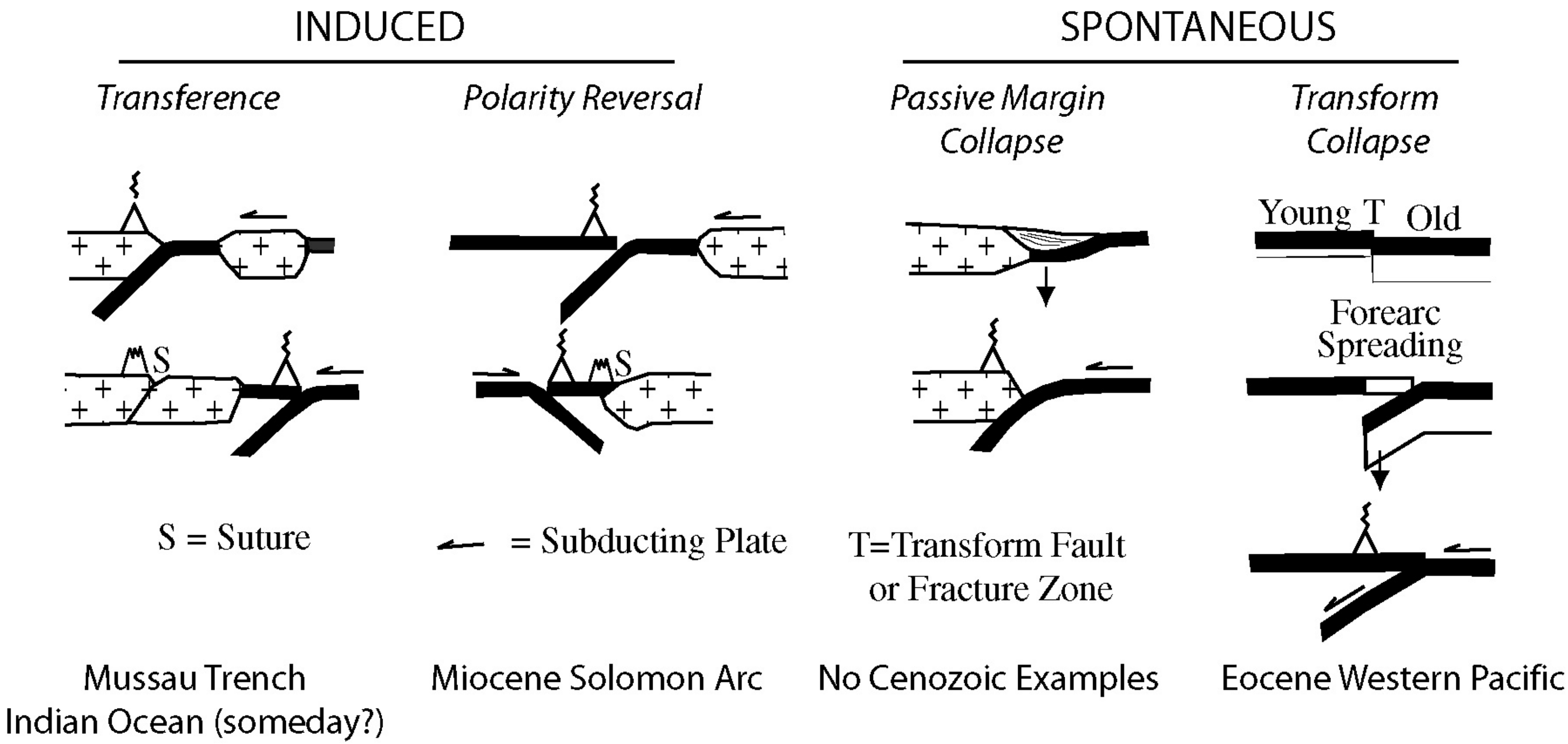
Many Subduction Zones have formed in Cenozoic – it must be pretty easy!





Left: modern convergent margins color-coded for SI age. Convergent margins which began before the Cenozoic are blue. Right: Length of Cenozoic convergent margins versus their age of initiation (Gurnis & Hall, 2004 G-cubed)

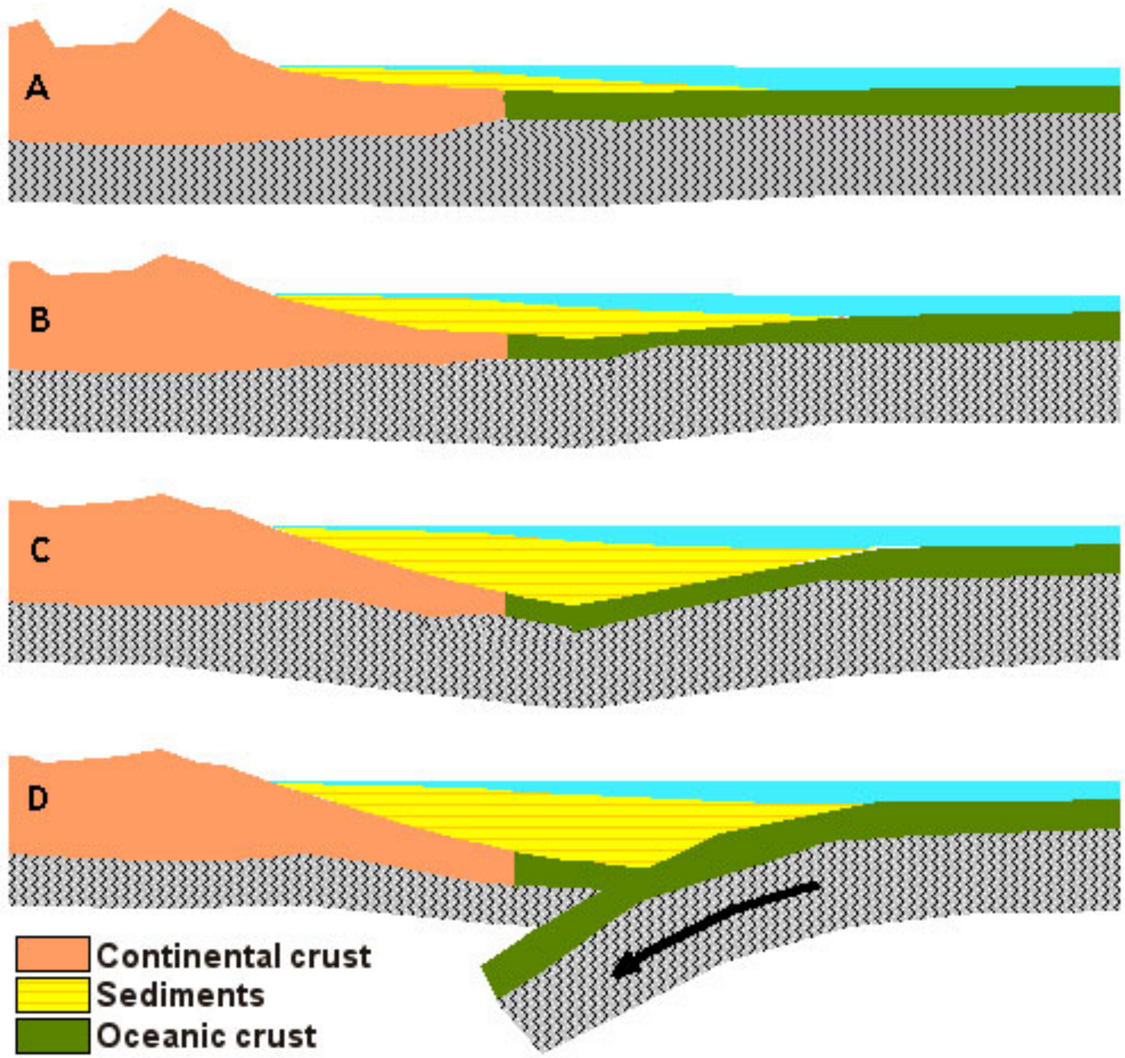
How To Start A Subduction Zone: induced (ISI) vs. spontaneous (SSI)



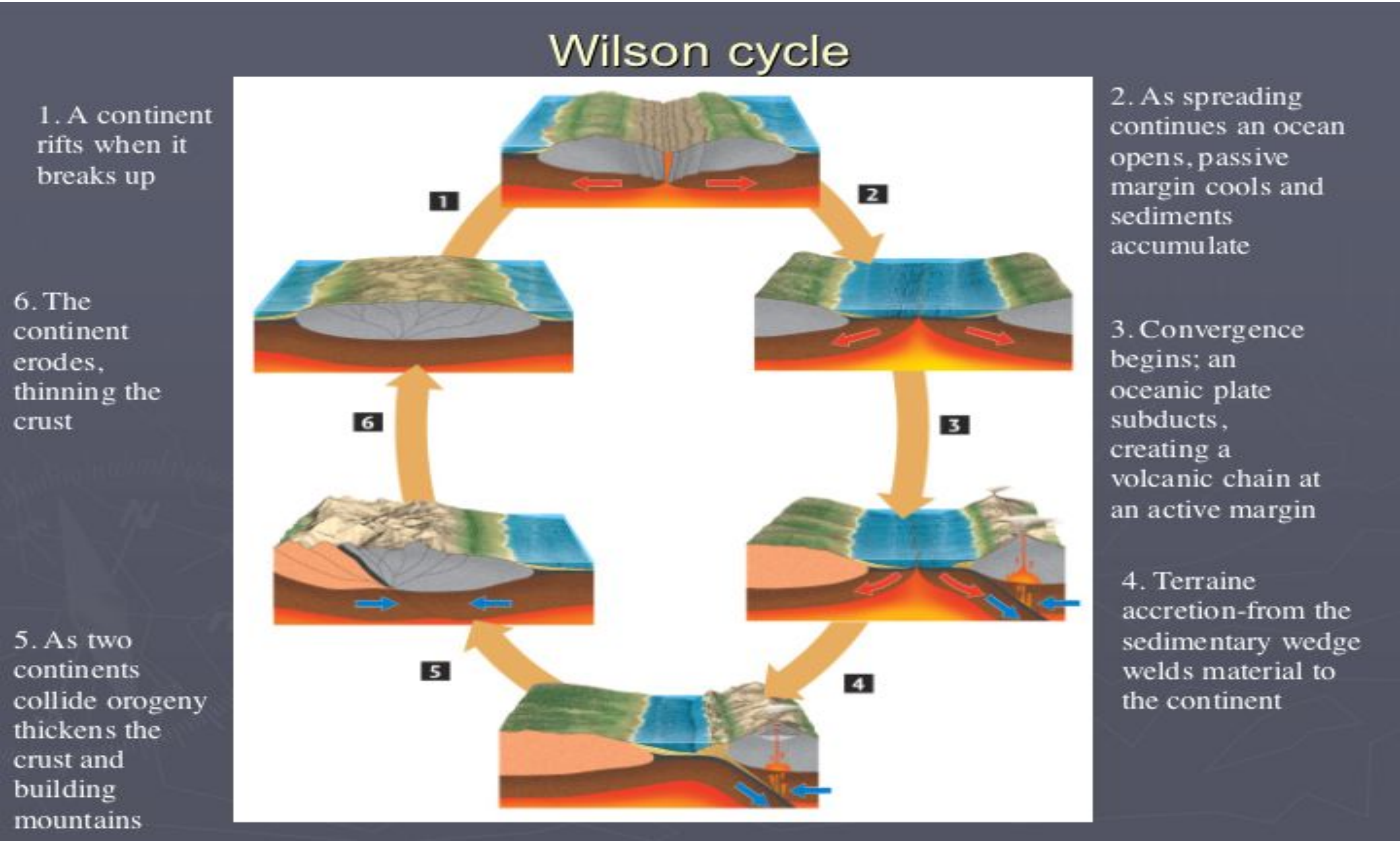
No Cenozoic examples of Transference or Passive Margin collapse; No Cenozoic examples of back-arc basin turning into a subduction zone.

Stern 2004 EPSL

No Cenozoic examples of Passive margin ISI or SSI



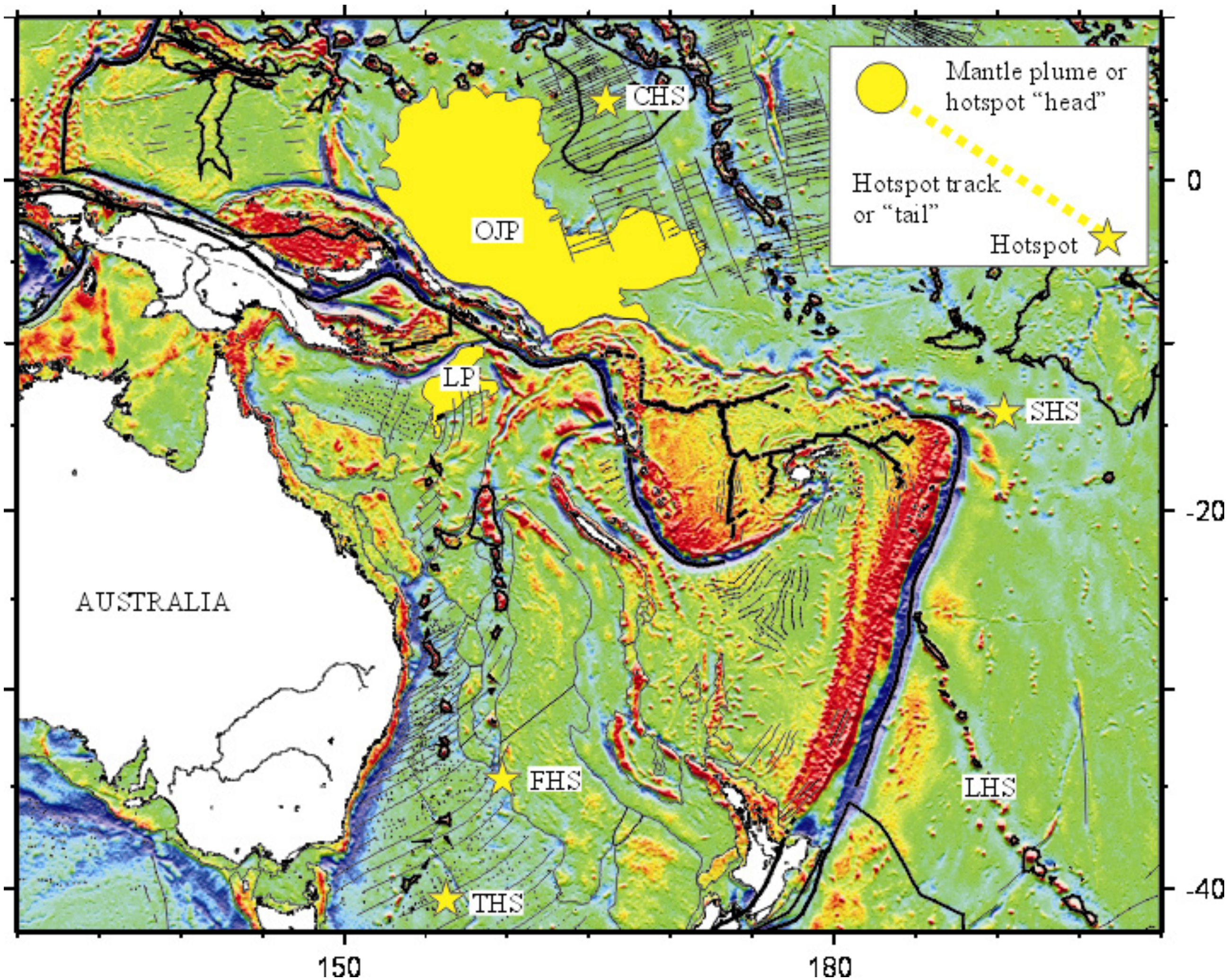
Is the Wilson Cycle a geomyth?



How can we better understand Induced Subduction Initiation?

- Focus on 3 Cenozoic examples:
  - Solomon arc Polarity Reversal
  - Puysegur subduction zone (New Zealand)
  - South of India
    - "To the curious incident of the dog in the night-time."

