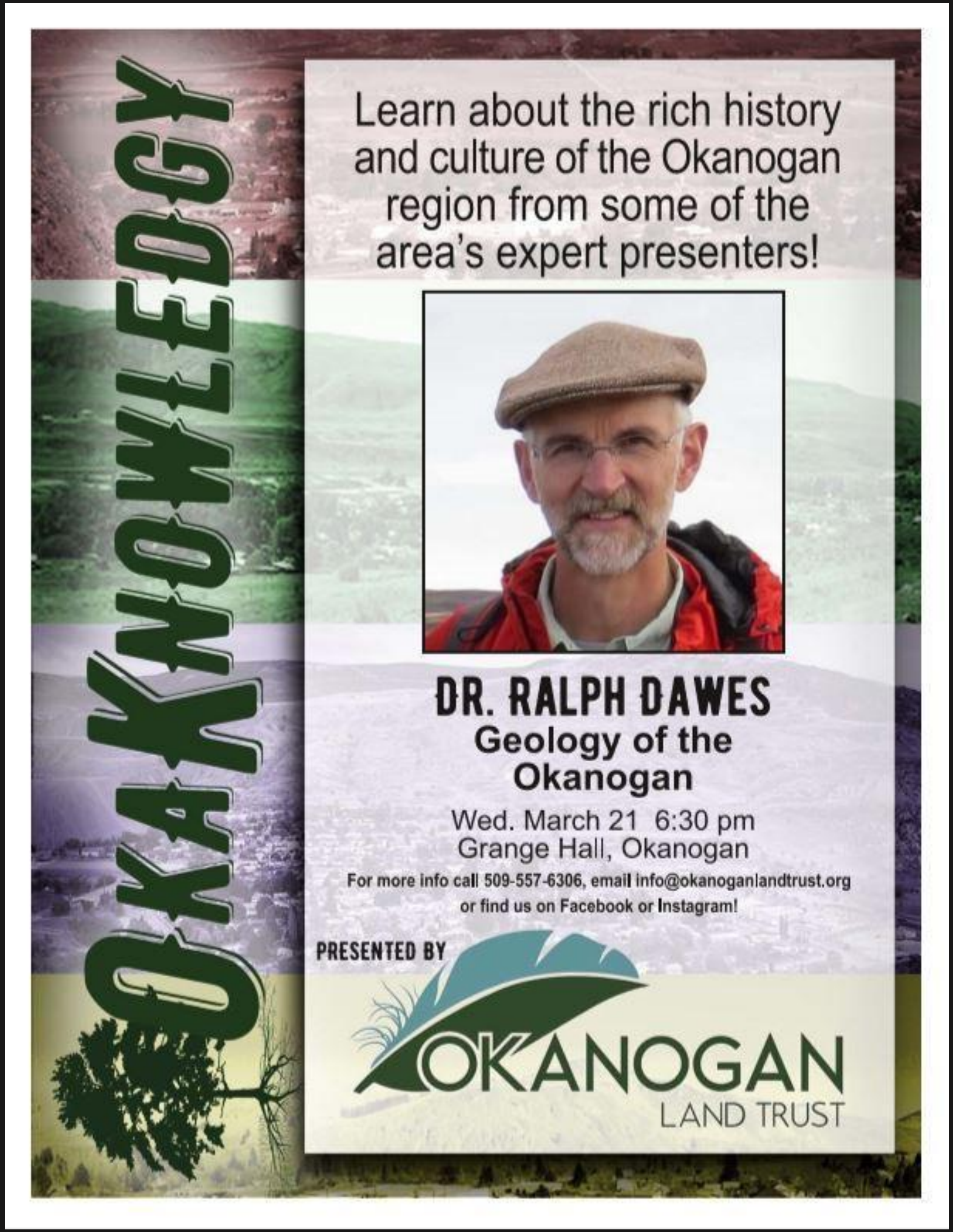
This is an invited talk I gave for the Okanogan Land Trust on the Geology of the Okanogan Region



Great audience, full house, home-baked goodies - what a wonderful group of people!

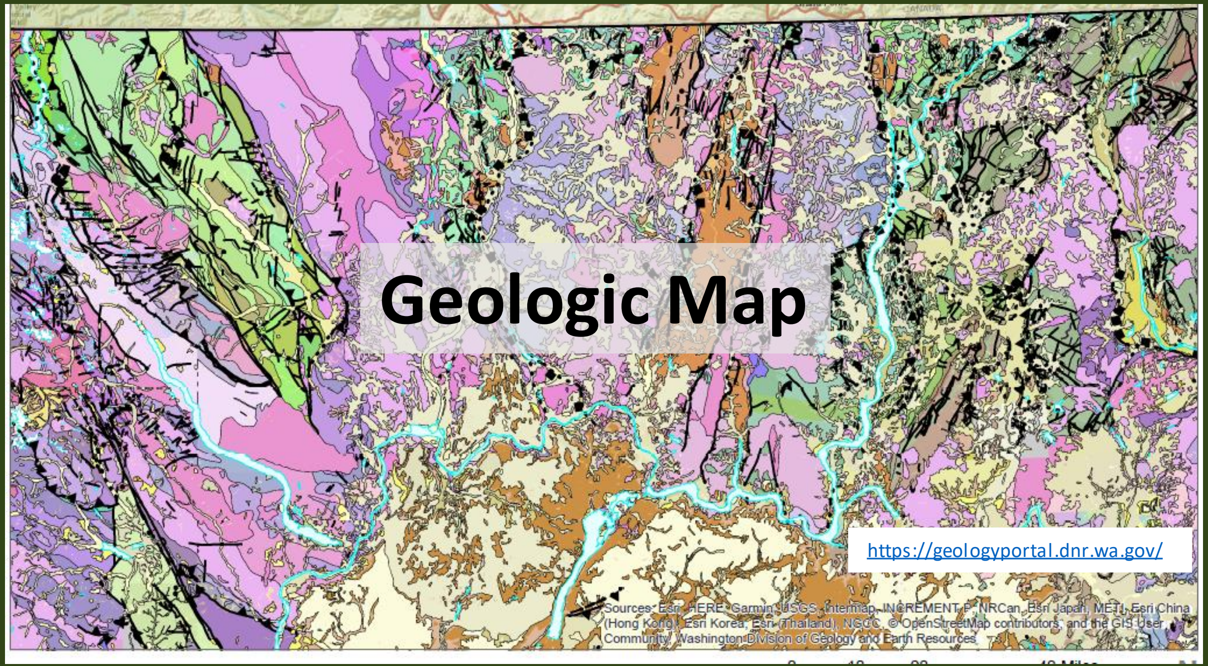
I threw a lot of information at them, but they seemed to take it well.

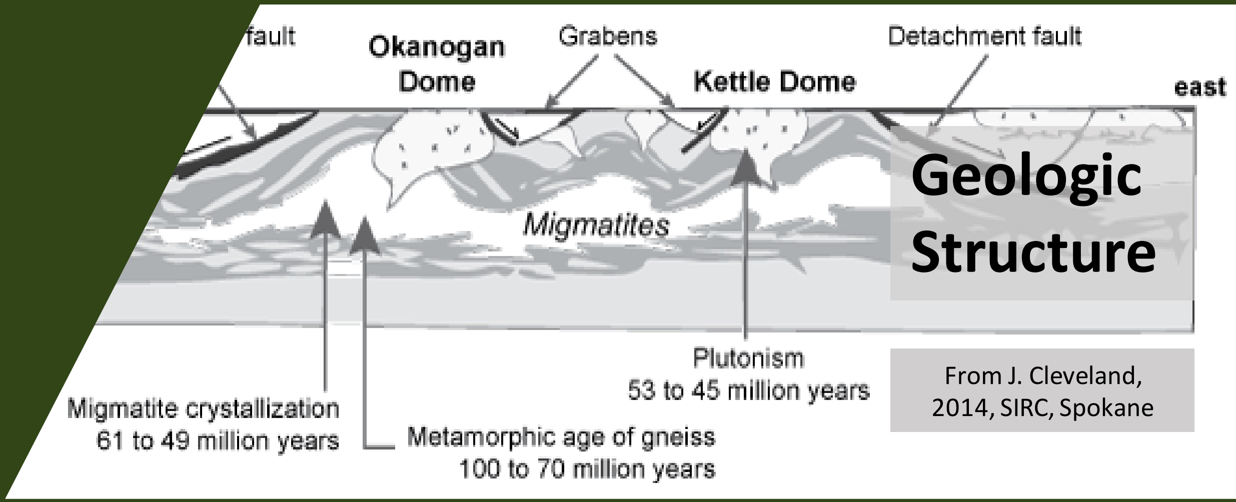
The geology up there in the Okanogan is such a great story, and the land is a testing ground for important, unresolved, geological questions.

Any of you can be involved in resolving the geology questions as participating inquirers!

Okanogan Geology:
A fundamental part of OkaKnowledgy!