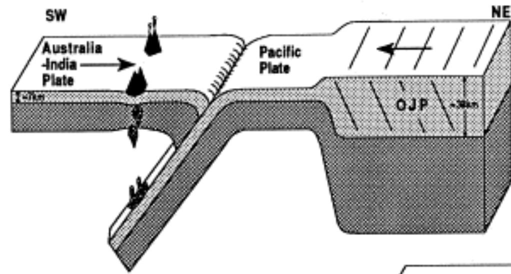
Polar Reversal ISI in the Solomon-Ontong Java Plateau System (Miocene)



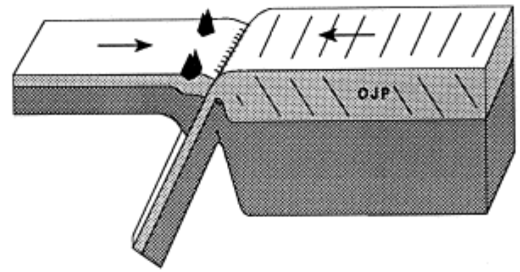
Collision terminated subduction on the north side of the Solomons (Vitiaz Trench) and induced formation of new subduction zone ~12 Ma on the south side of the Solomons.

OJP is about the size of the continental US, with 40 km thick crust

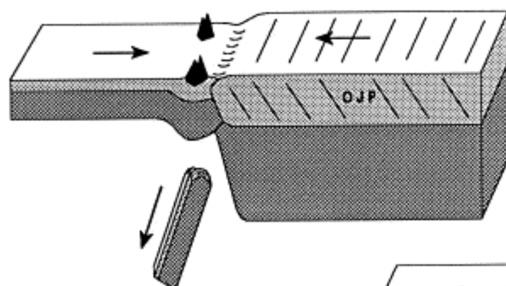
OJP-Solomons Collision & Polarity Reversal



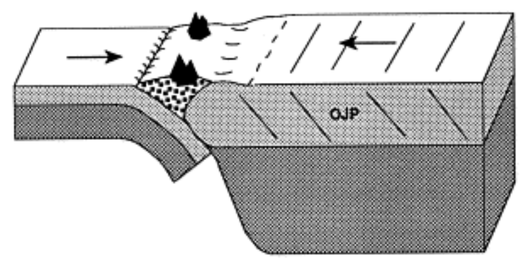
Eocene. Initiation of the SW-directed subduction of the Pacific Plate and formation of the Vitiaz (Stage 1) Arc.



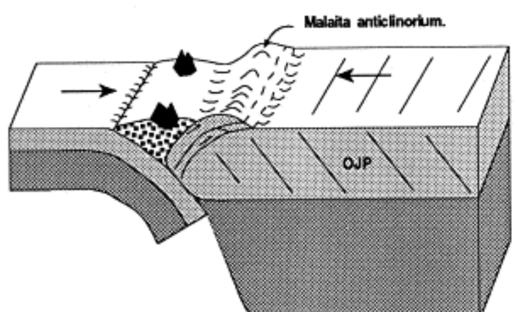
≈25-20 Ma. OJP docks with the trench. Lack of compression implies initial docking is 'soft'. Volcanic activity ceases possibly due to steepening of SW-dipping slab.



≈20-15Ma. SW-dipping slab breaks off in places. Continued absence of any obvious Vitiaz Arc-related volcanic rocks.



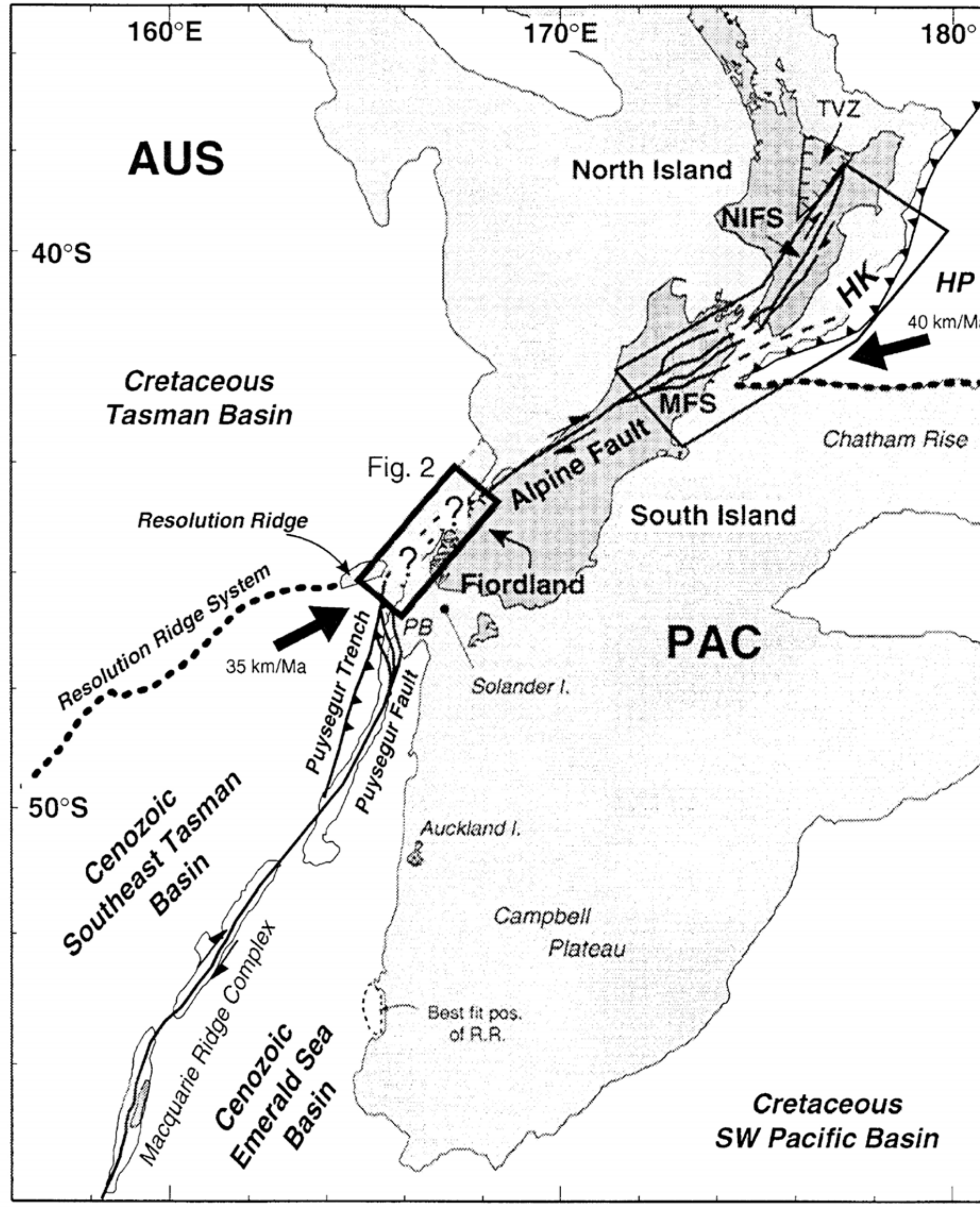
≈ 12 Ma. Subduction flips to a NE direction forming the San Cristobal/New Britain Trench system. **6Ma** sees the start of NE directed South Solomons (Stage 2) Arc Volcanism.



≈ 4-2 Ma. The formation of the Malaita Anticlinorium and its eventual emergence above sealeve. 30% shortening on Malaita indicates the formation of the anticlinorium was the result of a 'hard docking' event, with vertical stacking of horizontal backthrust sheets on Malaita. Subduction is shown as being to the NE, the prominent direction throughout the Solomon Islands today.

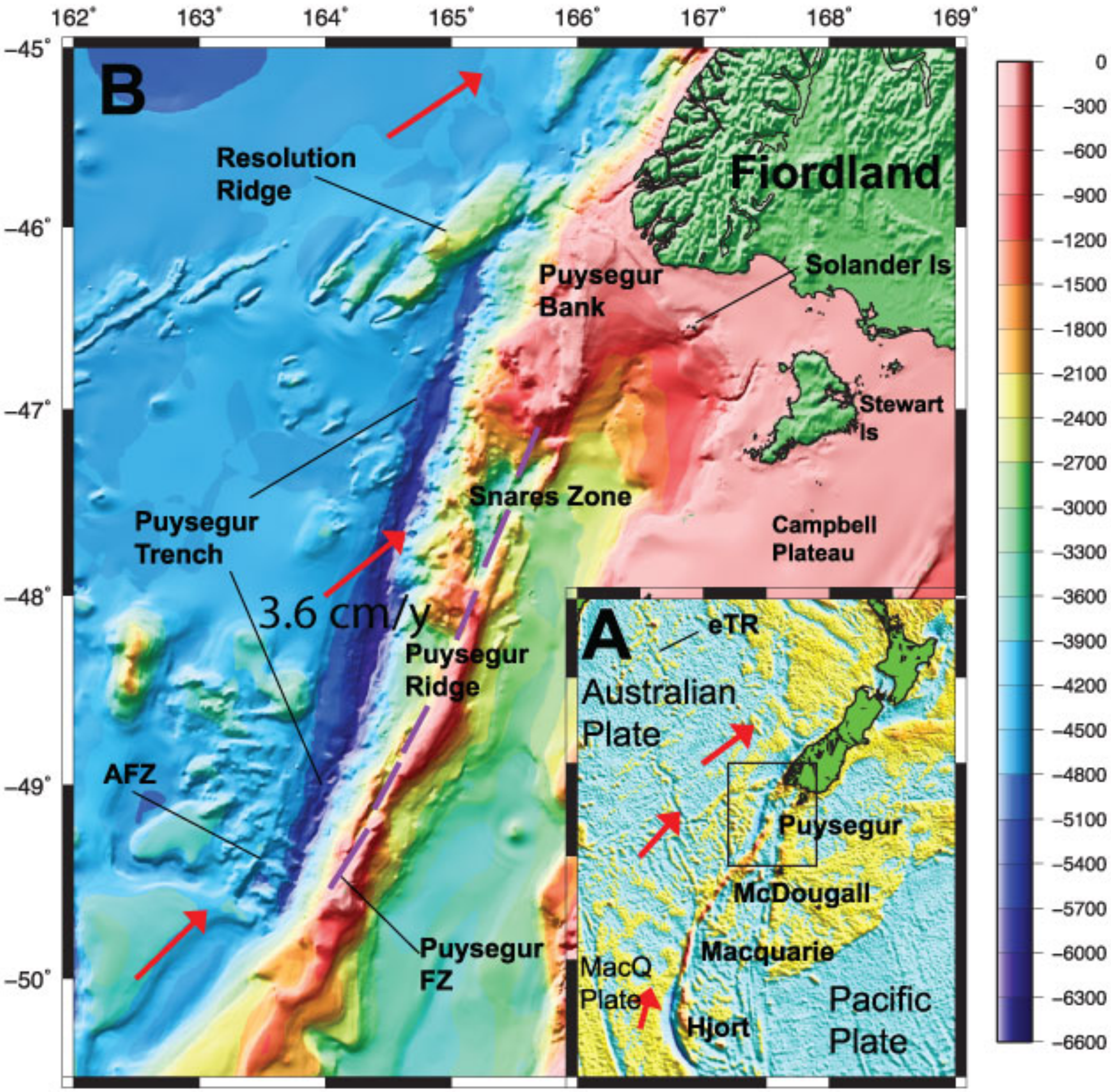
Petterson et al., 1999

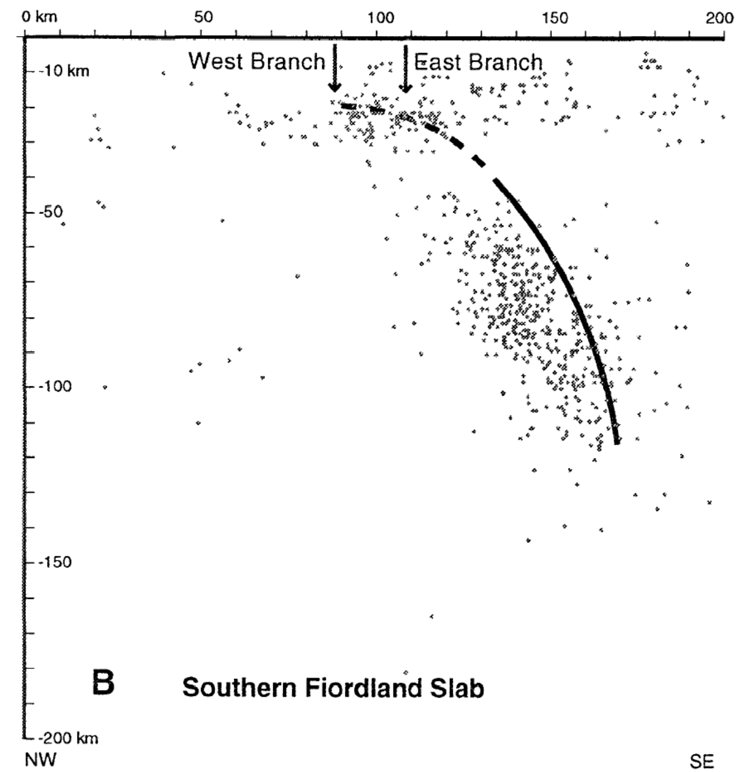
Australia-Pacific transform margin is the best (only) active example of SI



Lebrun et al., 2000

Puysegur Region





Lebrun et al., 2000

Gurnis et al. White Paper

Subduction has reached deep enough to generate an arc volcano (Solander)

What about the Biggest Collision of them all? India-Asia

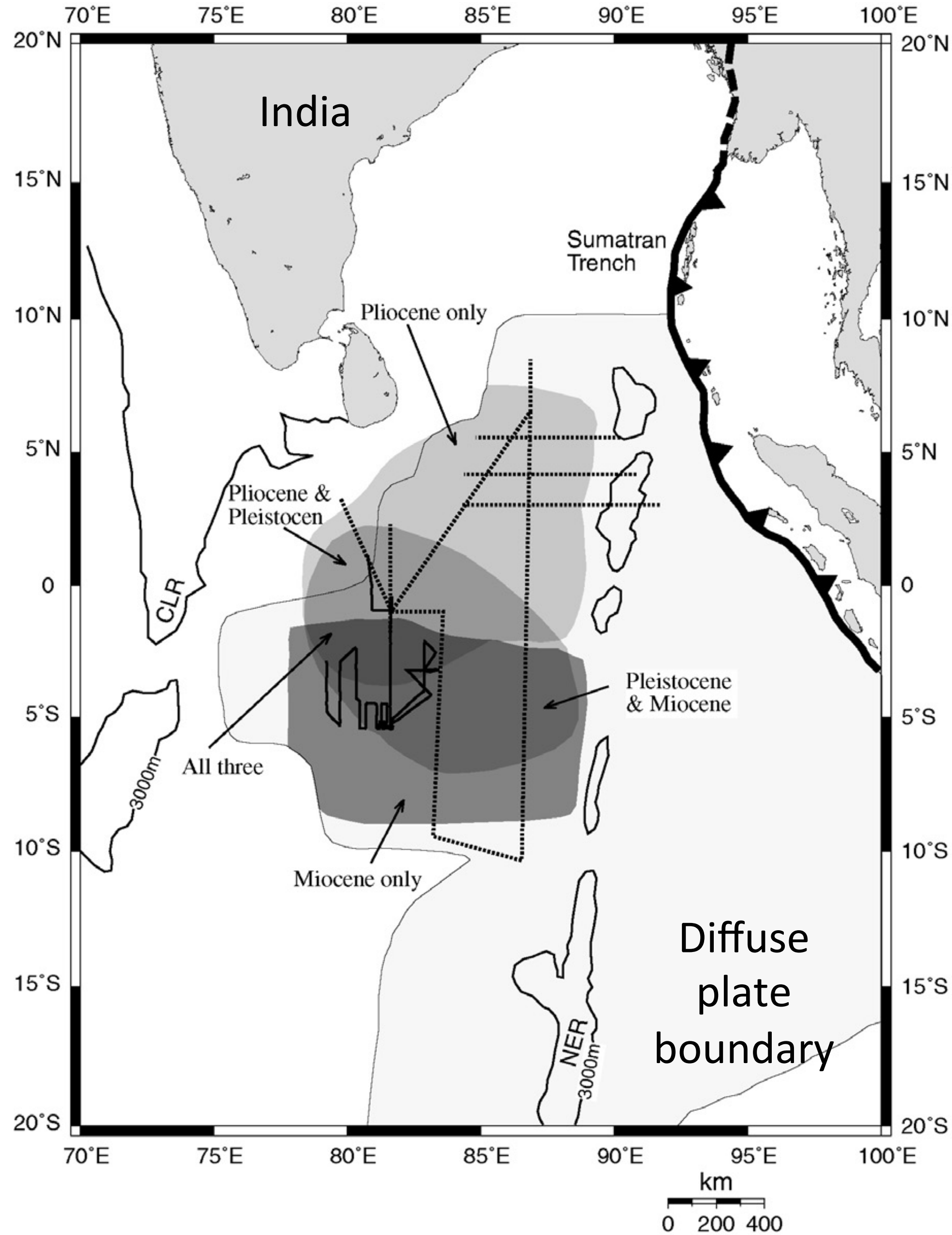
- India collided with Asia, destroying the intervening subduction zone.

- The Sherlock Holmes story "Silver Blaze" focuses on the disappearance of a famous racehorse named Silver Blaze on the eve of an important race and on the murder of its trainer. It hinges on the famed "curious incident of the dog in the night-time":
  – Detective: "Is there any other point to which you would wish to draw my attention?"
  – Holmes: "To the curious incident of the dog in the night-time."
  – Detective: "The dog did nothing in the night-time."
  – Holmes: "That was the curious incident."

Why didn't the dog (a new subduction zone) bark (form in the Indian Ocean to the south of India)?

Deformation of oceanic lithosphere in the central Indian Ocean has been occuring for a long time

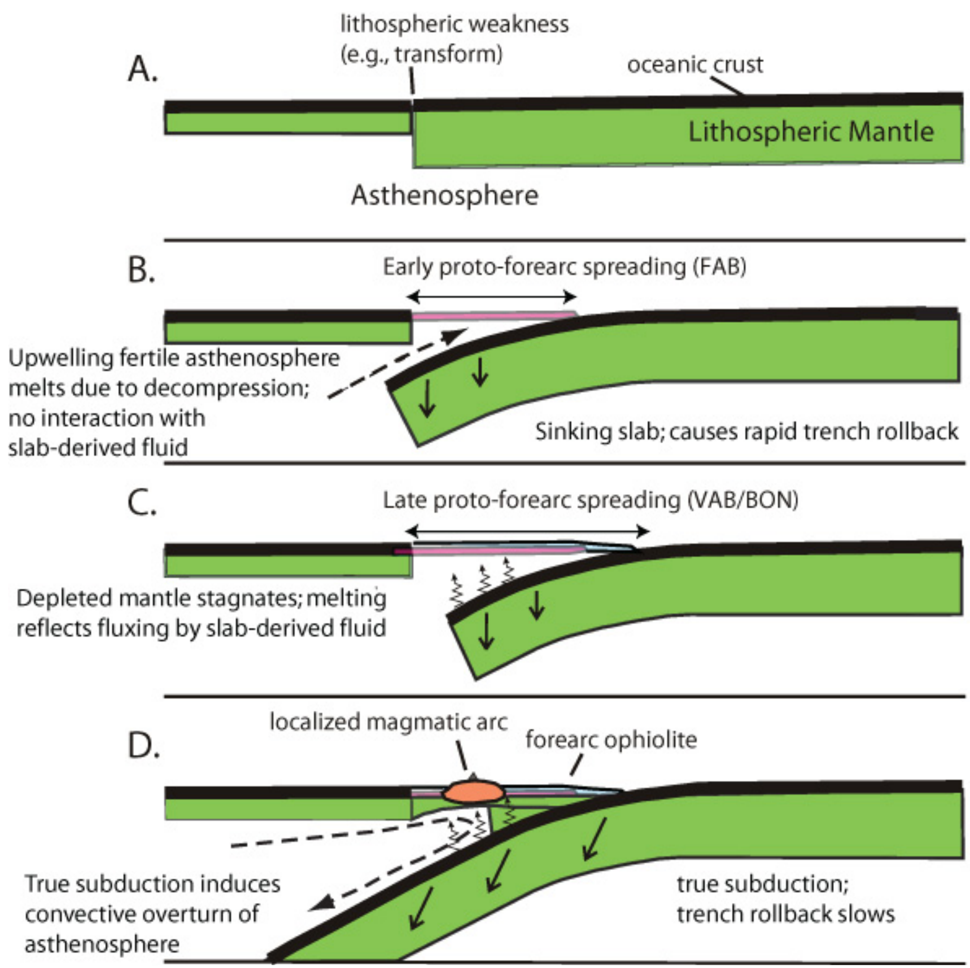
- Light shading shows position of diffuse plate boundary separating Capricorn, Indian, and Australian plates (Royer & Gordon, 1997). Darker shading shows extents of long-wavelength folding at 3 times (8.0-7.5 Ma, 5.0-4.0 Ma and 0.8 Ma).
- ***But no sign of a new subduction zone!***

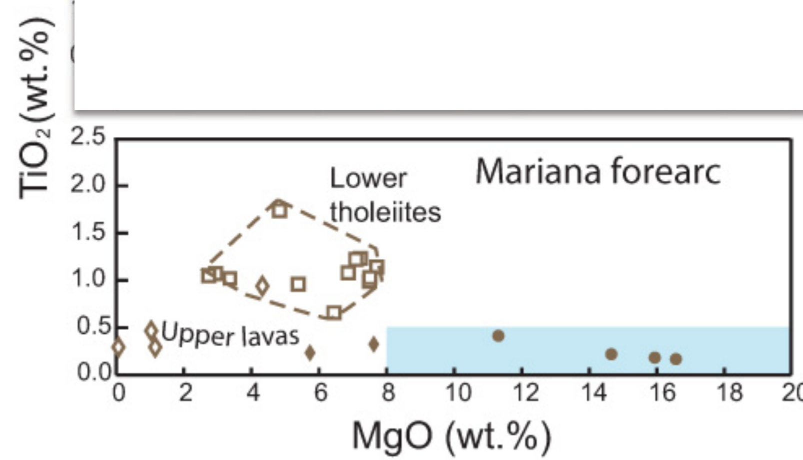


Why no ISI south of India?

- In spite of continued convergence of India and Asia and 8 m.y. of deformation of the Indian Ocean seafloor, no subduction zone has yet formed.
- Oceanic lithosphere may be too strong to break (cold, olivine-dominated rheology).
- Transference ISI is difficult; may have occurred if fracture zones were oriented E-W instead of N-S.

Izu-Bonin-Mariana Spontaneous Subduction Initiation (SSI)





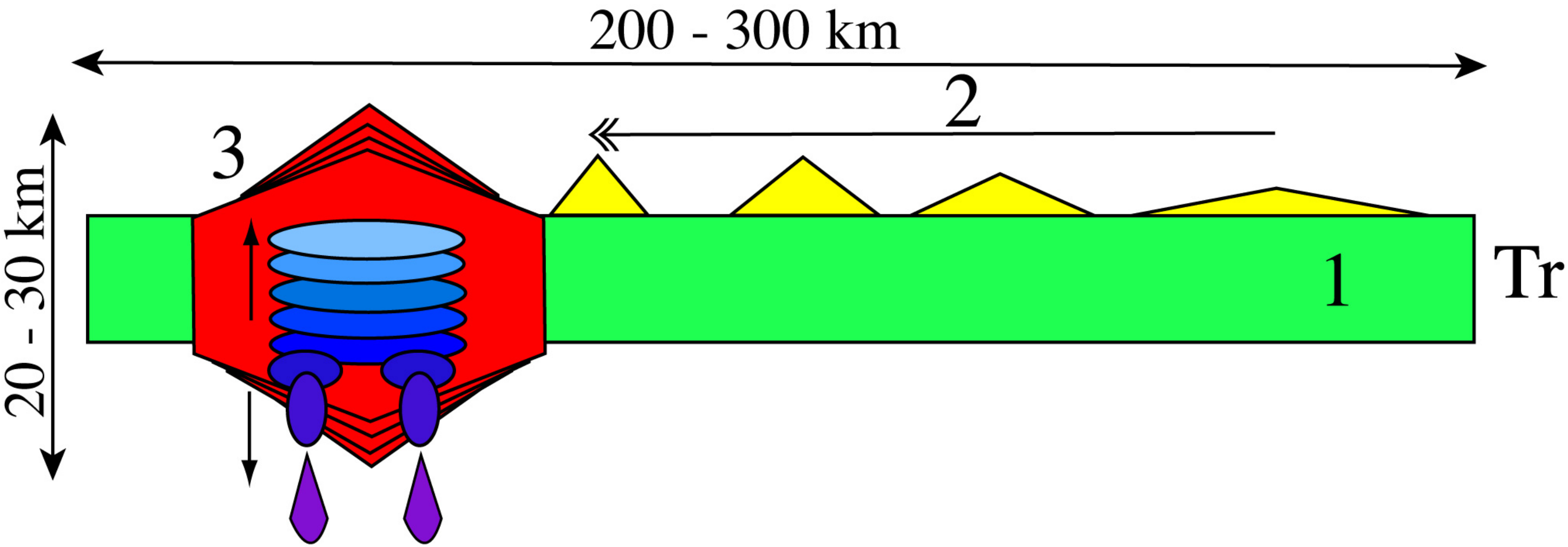
Lower tholeiites (high Ti) are formed from fertile mantle during (B); Upper lavas (low Ti) are formed from depleted mantle during (C).

~7 m.y. to evolve into a mature subduction zone (52-45 Ma)

Modified after Metcalf and Shervais (2008)

What about Spontaneous Subduction Initiation (SSI)? No active examples.
Three-pronged approach needed

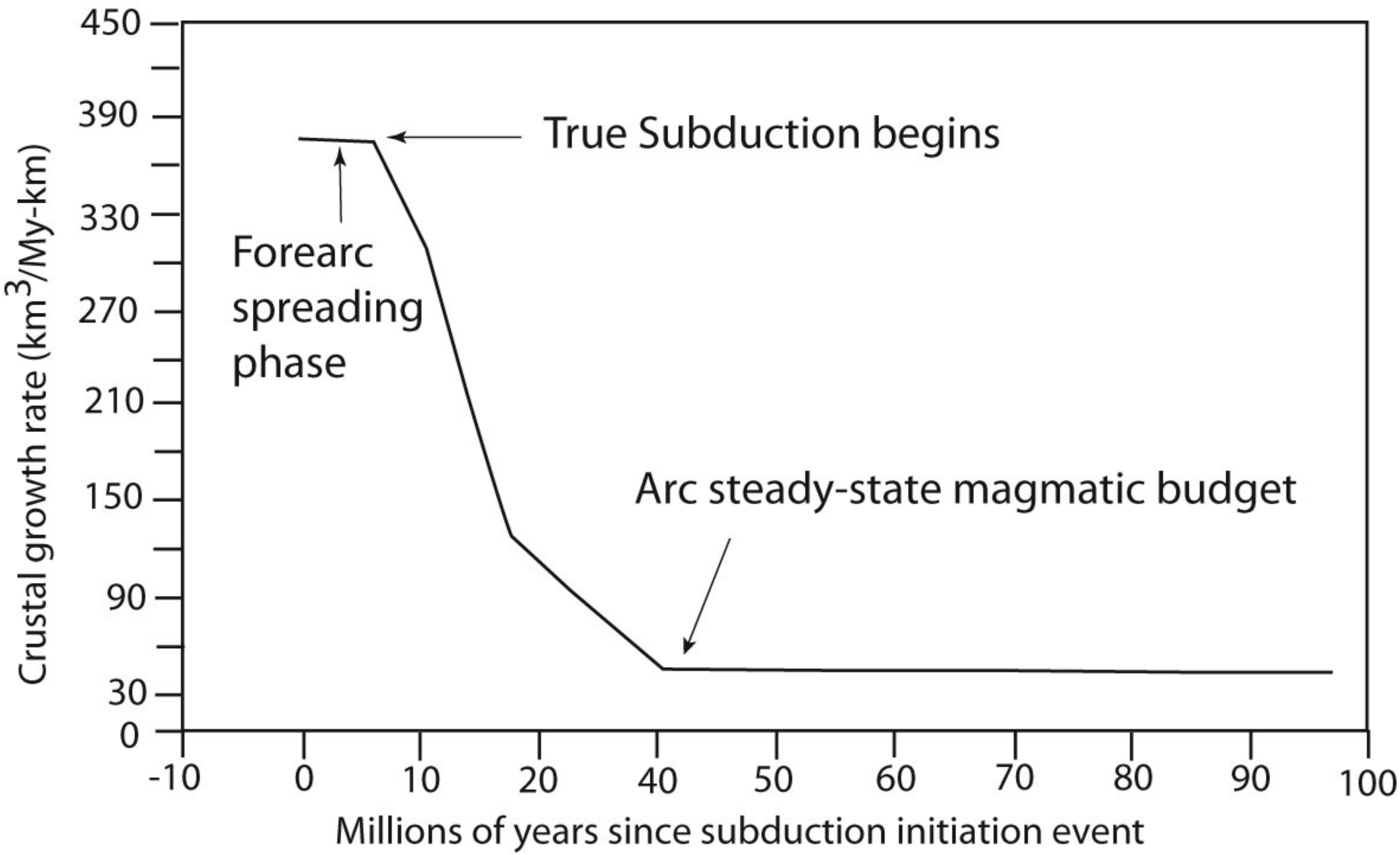
1) Field studies of Cenozoic examples
   - Evidence is preserved in forearc crust
     - Naked (intraoceanic) forearcs are best for study
   - Expensive: need ships to dive and drill
2) Use ophiolites
   - Cheap and easy to study but how to determine which ophiolites form during subduction initiation (SI)?
   - Use Ophiolite Rule to identify SI ophiolites***: First SI lavas are tholeiitic with little subduction input but show more such input with tim***e
3) Geodynamic modeling
   - Develop quantitative and realistic models to explain observations from forearcs and ophiolites.



How to Make an Island Arc via SSI (IBM recipe)

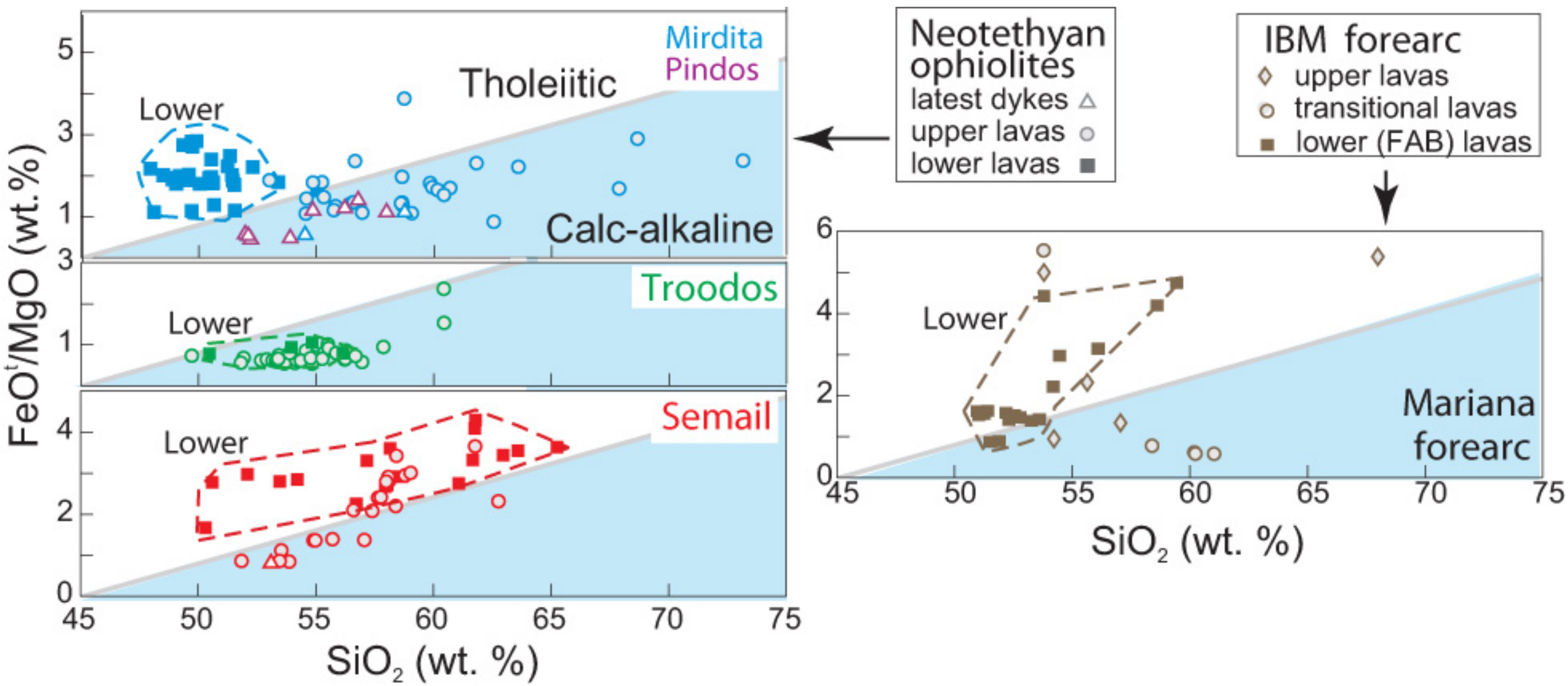
1 Generate broad arc substrate during subduction initiation/arc infancy stage.
2. Locus of magmatism moves away from the trench (Tr) during transition to true subduction and formation of mature arc.
3. Fix position of mature arc to allow crustal thickening, differentiation, anatexis, and delamination.