Dr. Ralph Dawes, Wenatchee Valley College





- We'll take this puzzle apart
- And put it back together

Geology defines Okanogan

landscape
climate
economy
ecology
hazards
human history

Palmer Lake, https://wdfw.wa.gov/fishing/washington/689/

Google Earth image detail

Whitestone Mtn. by J. Foster Fanning, http://okanoganhighland.blogspot.com/p/landscapes-of-okanogan-highlands.html

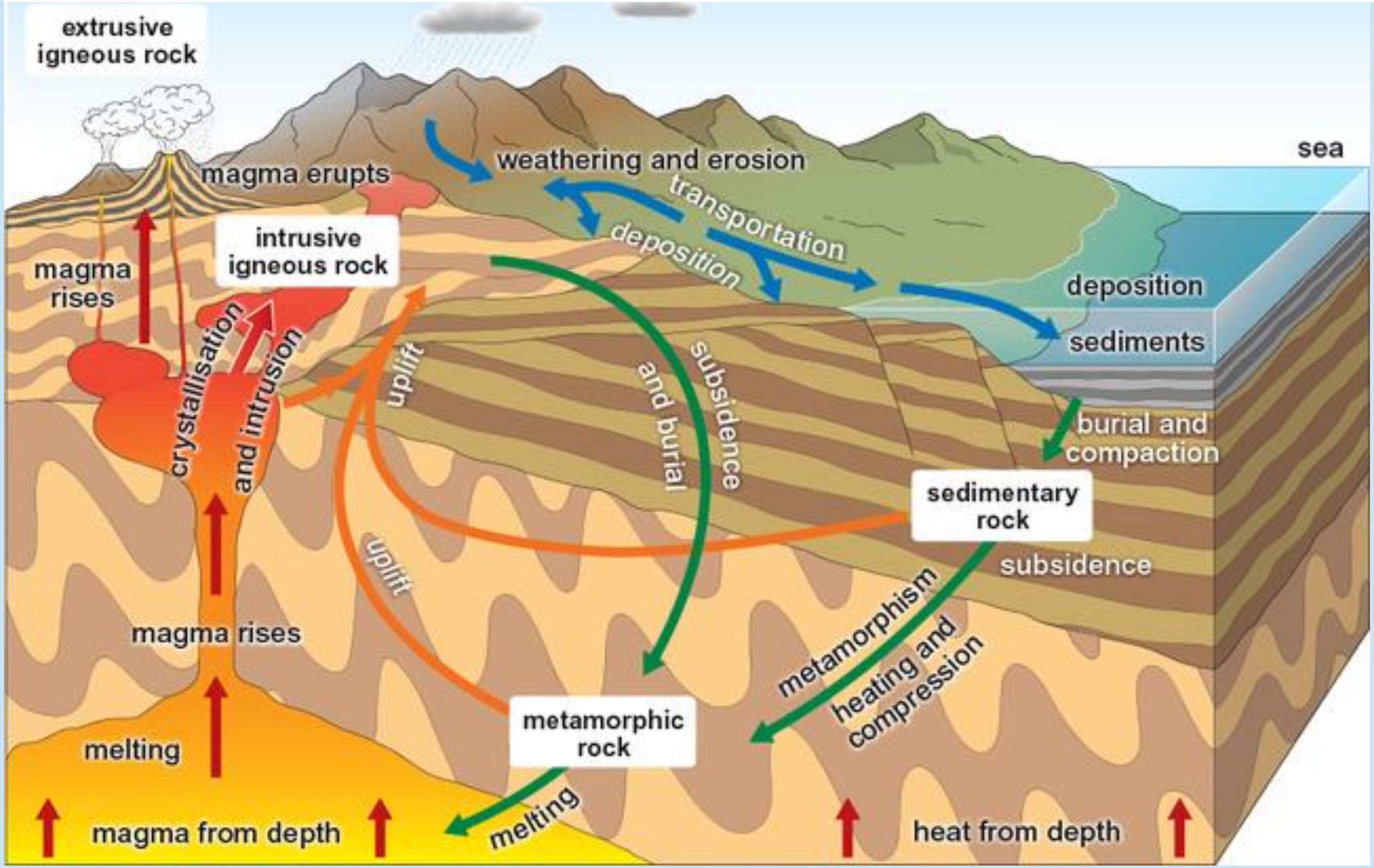
What we'll examine

- **Geologic Background**
  rocks, tectonics, & time
- **Continental Conundrum**
  the edge of a broken land
- **Quesnellian Quirkiness**
  the addition of new land
- **Eocene Eccentricity**
  a very odd time - what happened?
- **Ice Age Intrigue**
  solid vs. liquid

"Omak Rock," https://www.wikiwand.com/en/Omak_Rock

Geologic Preliminaries

the rock cycle

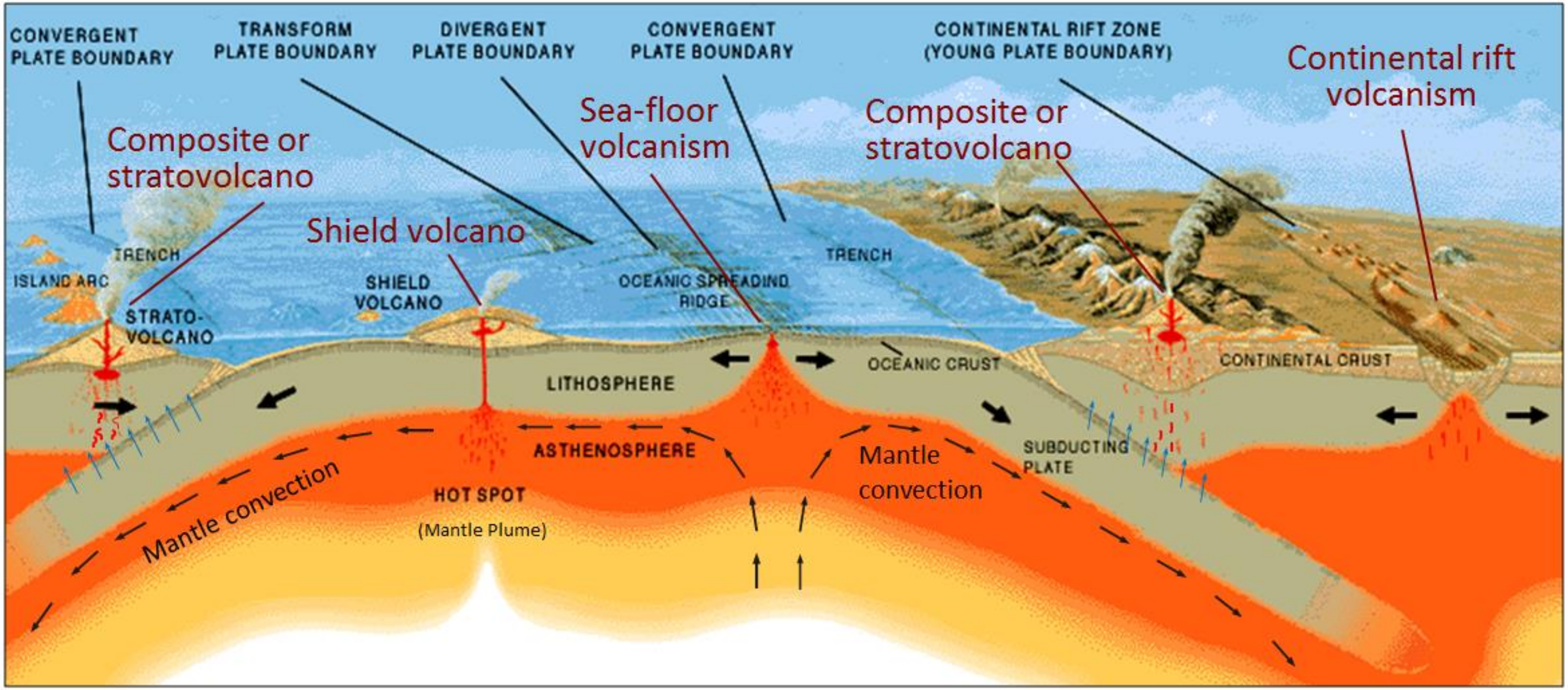


from The Open University: openlearn.com

- Rock cycle happening everywhere always
- Intrusive igneous rocks – granite! – are most abundant
- Hard to imagine sub-surface realm of lithification, metamorphism, melting, and magma –
- - rocks uplifted, exposed at surface are windows into those processes