Arcs, like people, grow fastest when they are young

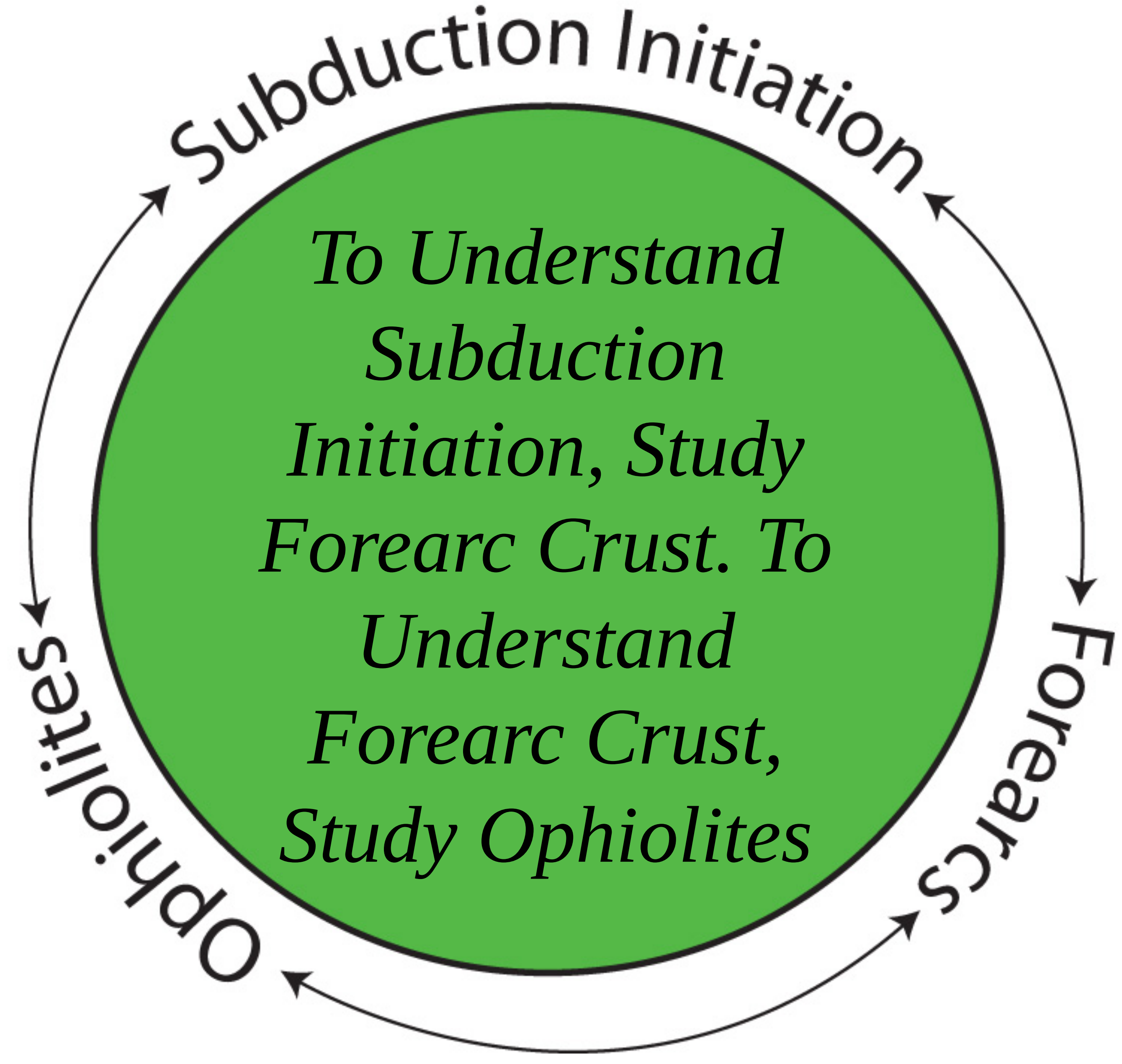


Stern & Scholl, in press

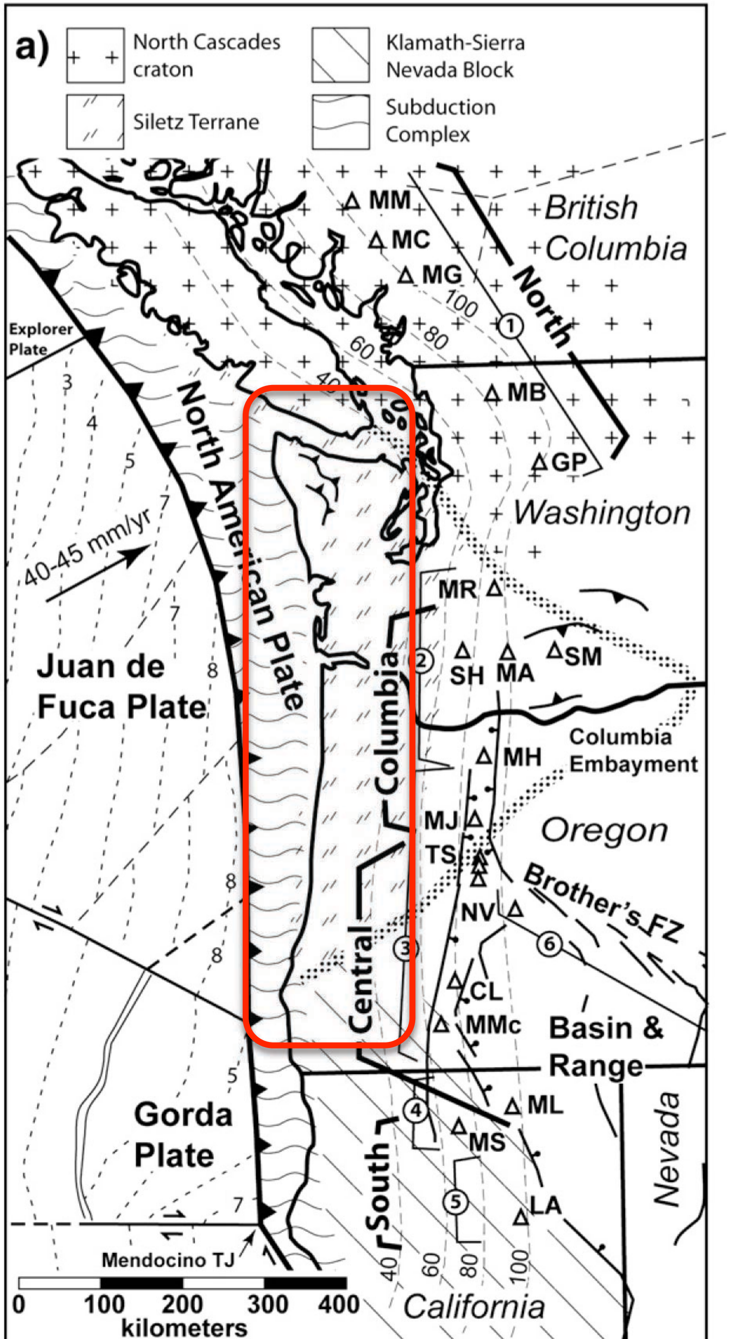
IBM forearc crust and most ophiolites have similar magmatic evolution: Proceed from MORB-like to arc-like with time



Early MORB-like tholeiites, late arc-like basalts or boninites


Subduction Initiation
Forearcs
Ophiolites
To Understand Subduction Initiation, Study Forearc Crust. To Understand Forearc Crust, Study Ophiolites

Co



What about SI for the Cascade Arc? Began ~45 Ma

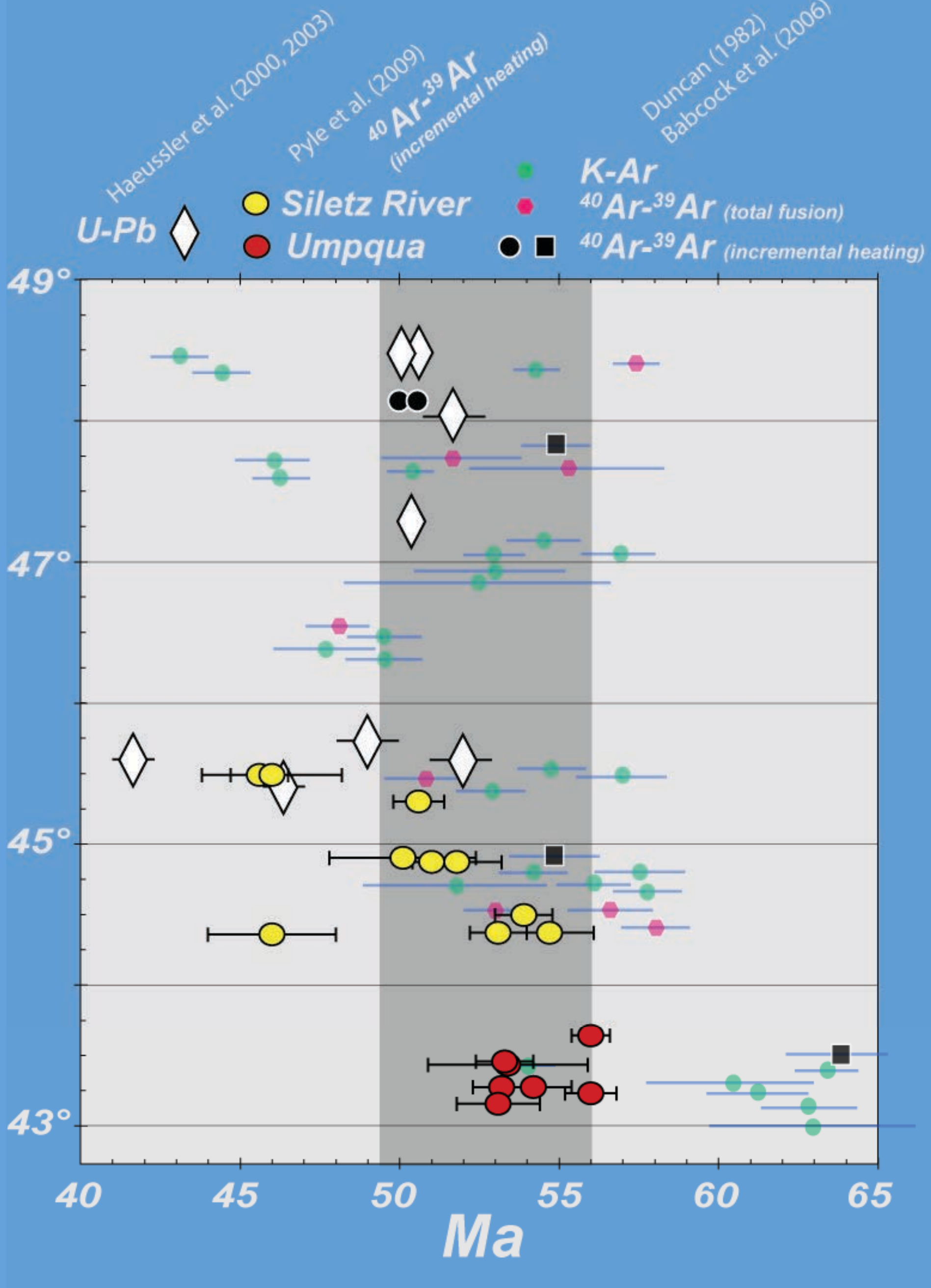
ISI or SSI?

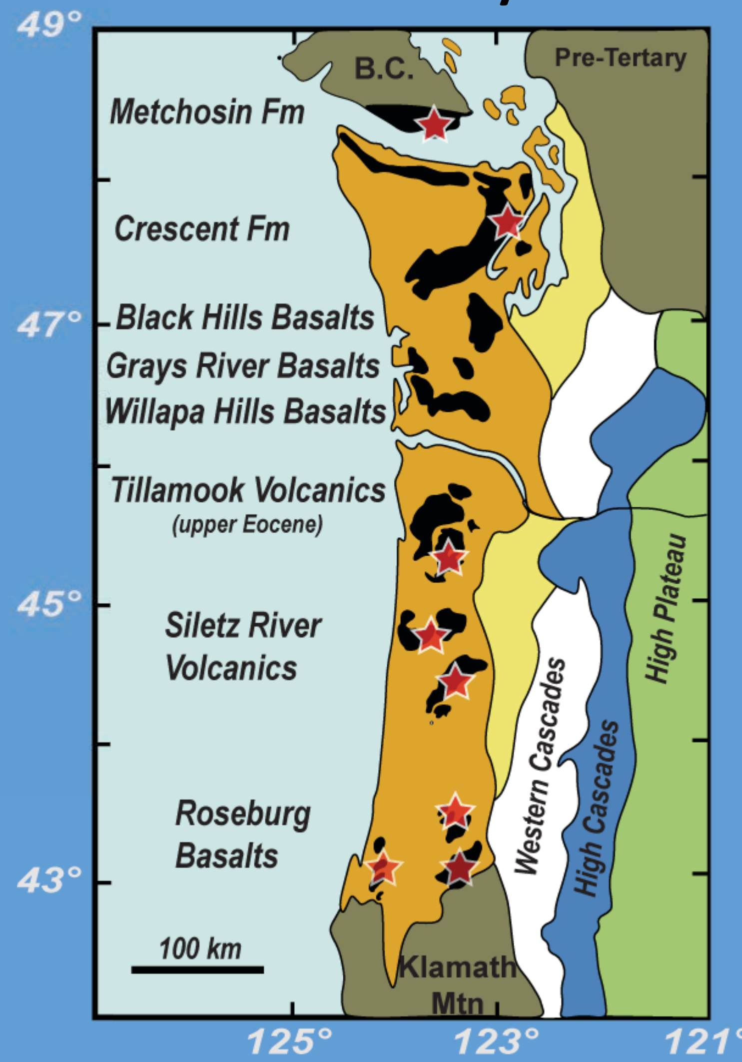
Cascade forearc crust = Siletzia

Submarine tholeiitic pillow basalt, Trask R. OR

Thanks to Ray Wells

Age Constraints (Siletzia formed ~6 m.y.





Pyle et al. 2009 GSA abstract

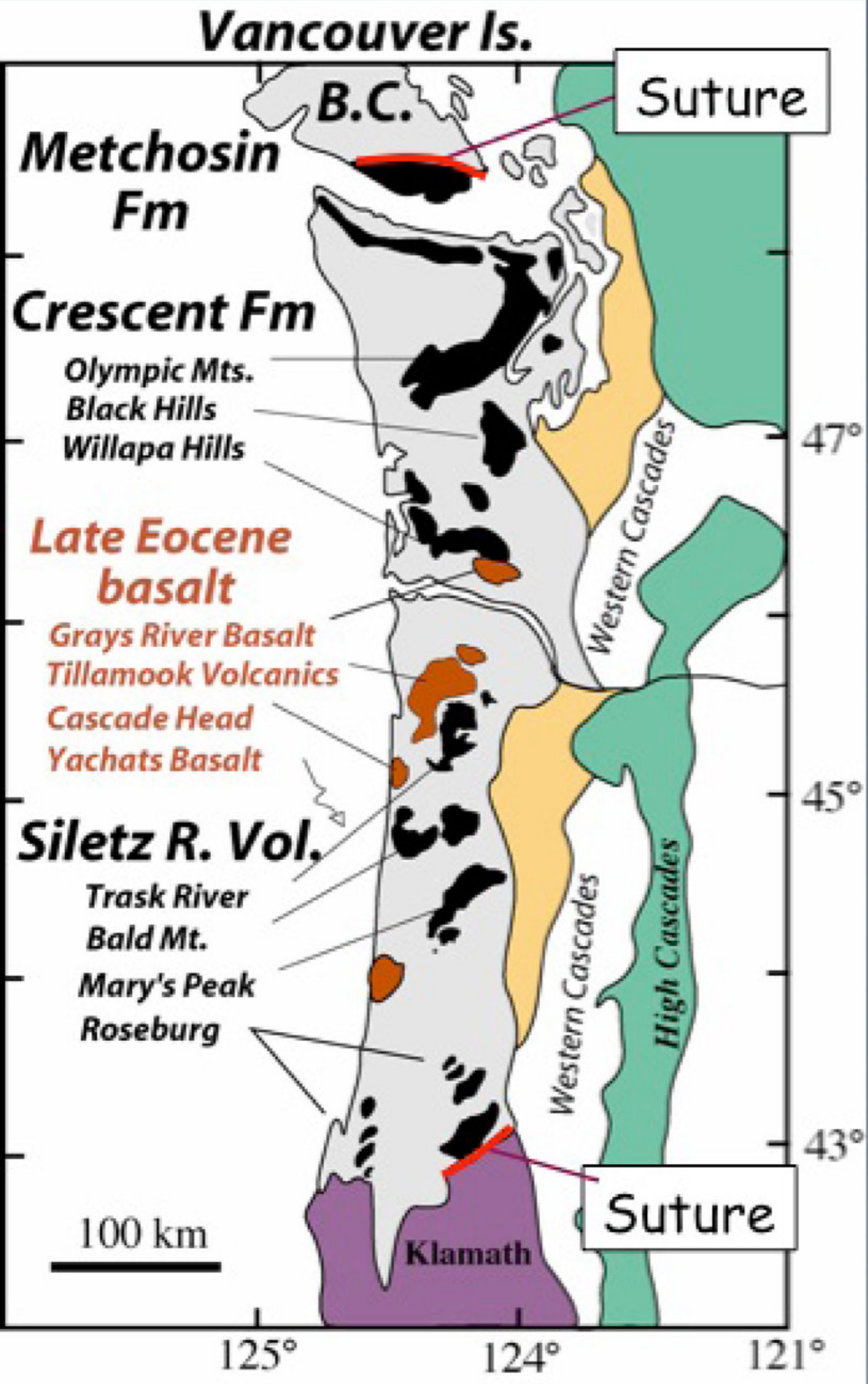
Explanations

- Snavely et al. 1968 - Oceanic Affinity
  - Tholeiitic to alkalic submarine and subaerial flows
- Morgan 1978 – Hotspot
  - Proposed link to Yellowstone Hotspot
- Duncan 1982 – Age-Progressive Volcanism
  - Accreted ridge-centered hotspot
- Wells et al. 1984 – Accreted Hotspot
  - -- Transform-Ridge-Hotspot interaction
- Thorkelson 1996 – Result of subducting ridge
  - Slab window

From Pyle et al. 2009 GSA abstracts

- Product of Subduction Initiation?

- Conclusions:
  - Lots of work to do to understand Subduction Initiation
  - Different mechanisms are likely
  - More work needed, but with better co-ordination between geologists, geochemists, geophysicists, and geodynamic modelers
  - *Focus site approach may work but "focus problem" strategy should also be considered*

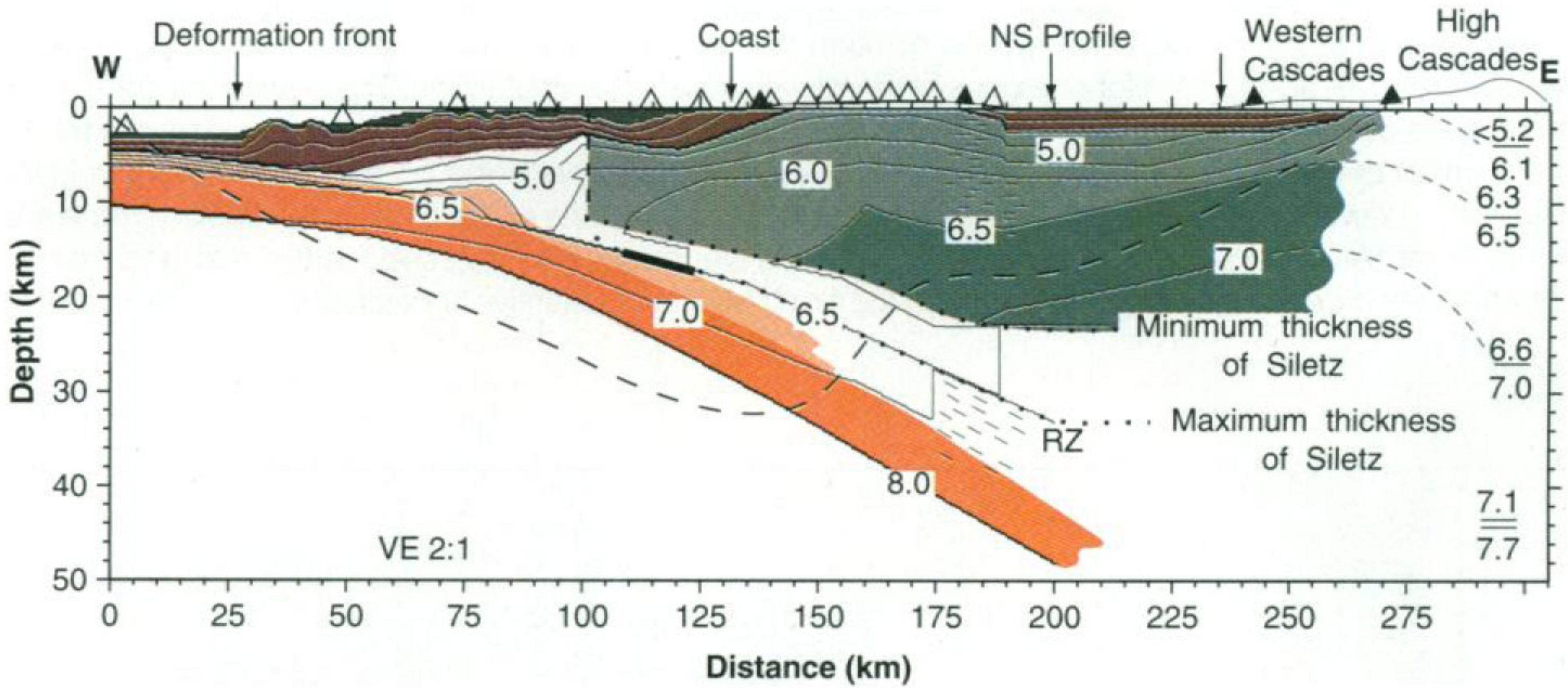


Siletzia

* Paleocene and Eocene CR basement from V.I. To Roseburg consists of oceanic tholeiite and alkalic basalt (black).
* Long considered allochthonous – (Hamilton, 1969; MacLeod and Snavely, 1974; Duncan, 1982; Jones et al. 1983)
* Olympic and Siletz terranes:
  * Distinctive deep marine stratigraphy and oceanic chemistry
  * Fault bounded
  * Critical onlap relations exposed
  * subdivided based on rotation
* **Accreted island chain, oceanic plateau, or marginal rift/slab window magmatism?**

Modified from Pyle et al., 2003

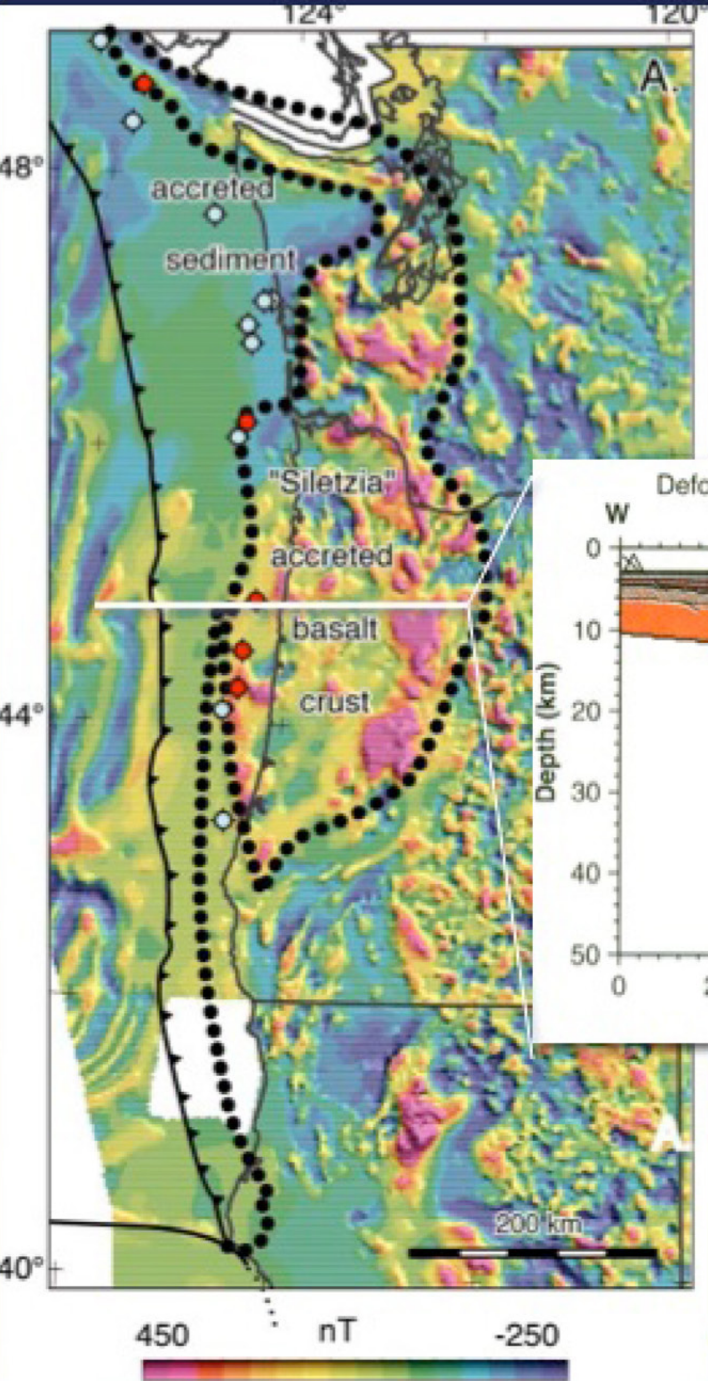
Cascade Forearc = Siletzia

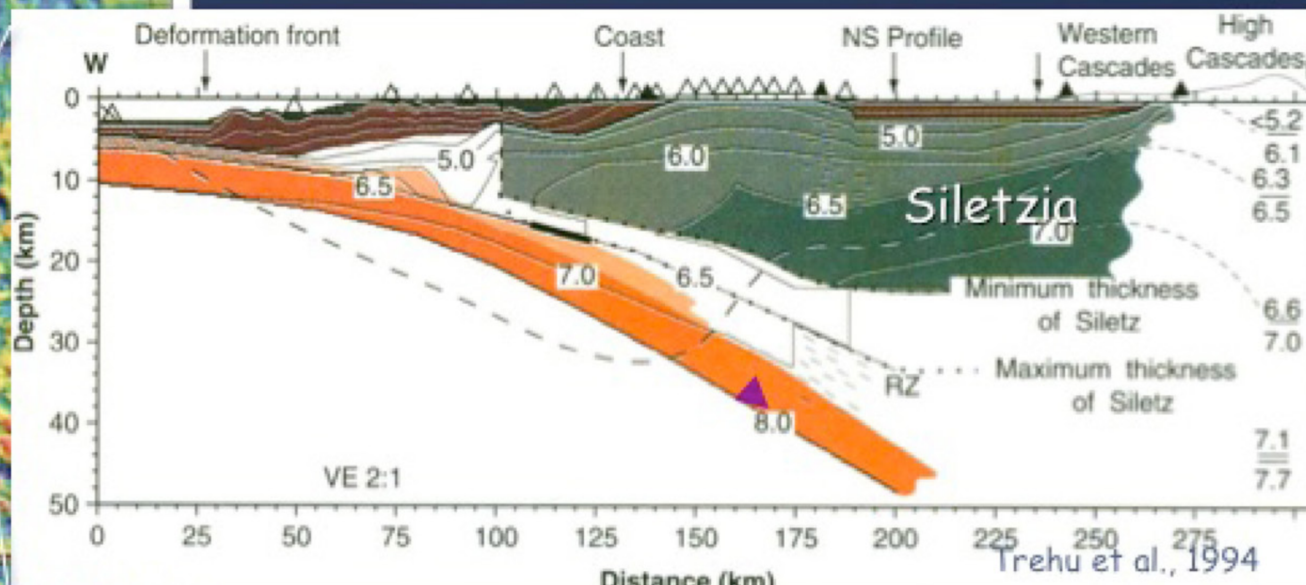


E-W velocity model of Oregon forearc crust. Contour interval is 0.5 km/s. Open triangles = seismometers, filled triangles = shots (Trehu et al. 1994).

Siletzia has thick, high velocity mafic crust.

* Aeromagnetic survey and exploration wells outline extent of Siletzia's basaltic crust 600 x 200 km.