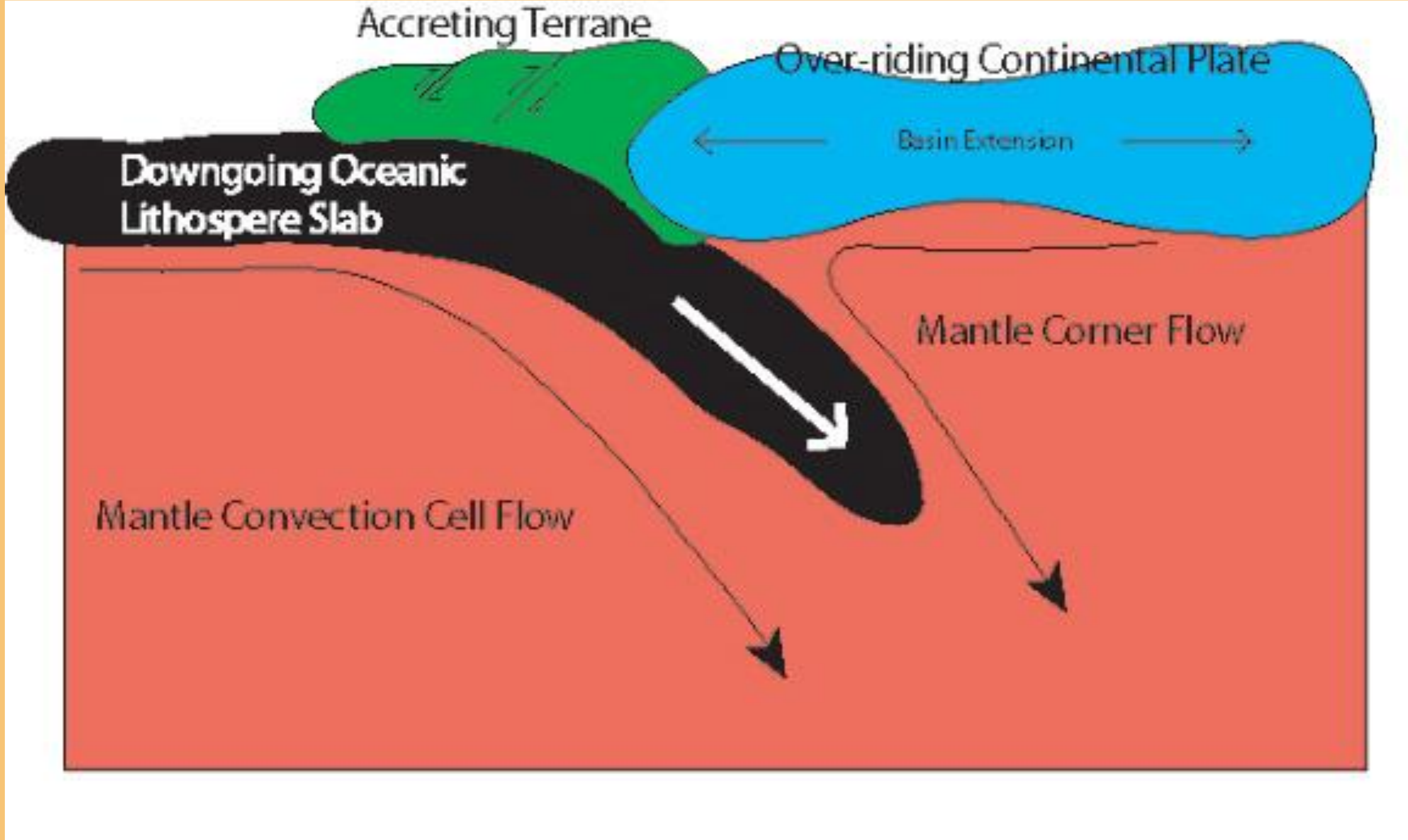
Geologic Preliminaries

plate tectonics



Geologic Preliminaries

terrane accretion

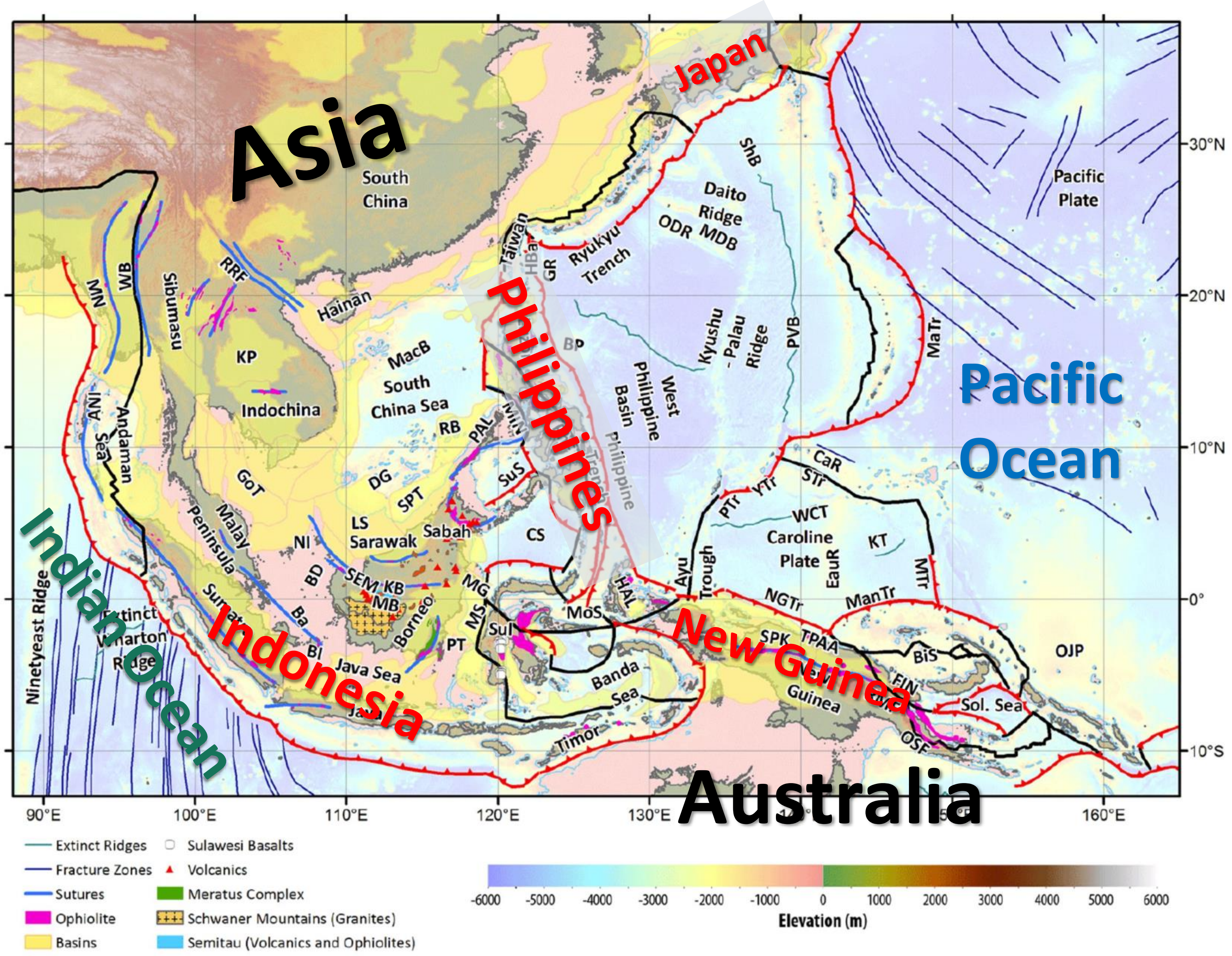


"Exotic" terranes: pieces of Earth's crust brought in on moving plates & transferred to continent

- Commonly composed of either oceanic crust or island arc crust
- Terranes don't just come straight in on a subducting plate –
- – terranes can also be translated sideways along coast

Geologic Preliminaries

terrane accretion



terrane accretion complexity: see SW Pacific Ocean today

Asia and Australia will grow through accretion of:

- Island arcs
- Oceanic plateaus
- Accretionary prisms
- Ophiolites*

Imagine past N. America coast like SE Asia coast today.