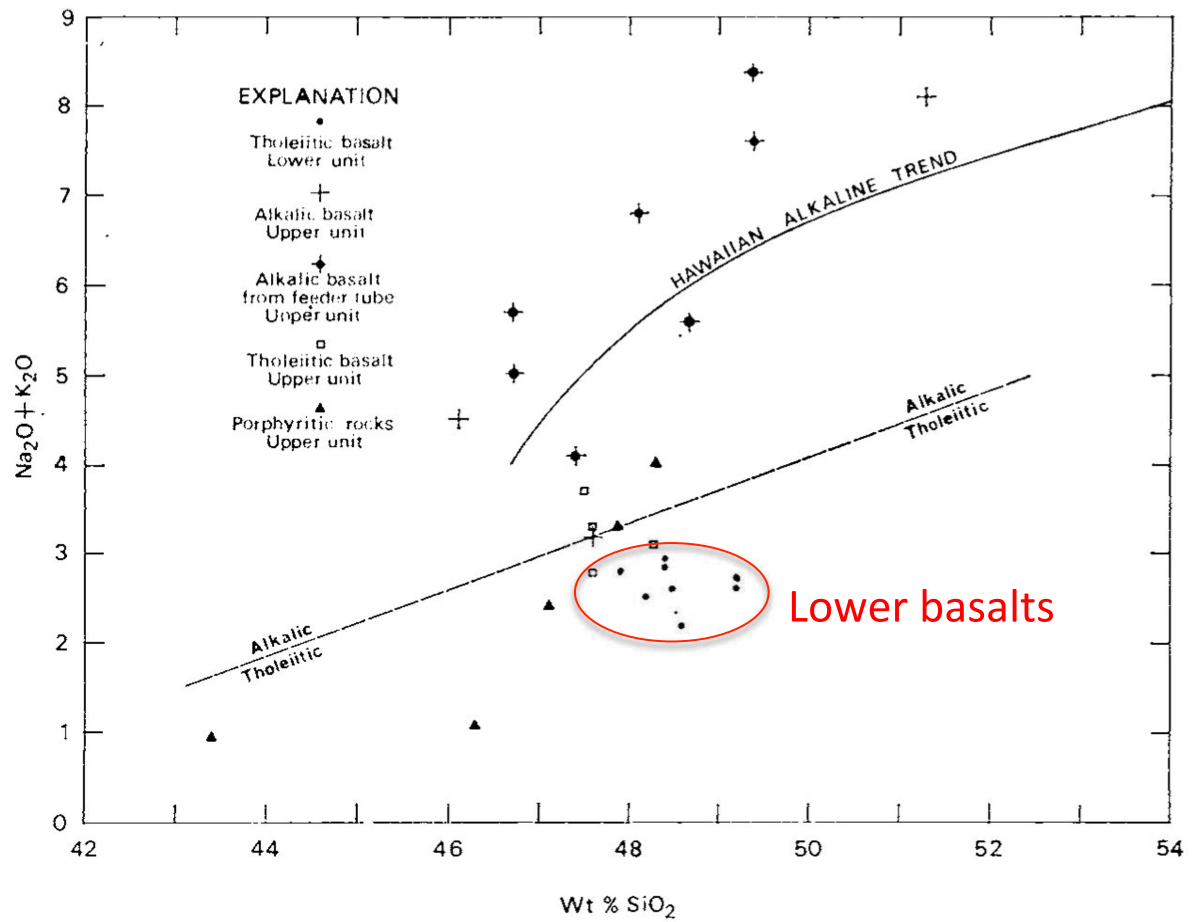


- Seismic profiles indicate crust 22-32 km thick in OR, thinning to 20 km in WA, 16.5 km exposed in Olympics, 10 km on V.I.
- **2,360,000 km^3 > 10x CRB vol. (170x10^3 km^3).**

Thanks to Ray Wells

Lavas are mostly basalt: Lower tholeiites, upper alkalic

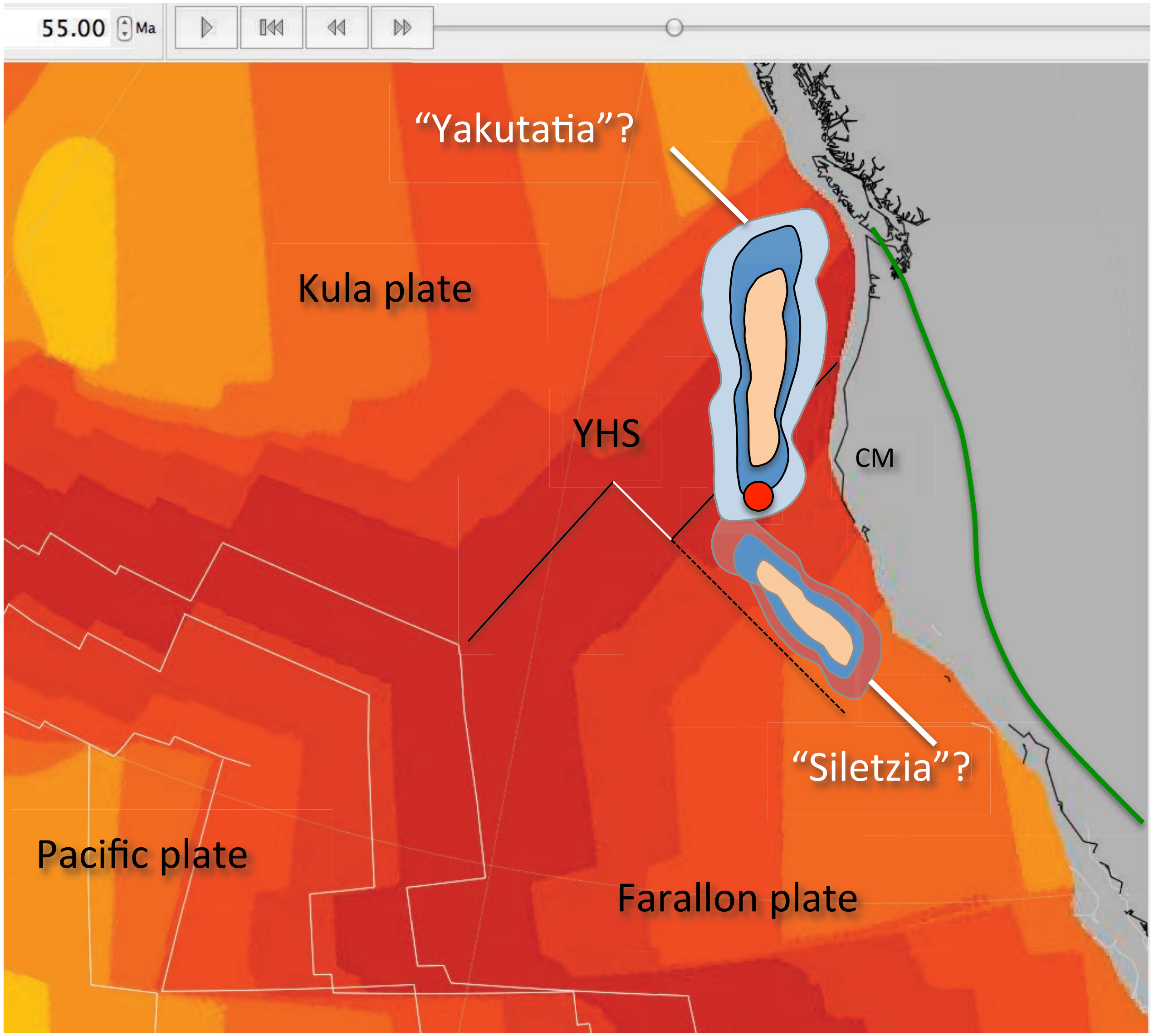
P. D. Snavely, Jr., N. S. MacLeod, and H. C. Wagner



1968 AJS

Fig. 4. Alkali-silica diagram for rocks of the Siletz River Volcanics. The Hawaiian alkaline trend is from Muir and Tilley (1961), and the diagonal dashed line, which represents the boundary between the Hawaiian tholeiitic and alkalic fields, is from Macdonald and Katsura (1964).

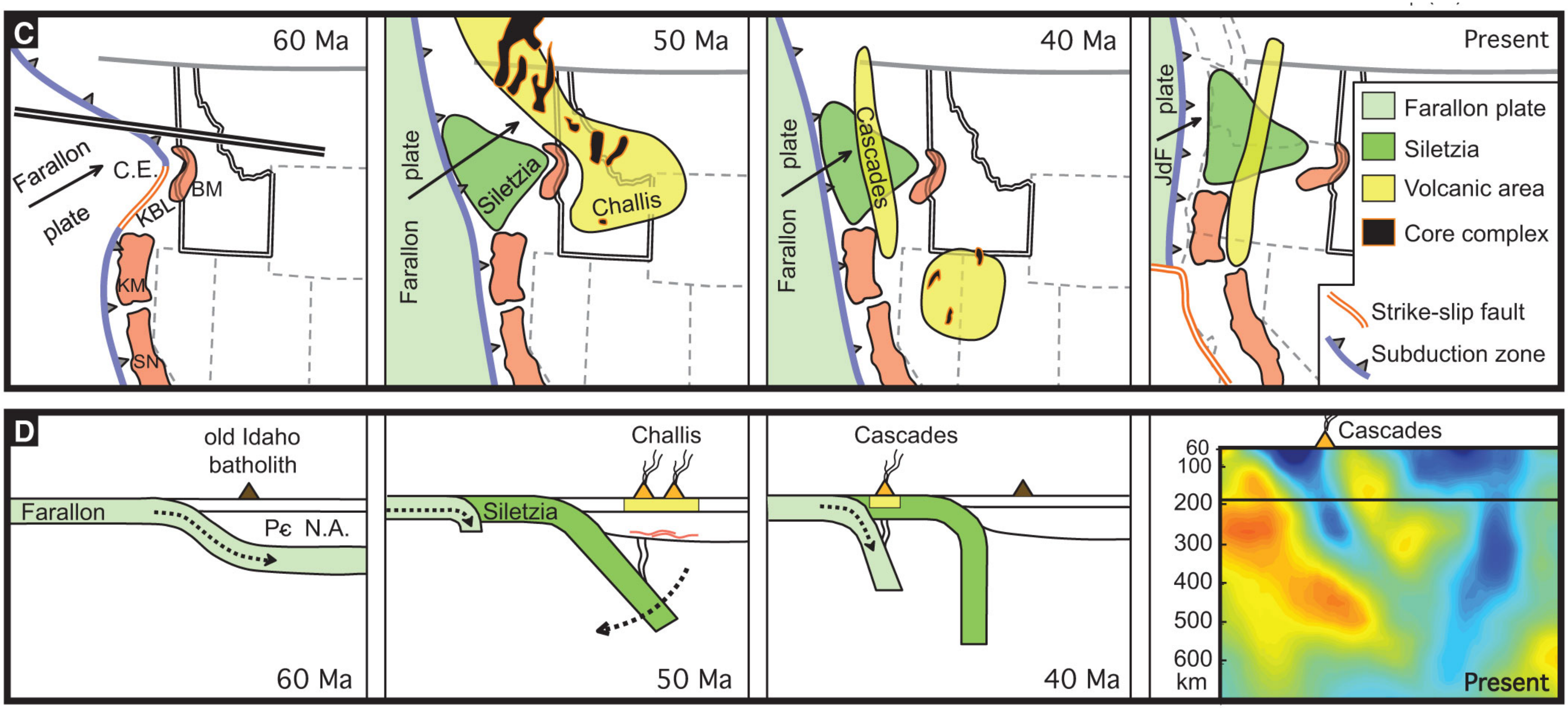
Is Siletzia an Accreted Terrane?



Moving hot spot model (55 Ma) with Kula-Farallon ridge, Yakutat Hot Spot is just offshore, on a spreading ridge.

(Gplates, Muller et al, 2010). Modified idea of Duncan 1982

Tomographic evidence for two slabs



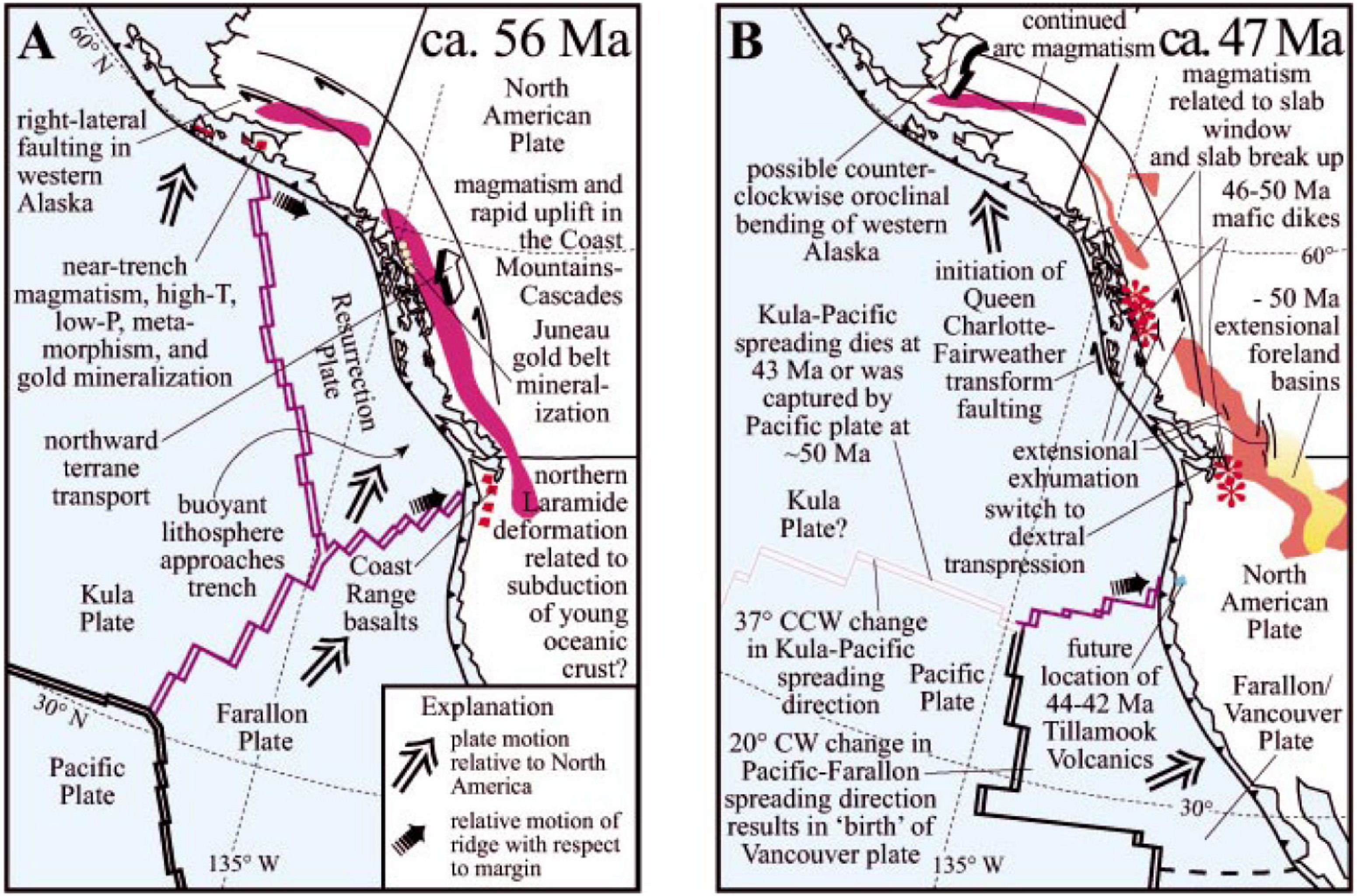
Farallon plate subduction New subduction zone

Schmand and Humphrey 2011 Geology

Accreted Hotspot hypothesis Pros and Cons

- Few hotspots on Cenozoic E. Pacific seafloor
- Why hotspot right at trench? Yellowstone plume?
- Sediments on top of Siletz River Volcanics contain N. American detritus
- Paleomag indicates formation at same latitude but 70° rotation
- If it is accreted, requires Transference ISI to generate present Cascadia subduction zone.
  - Would be only such Cenozoic example

Resurrection plate hypothesis



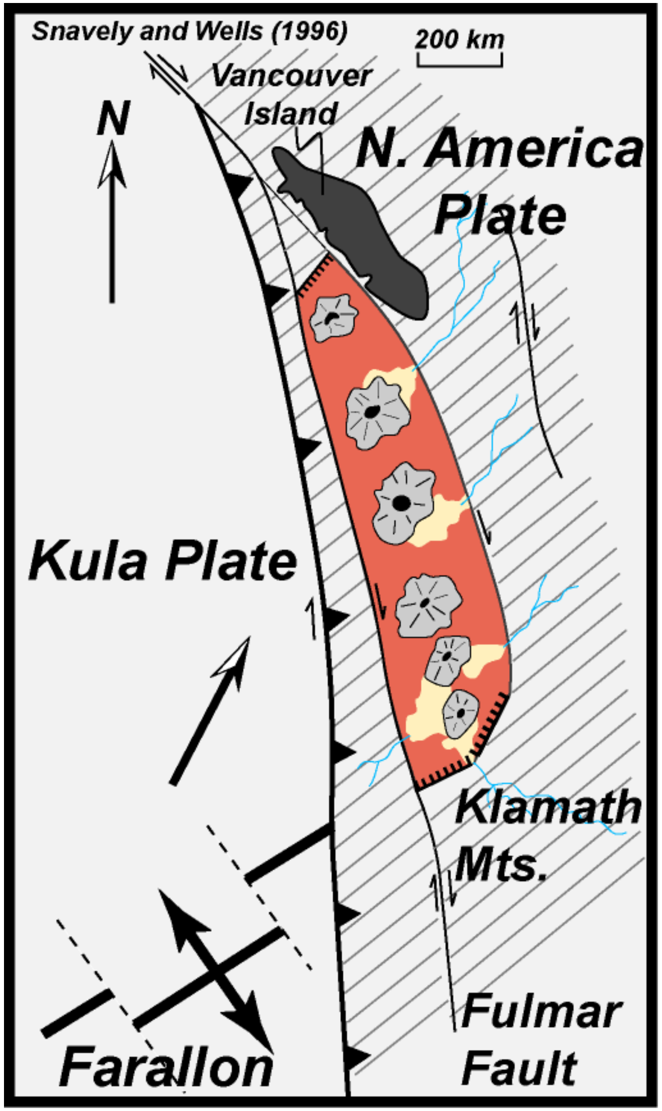
(A) About 56 Ma. Plate motions relative to North America and orientations of spreading-center segments in purple are unconstrained by the oceanic magnetic anomalies. (B) About 47 Ma. Kula-Pacific Ridge, shown in light purple, may have ceased spreading in this interval. Hauessler et al 2003 GSA Bull.