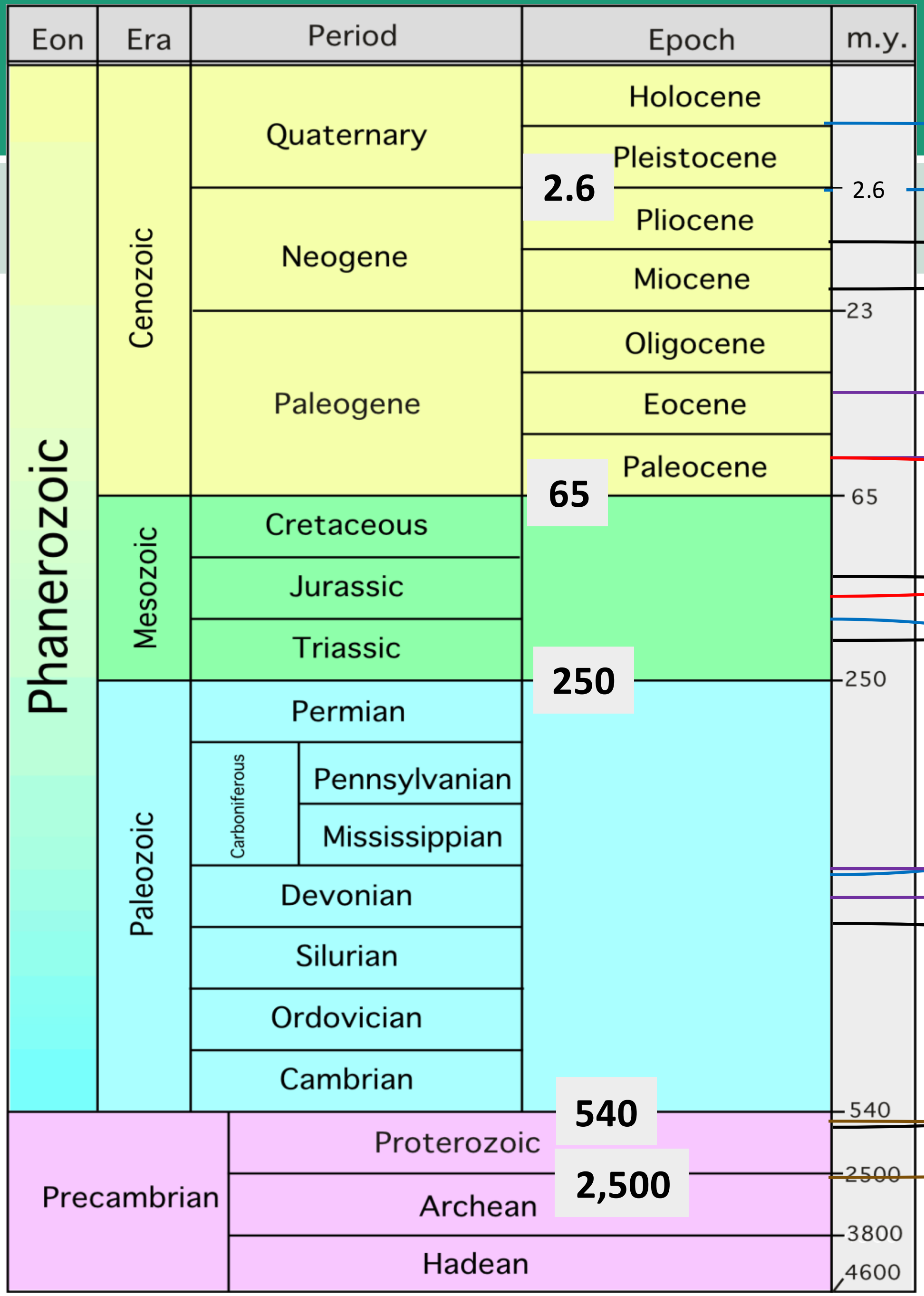
Run your mental movie forward a couple hundred million years.

*Ophiolites are oceanic crust AND underlying mantle rocks

Geologic Preliminaries

Geologic Time

numbers are millions of years ago (Ma)



Ice Ages

(Columbia River Basalt)

Eocene Eccentricity

Granitic intrusions & crustal metamorphism

Accretion of Quesnellia to N. America

Quesnellia terrane forms, amalgamates with other terranes

(Antler orogeny)

Laurentia passive margin sediments

Rodinia-Laurentia sequence:

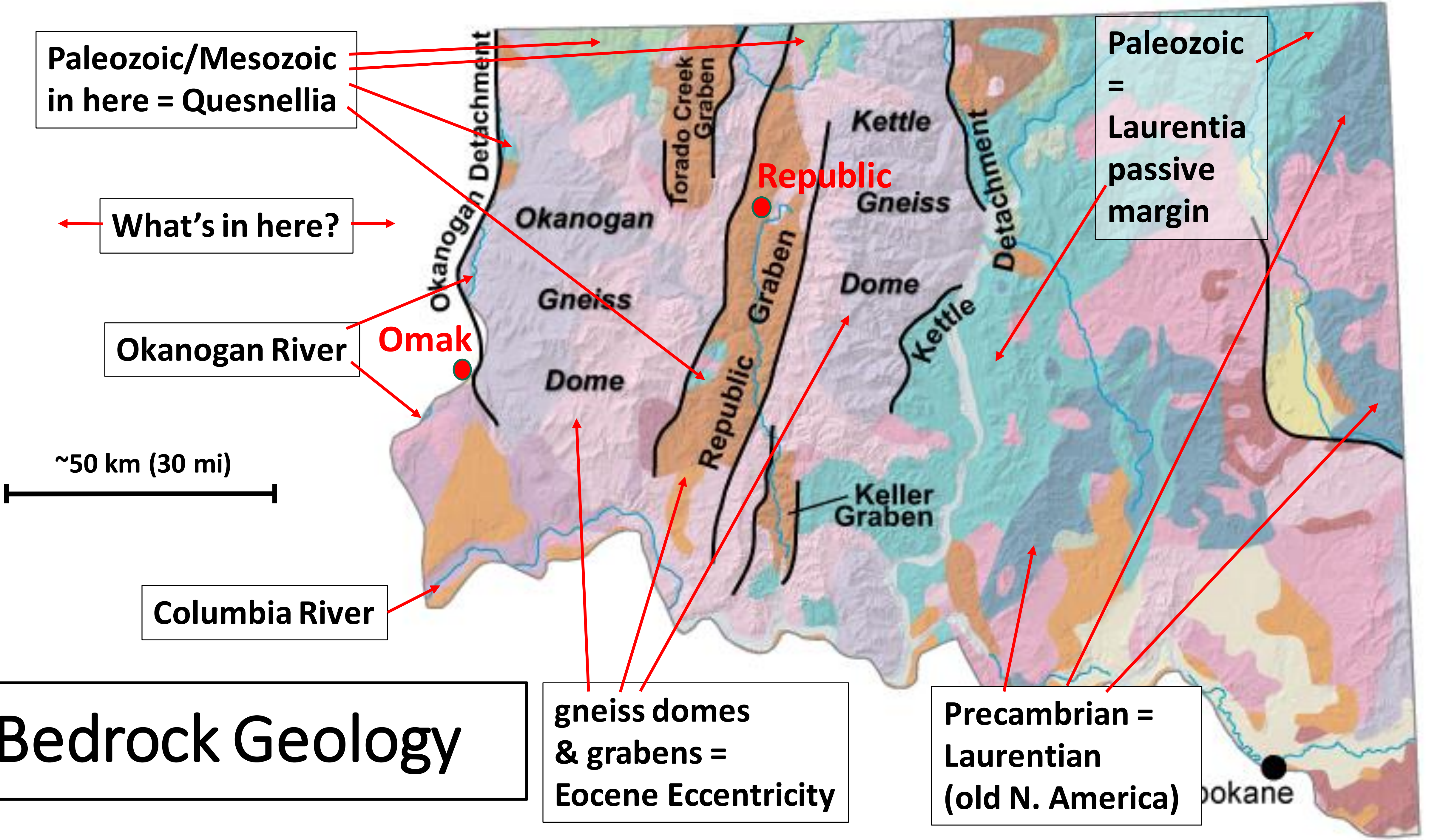
1. **Older craton (>1500 Ma)**
2. **Belt Supergroup (1400-1500 Ma)**
3. **Pre-rift & rift rocks (600-1400 Ma)**

The Sequence
Oldest at Bottom, Youngest at Top

Focus Topic in Bold	When*	Focus
after the ice age	11,700 years – now	
Ice Age Intrigue	2.6 Ma –11,700 years	**How ice & liquid water shaped the land**
gap	40 – 2.6 Ma	
Eocene Eccentricity	~60 – 40 Ma	**Odd tectonics & igneous flare-up**
intrusion, metamorphism	150 – 60 Ma	
Quesnellian Quirkiness	350 – 150 Ma	**Okanogan's accreted terrane**
Continental Conundrum	>1,500 Ma – 350 Ma	**Edge of Old North America. Where?**

(* Ma means millions of years ago)

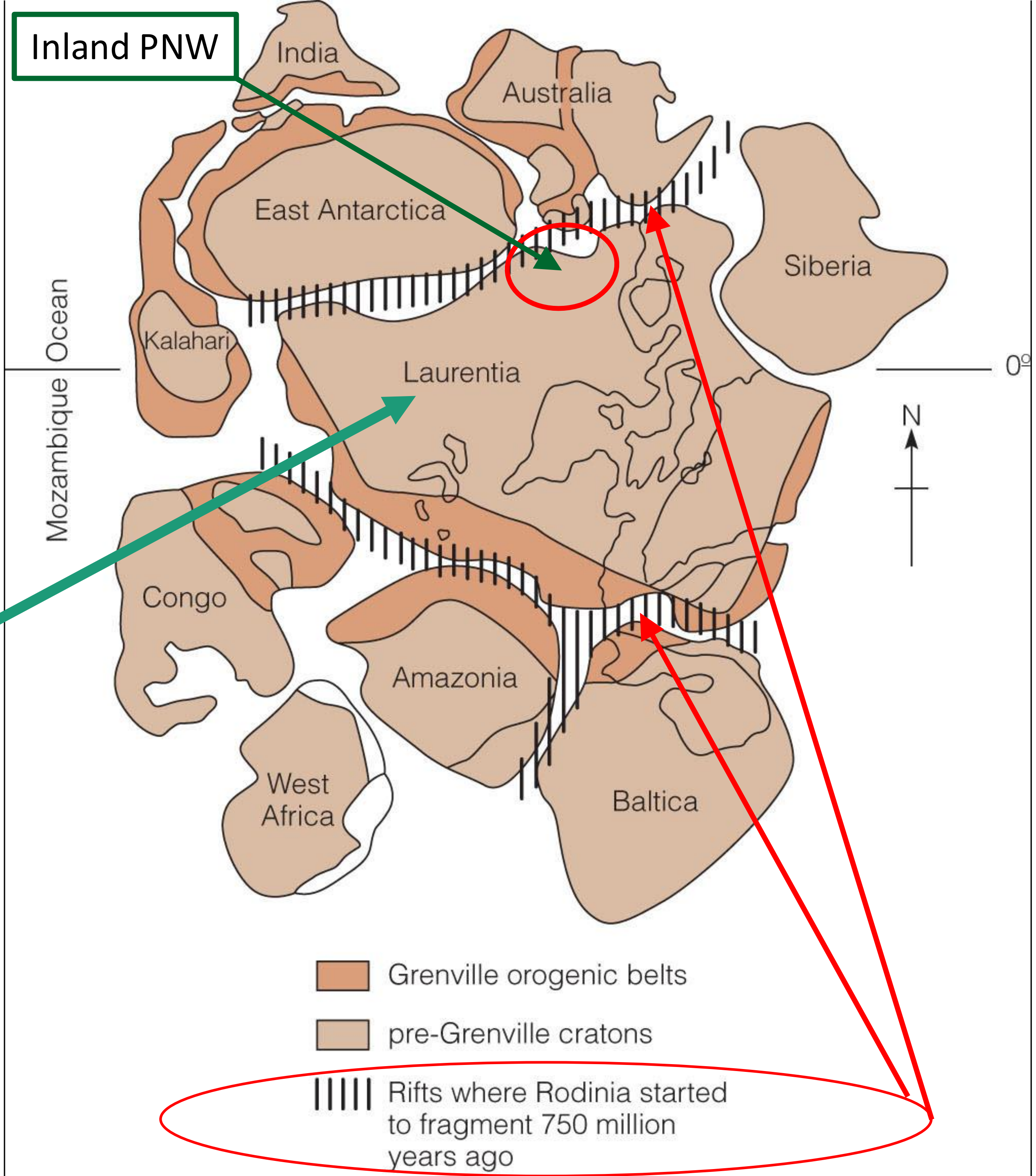
Bedrock Geology



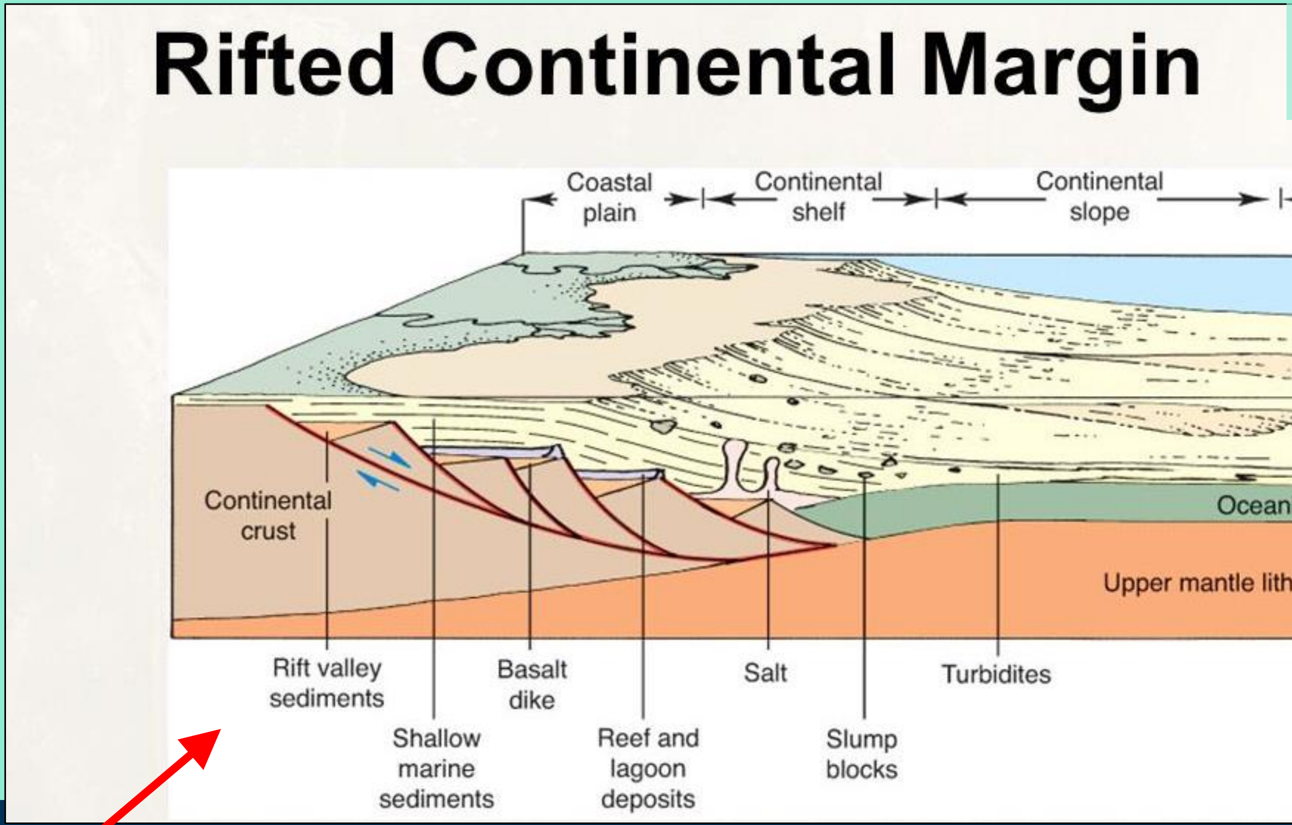
Supercontinents come, supercontinents go: Rodinia preceded Pangea

- late Precambrian: North America part of supercontinent Rodinia
- North America's old core, or *craton*, is called ***Laurentia***

  Note that Laurentia (N. America) is tipped on side, straddles equator



After Rodinia rifted, things quieted down…



original image from Jones & Bartlett Learning LCC, copied from http://slideplayer.com/10657749/36/images/53/Rifted+Continental+Margin.jpg

- Laurentia **passive margin** accumulated sediments through Paleozoic era, ~550-250 Ma
- Including while supercontinent Pangea assembled and existed, 350-200 Ma

(the continents sutured into Pangean supercontinent on other sides of Laurentia, not here)

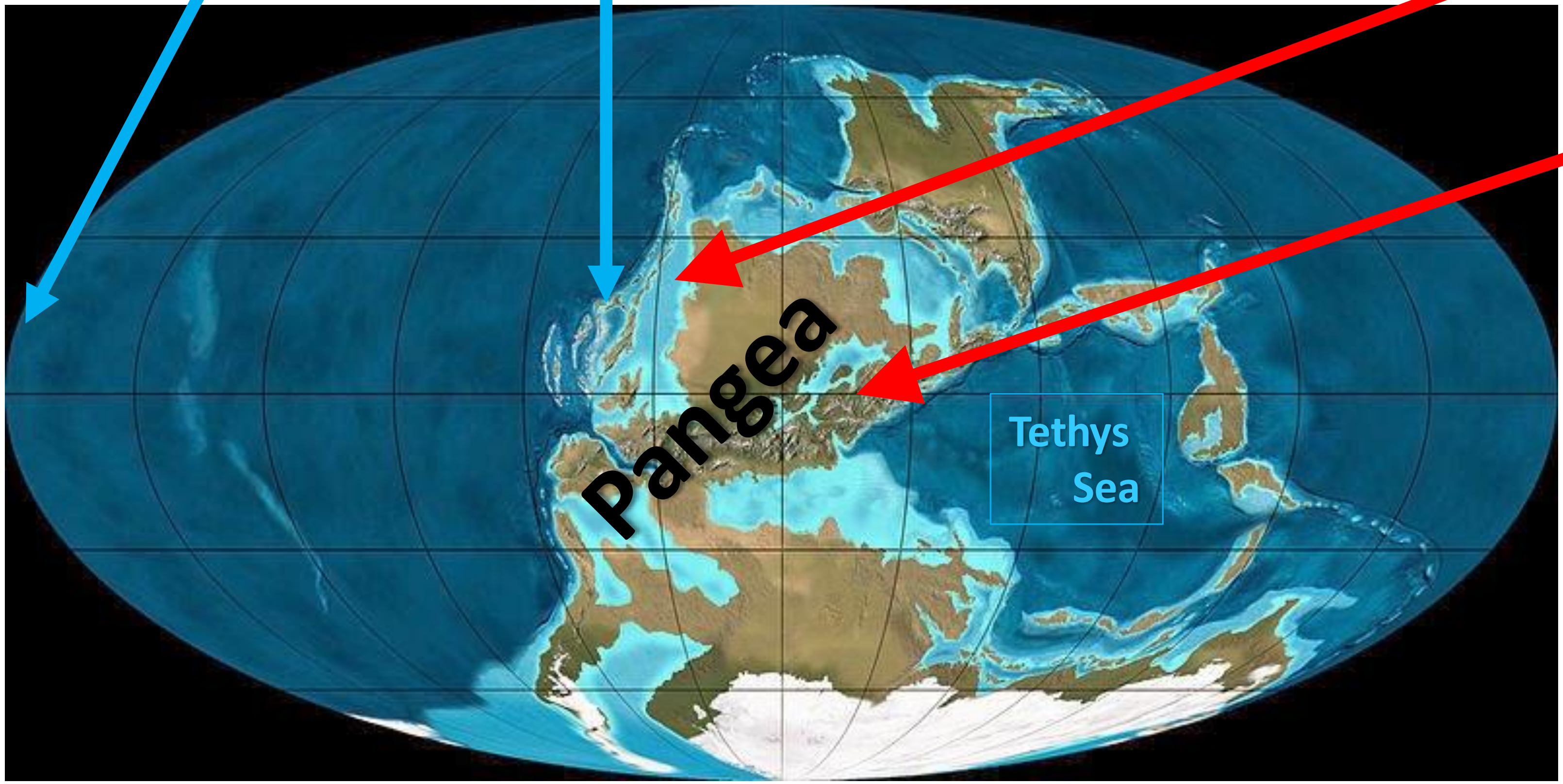
- The rest of the PNW was subsequently added to Laurentian margin