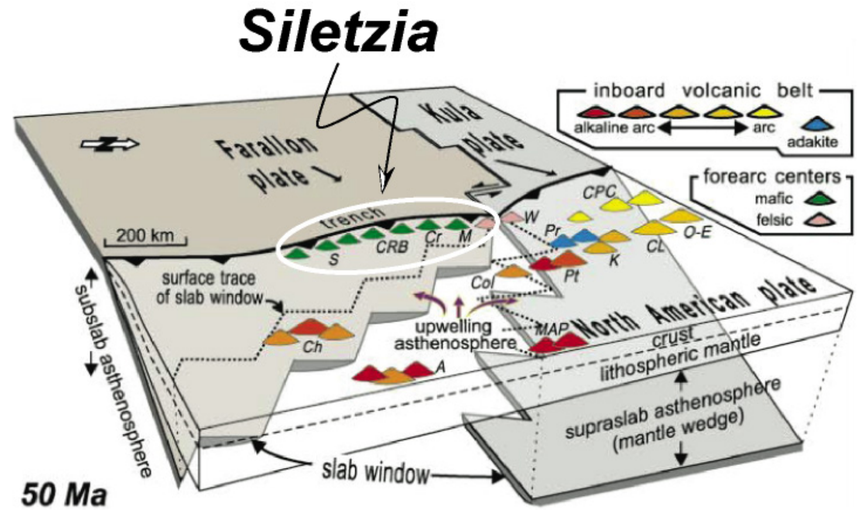
Resurrection plate pros and cons

- PROS
- Makes Siletzia part of North America

- CONS
- Little other evidence of Resurrection plate
- No adakites (melts of hot, young slab) in Siletzia volcanics

In Situ Tectonic Models





Breitsprecher et al., 2003

Slab Window

- Each model implies close proximity to arc and/or fore-arc volcanism

Rifted Margin

Pyle et al. 2009 GSA abstract

Crustal Thickness

Crescent Fm.

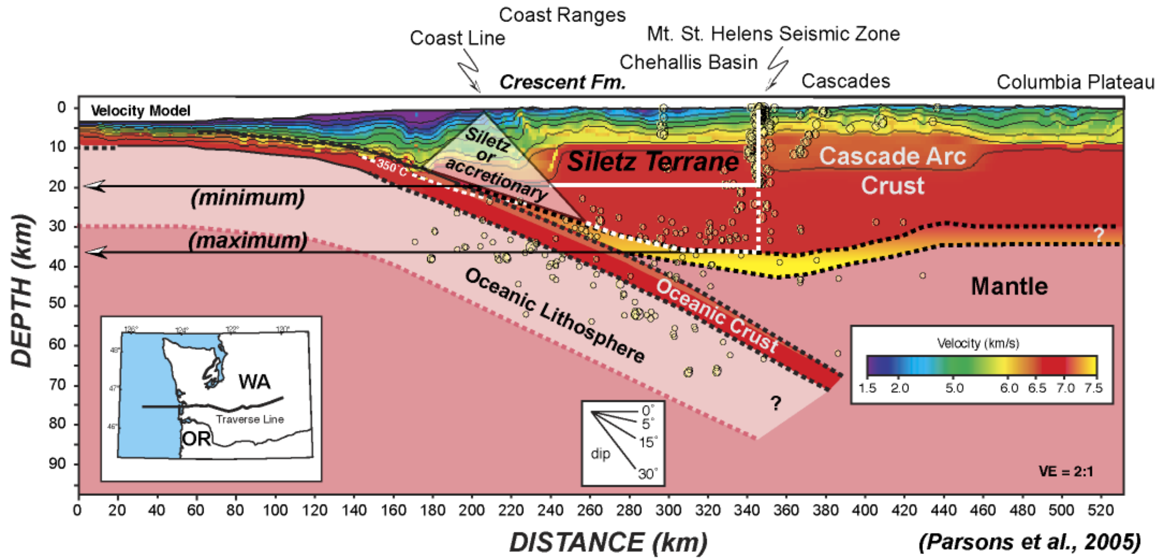
(Washington)

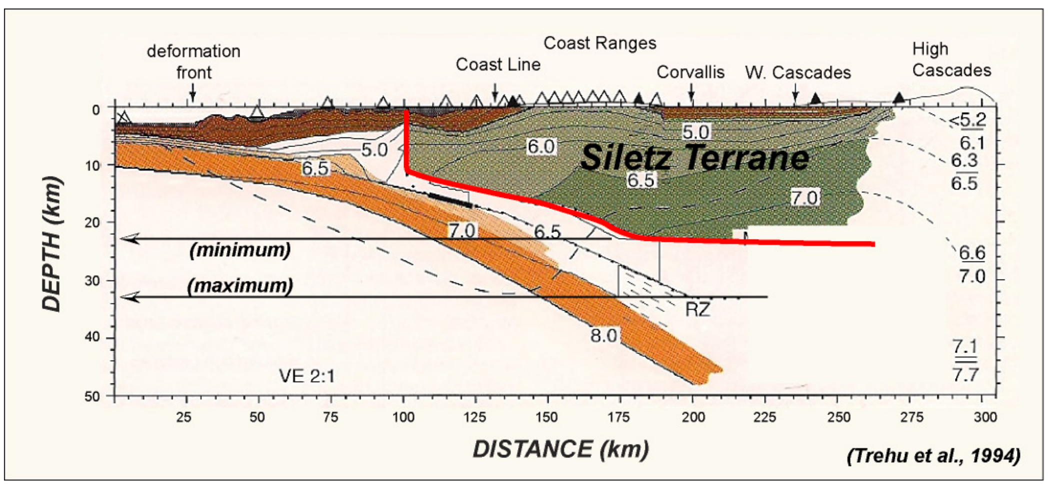
~ 20-35 km

Measured composite section

>16 km

Babcock et al. (1992)





Siletz River Basalts

(Oregon)

~ 20-35 km

Volume Estimate

Gravity and Magnetics

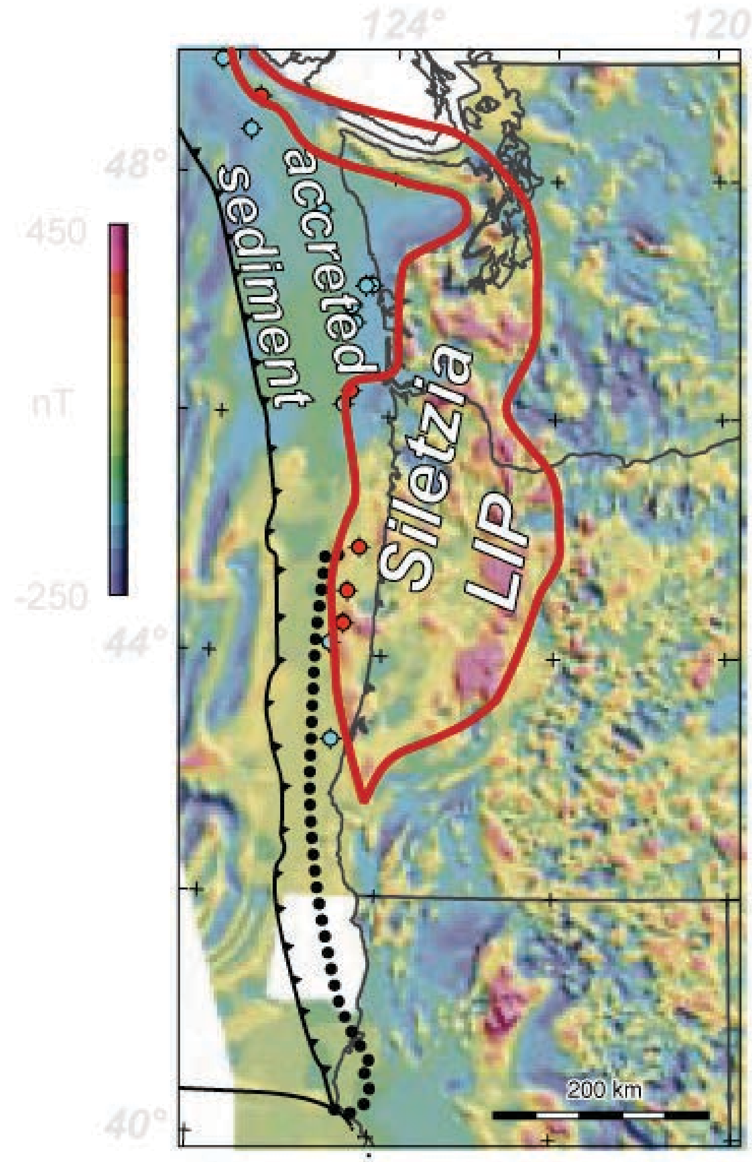
Area

~ 87,000 km^3

Crustal Thickness

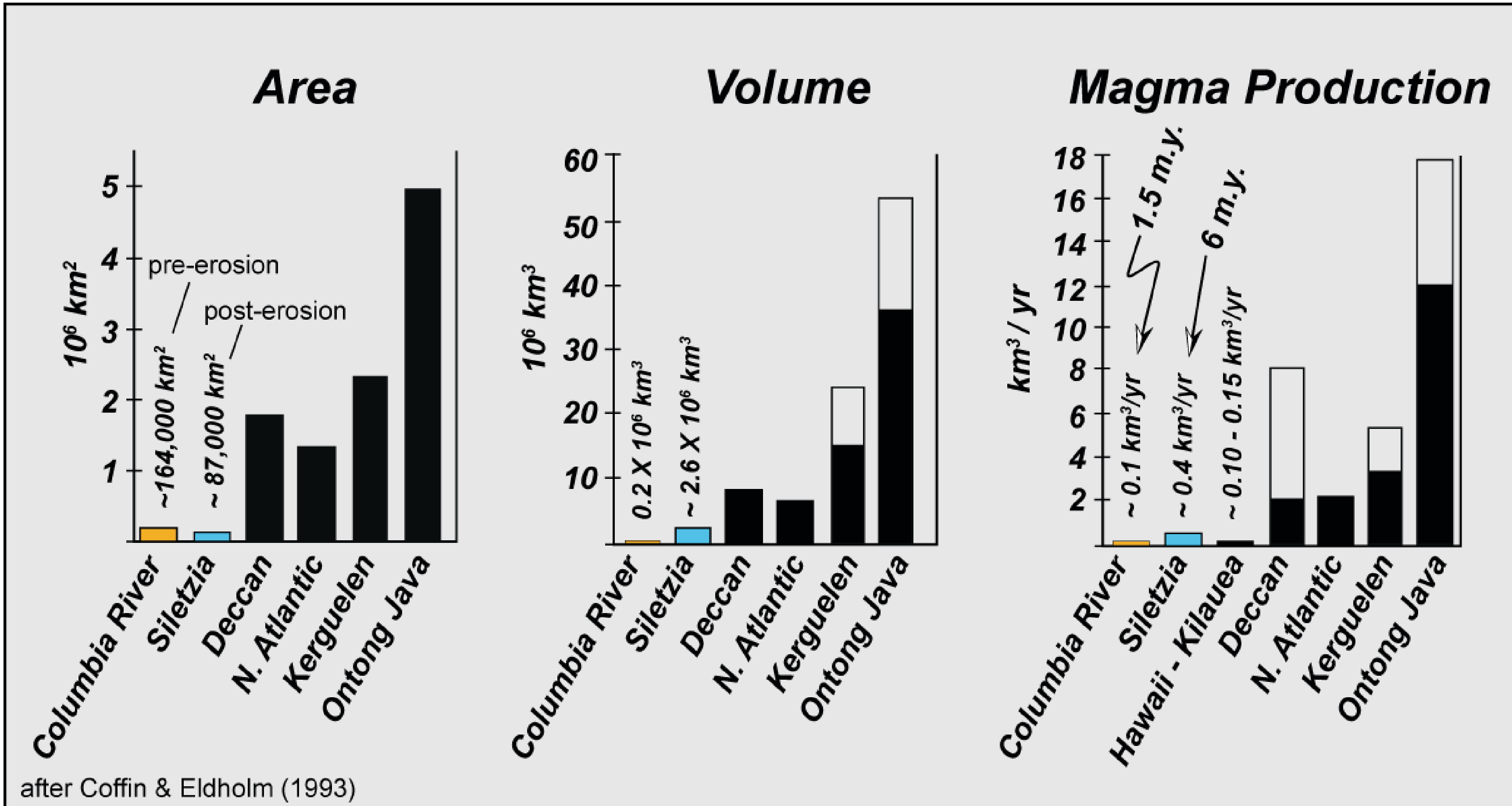
30 km – 2.6 x 10^6 km^3

20 km – 1.7 x 10^6 km^3

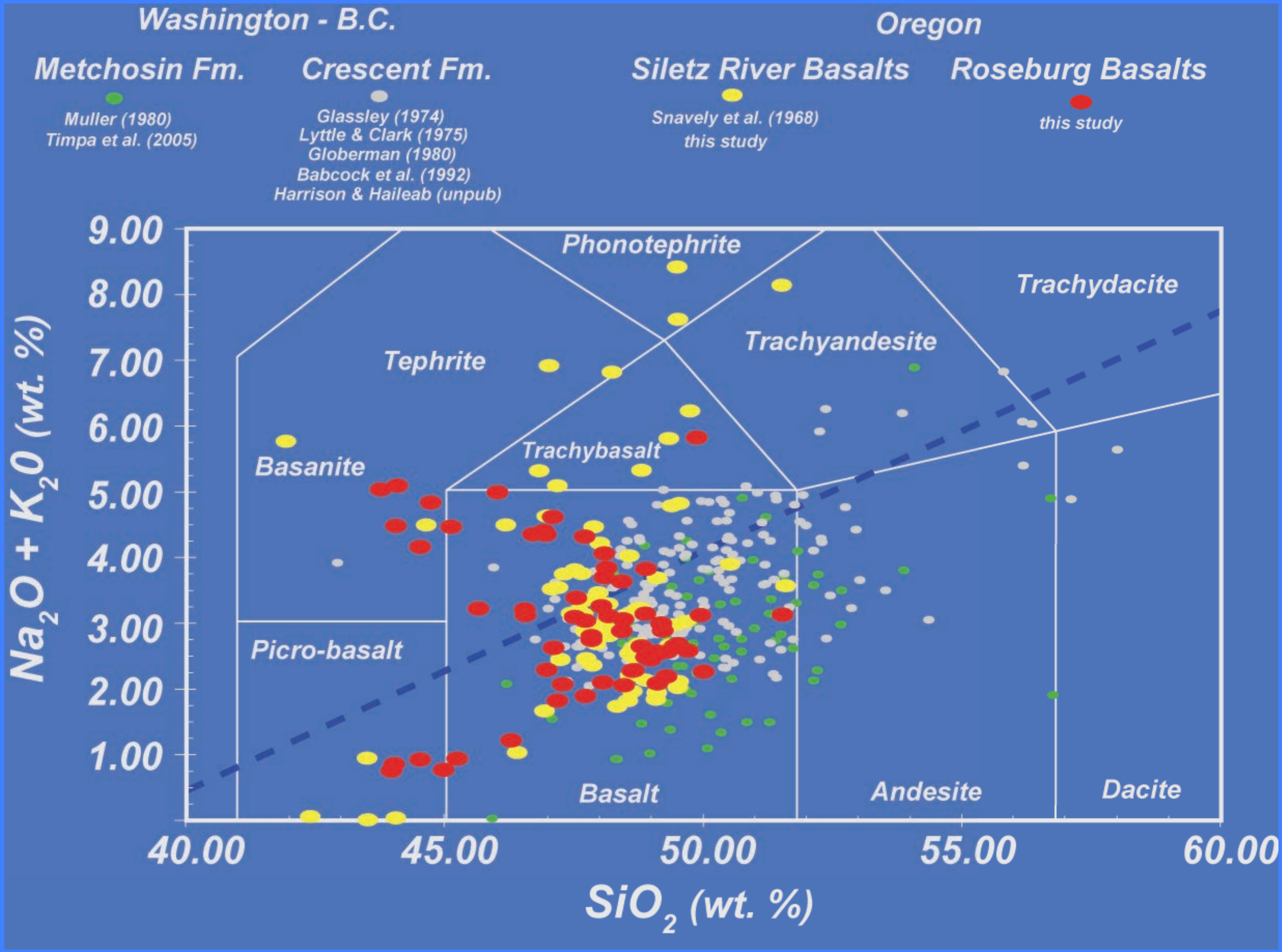


Wells et al. (1998)