Long after Rodinia, starting ~350 m. yrs. ago, supercontinent Pangea assembled

3. Exotic terranes, mostly island arcs, offshore as far as Tethys Sea area

2. PNW ~ in here

1. Pre-Atlantic ocean closing here, forming Appalachian Mountains

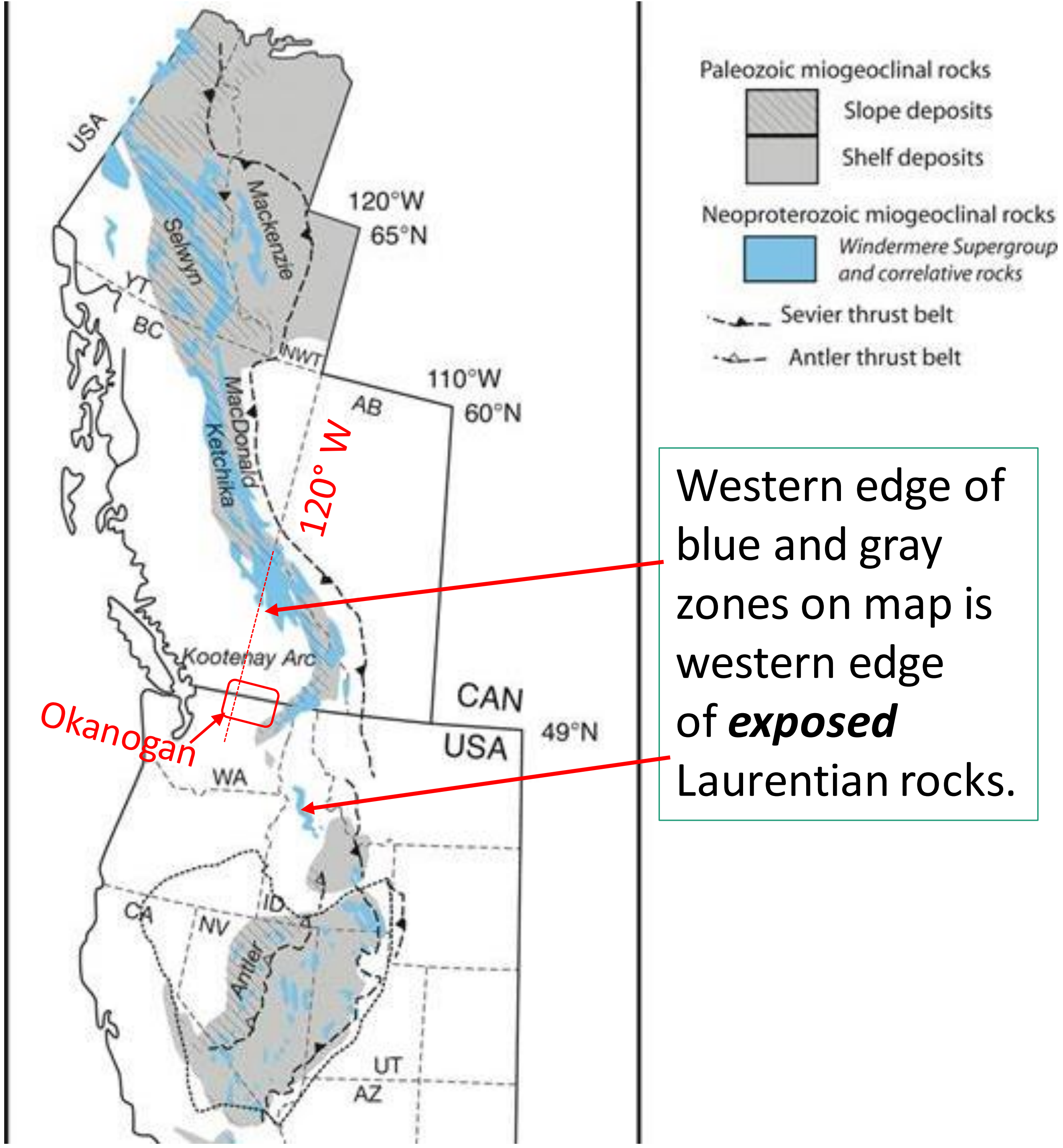


Edge of “old N. America”

- Rodinia, precursor to Pangea, rifted apart towards end of Precambrian (600-800 Ma).
- Laurentia, “old North America,” was one of the big pieces that rifted away.
- Rifted western edge of Laurentia was passive (not at a plate boundary) continental margin for hundreds of millions of years.

____

- Where is the edge of Laurentia, the margin of old North America, relative to us right here right now?



Western edge of blue and gray zones on map is western edge of ***exposed*** Laurentian rocks.

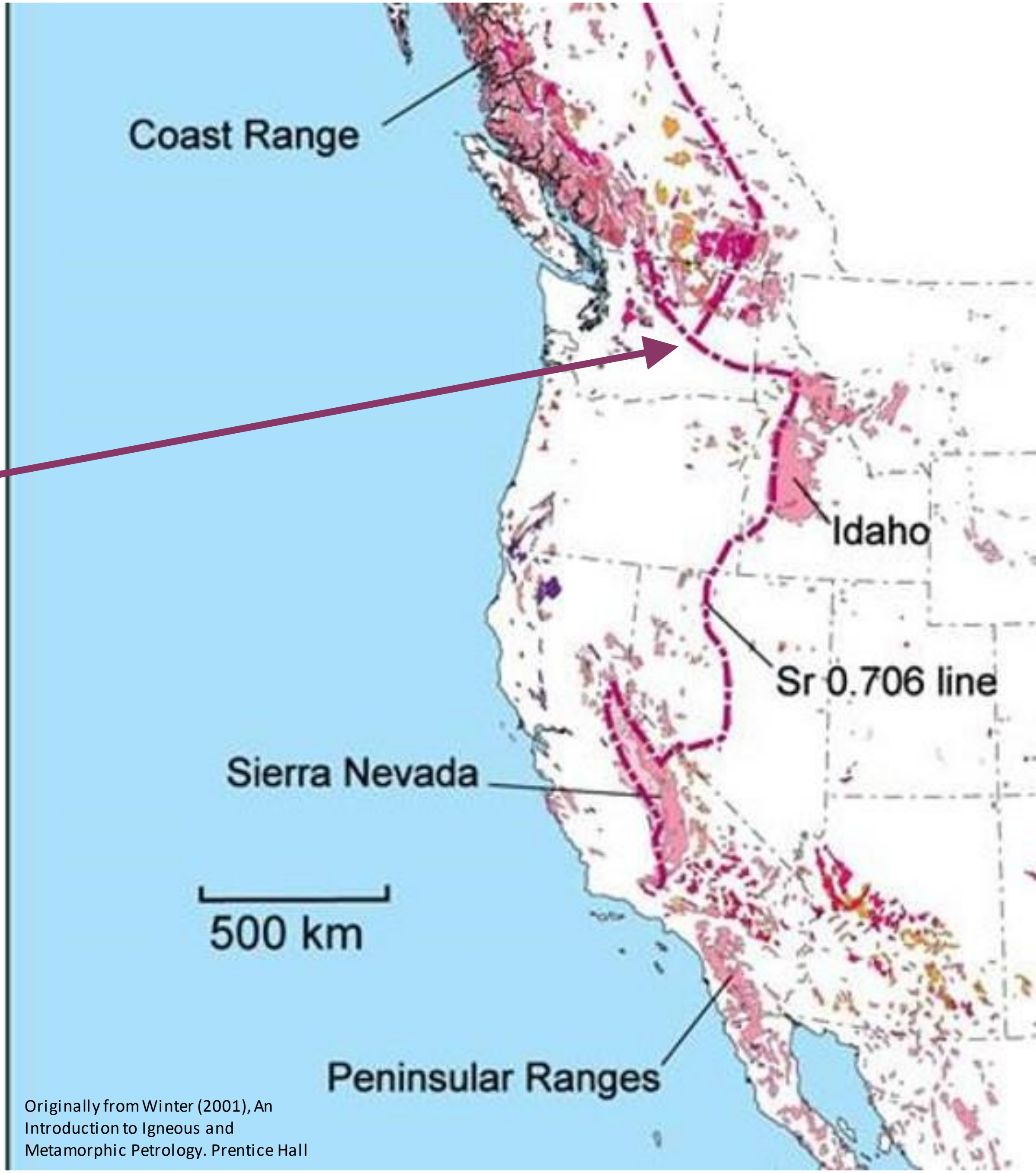
Several types of evidence find craton edge at depth

1. **The famous Sr 0.706 line from granites, by Armstrong *et al.*, 1977**
   - **Line becomes ambiguous in Washington**

2. **Other chemical and isotopic signals in igneous rocks**

3. **Xenoliths in volcanic rocks**

4. **Seismic imaging (next slide)**



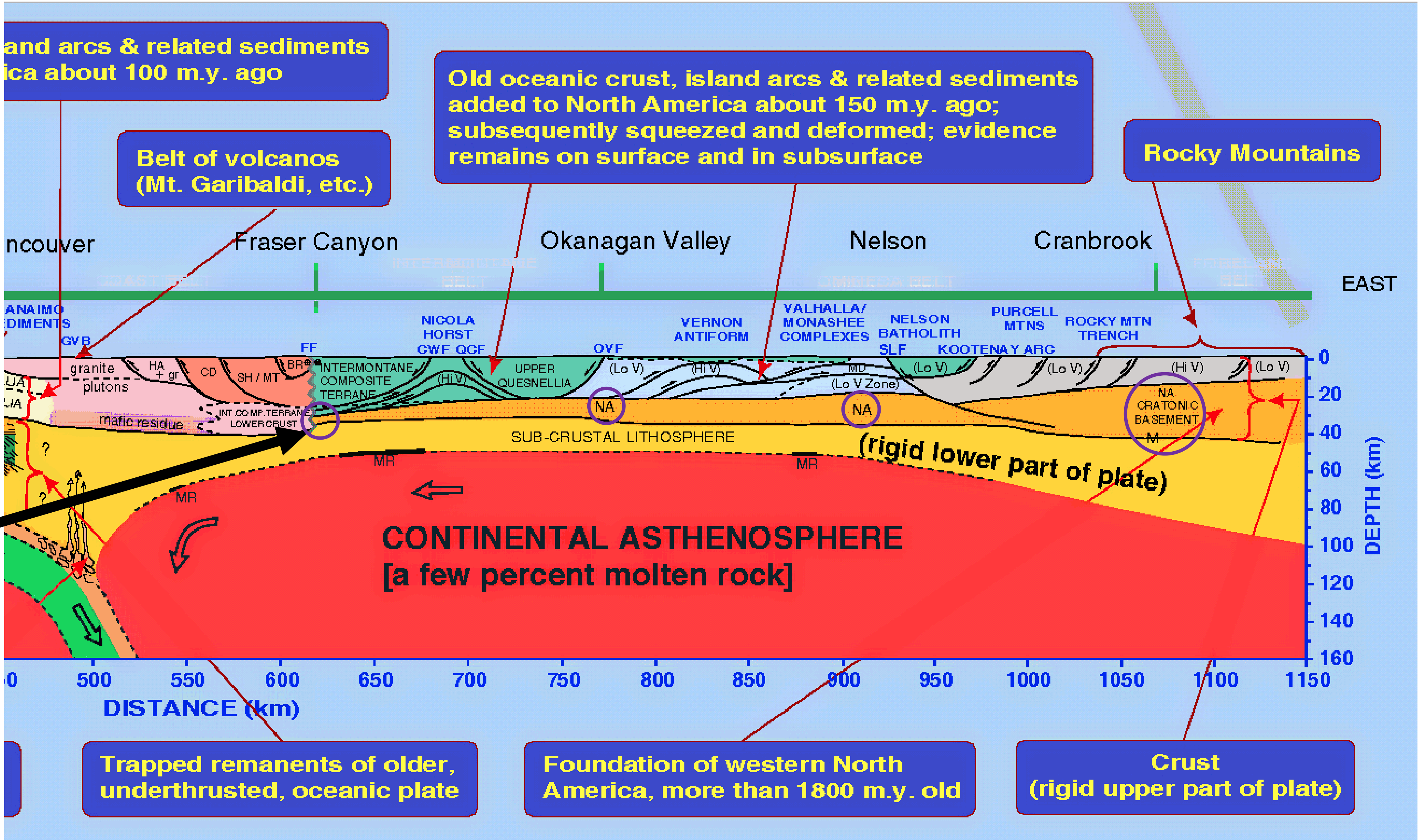
Originally from Winter (2001), An Introduction to Igneous and Metamorphic Petrology. Prentice Hall

Interpretation of seismic imaging across southern British Columbia

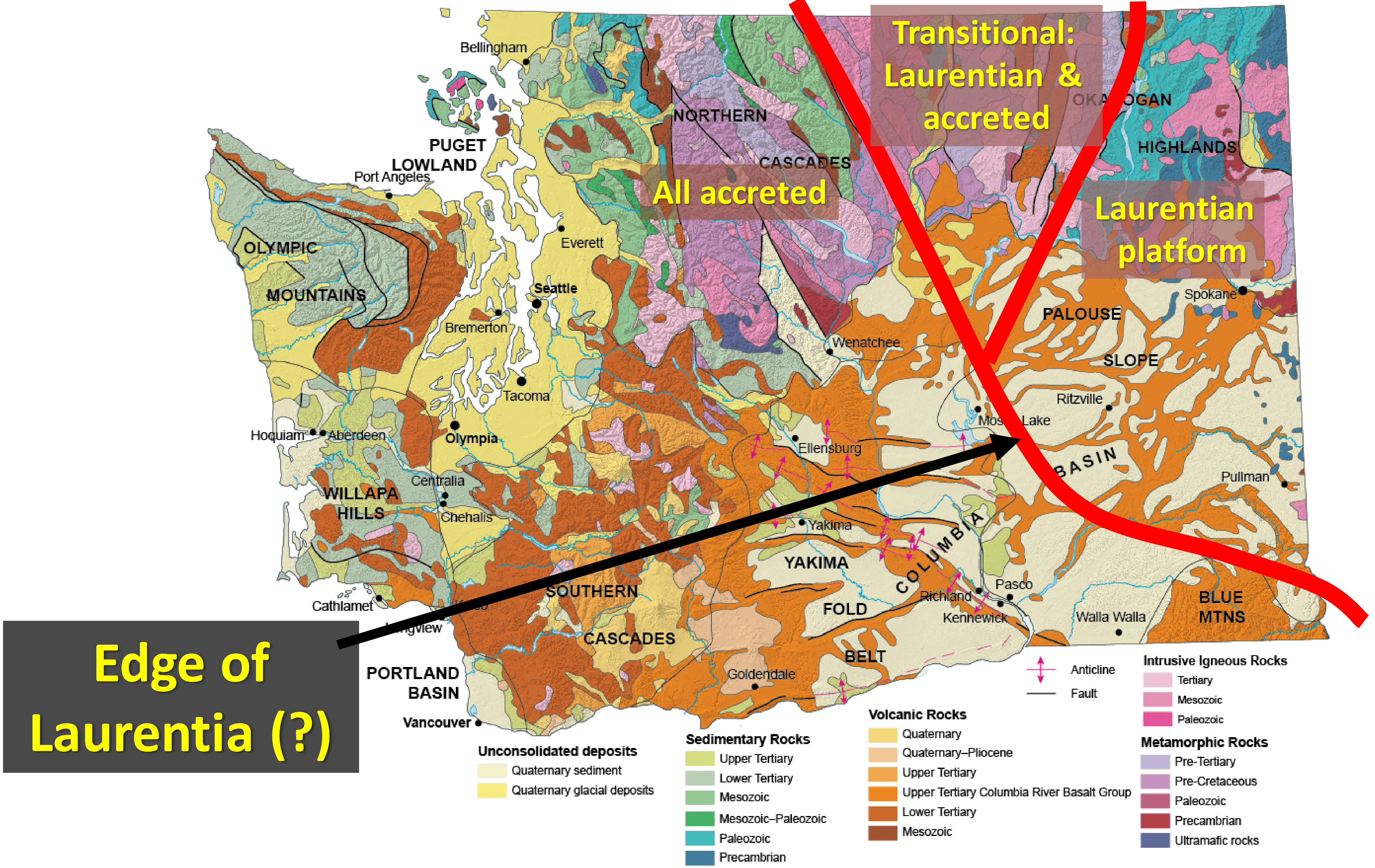
Deep crust of old North America -

(NA craton basement, see purple circles)

- forms ramp beneath Quesnellia & other Intermontane terranes



Detail from poster by Canadian Lithoprobe group: http://lithoprobe.eos.ubc.ca/media/poster/panels/5.html



https://www.dnr.wa.gov/pictures/ger/ger_popular_geomap_state.png?lazgk7

Though probably more complicated at depth (and at surface) than we currently know, it looks like:

1. Laurentia surface exposures extend about as far west as Kettle Falls

2. Craton basement at depth reaches west of Okanogan Valley

So if asked if edge of old north America is east of the Okanogan or west of the Okanogan, the answer is yes.