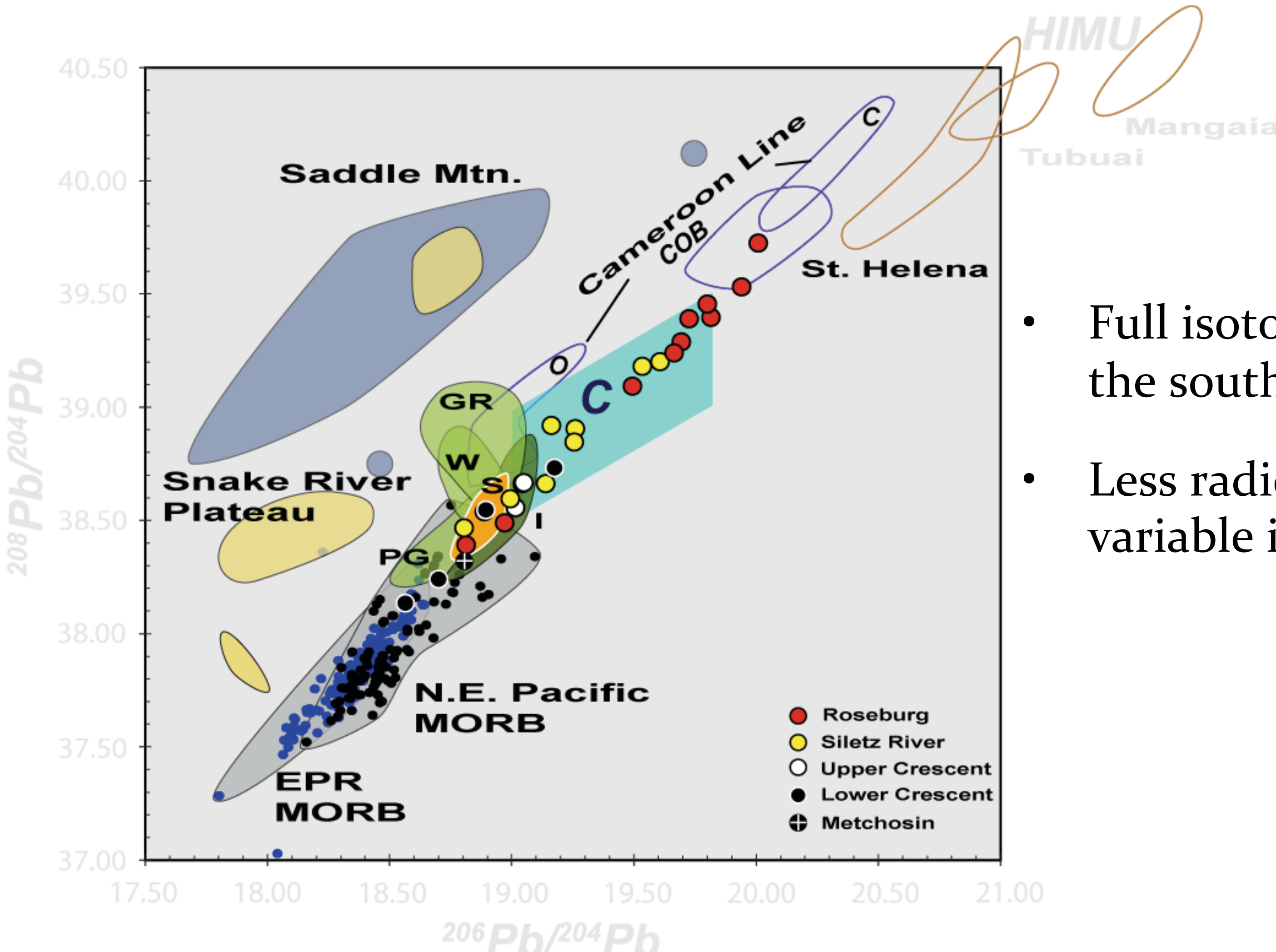
LIP Comparison



Compositional Trends



Pb-Pb

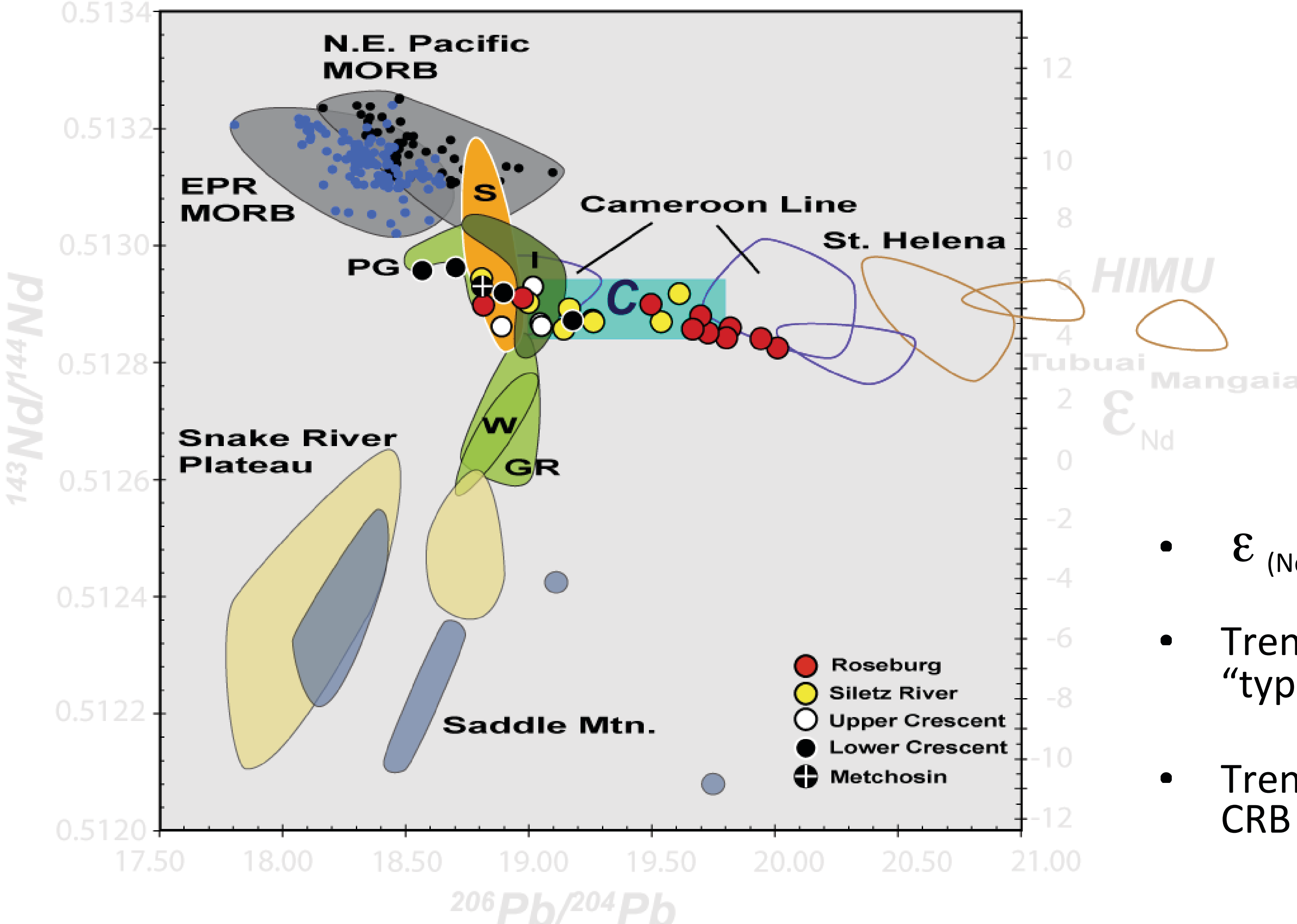


- Full isotopic spectrum in the south
- Less radiogenic and less variable in the north

C – “common component”
Hanan & Graham 1996

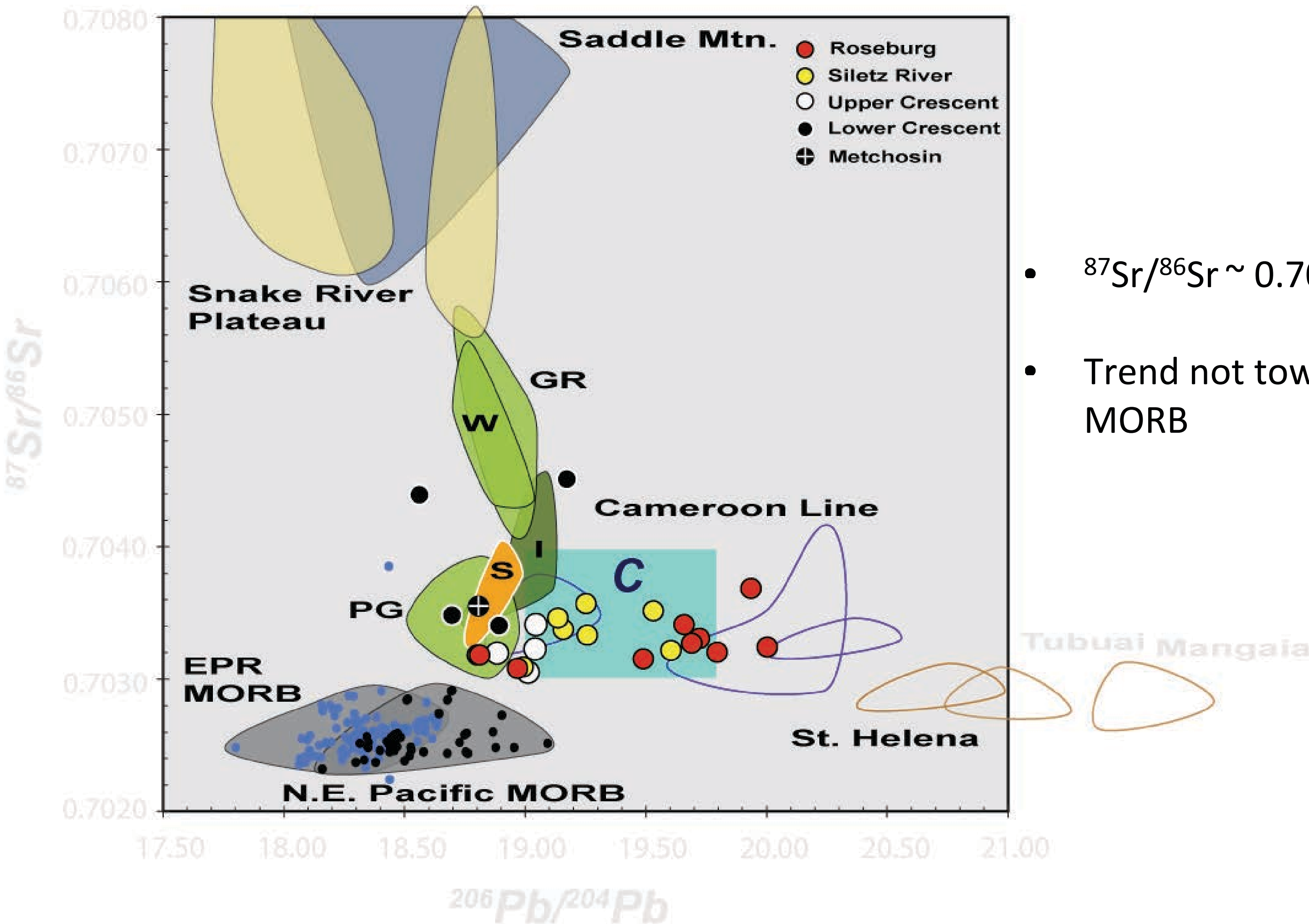
HIMU – aged high U/Pb source
Zindler & Hart 1986

Nd-Pb



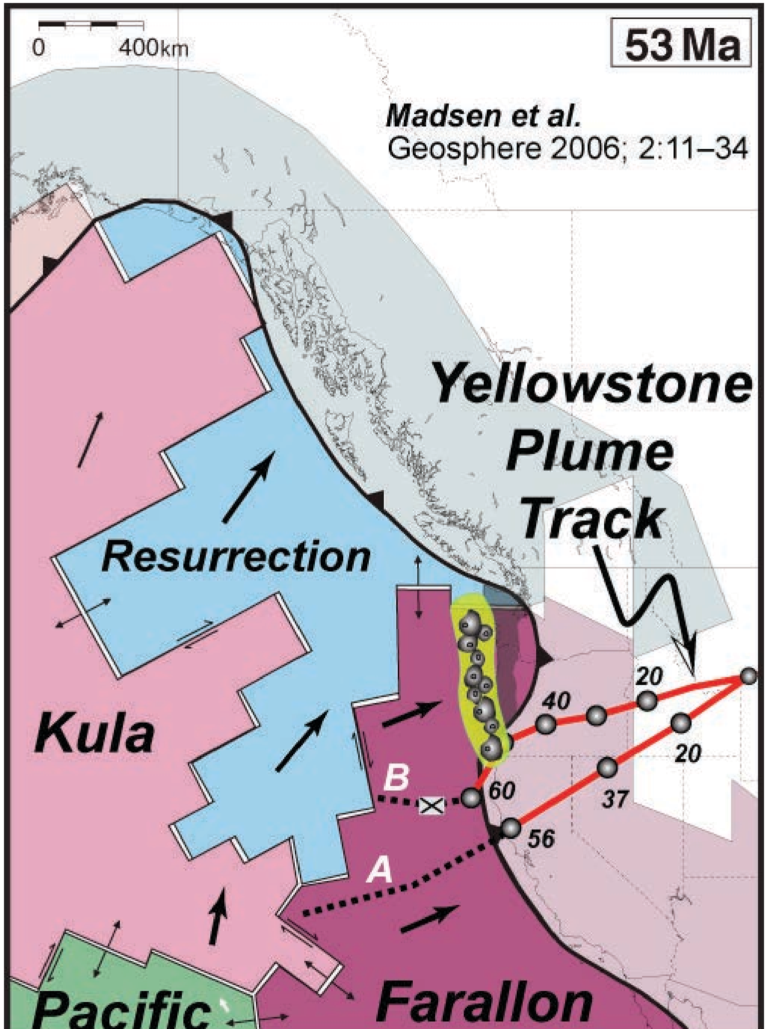
- $\varepsilon_{(Nd)}$ +4 to +6
- Trend not toward "typical" MORB
- Trend toward early CRB source

Sr-Pb



- $^{87}Sr/^{86}Sr$ ~ 0.7030 to 0.7036
- Trend not toward "typical" MORB

Plate – Hotspot Reconstruction



A -Engebretson et al. (1985)
B - Johnston & Thorkelson (2000)

- Plume interacts with Klamath Terrane
- Plate motion drags plume material north
- Plume may feed a spreading ridge
- Crescent-Metchosin more affected by rift environment
- Siletz-Roseburg dominated by plume environment

Summary

- Fits a LIP Model
  - size & duration
- Multiple tectonic components
  - hotspot & rifting
- Multiple mantle sources
  - moderate HIMU to C
  - MORB?
- Plume Head?
  - maybe / maybe not
- Yellowstone Plume?
  - geochemically viable
  - track coincides
- Needed Constraints:
  - <u>more</u> geochemical data (trace element & isotopic)
  - <u>more</u> radiometric ages (timing and duration)