Then Pangea rifted & Laurentia drifted west…

The passive continental margin became tectonically very active

- **rife with subduction zones, transform faults, & offshore spreading ridges**

Leading to

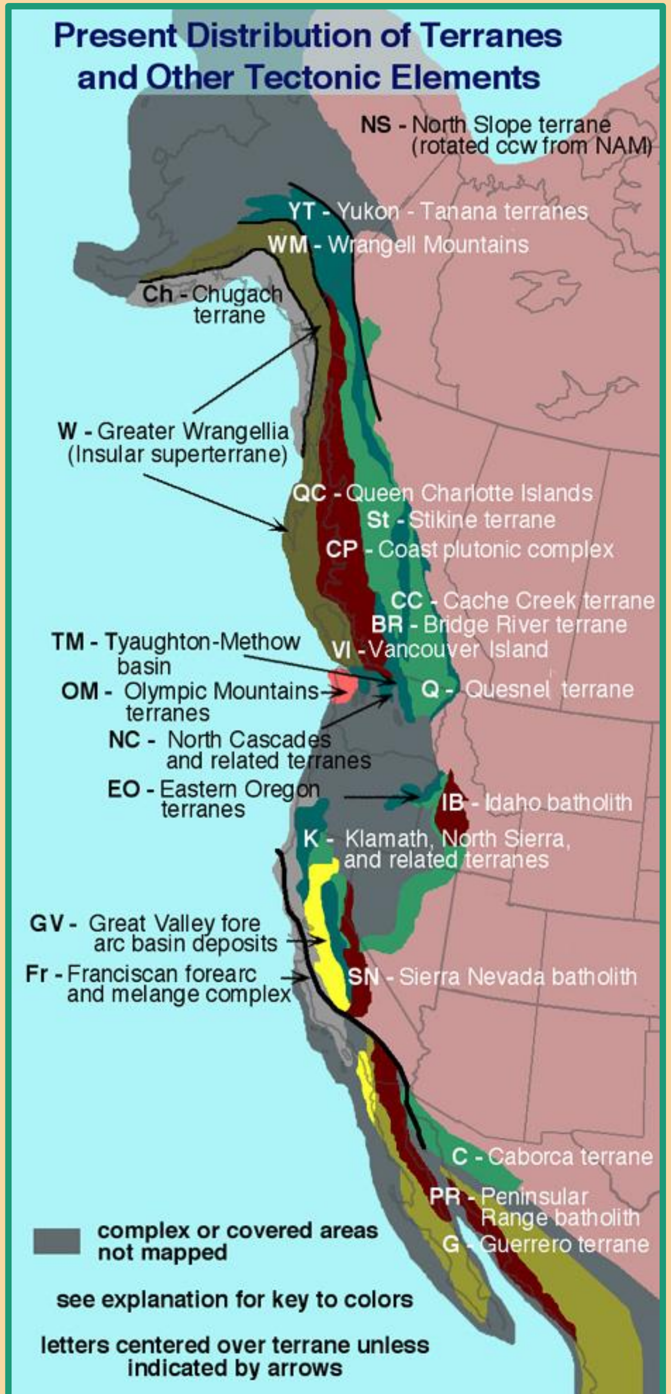
- **thrust faults - telescoping, shortening, piling-up of rock layers**
- **transform faults - major sideways offsets of crustal fragments**
- **terrane accretion - major pieces of oceanic and island arc crust added to the edge of the continent, growing the continent out to the west**

original by Ron Blakey, this version copied from
http://written-in-stone-seen-through-my-lens.blogspot.com/2014/10/

The big picture: Accreted terranes of western North America

- All added to margin of continent since early Jurassic time, ~200 Ma
  - After continent rifted from rest of Pangea
  - And started drifting westward
  - Developing active plate boundaries along leading edge
  - And sweeping up terranes

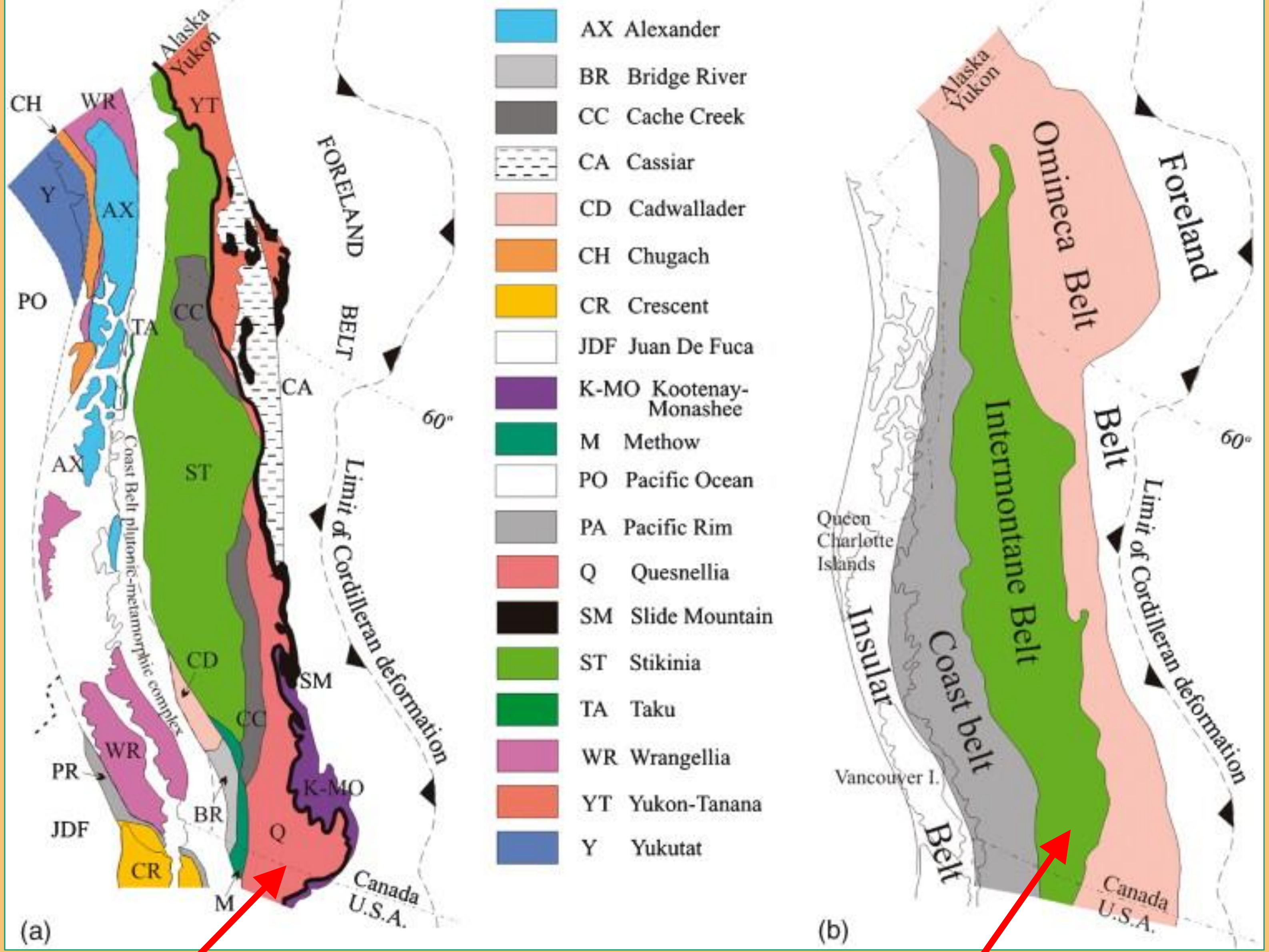
- In the Quesnellia terrane (Q), Okanogan region shares piece of accreted terranes jigsaw puzzle



http://jan.ucc.nau.edu/rcb7/present_terrane.jpg

Quesnellia terrane

Ricketts, 2008, https://doi.org/10.1016/S1874-5997(08)00010-5



Q = Quesnellia

Quesnellia is part of Intermontane superterrane

- the one accreted terrane in Okanogan region is **Quesnellia**
- part of the **Intermontane superterrane**
- made of island arc crust (on oceanic crust basement)
- accreted during Jurassic period (160-190 Ma)

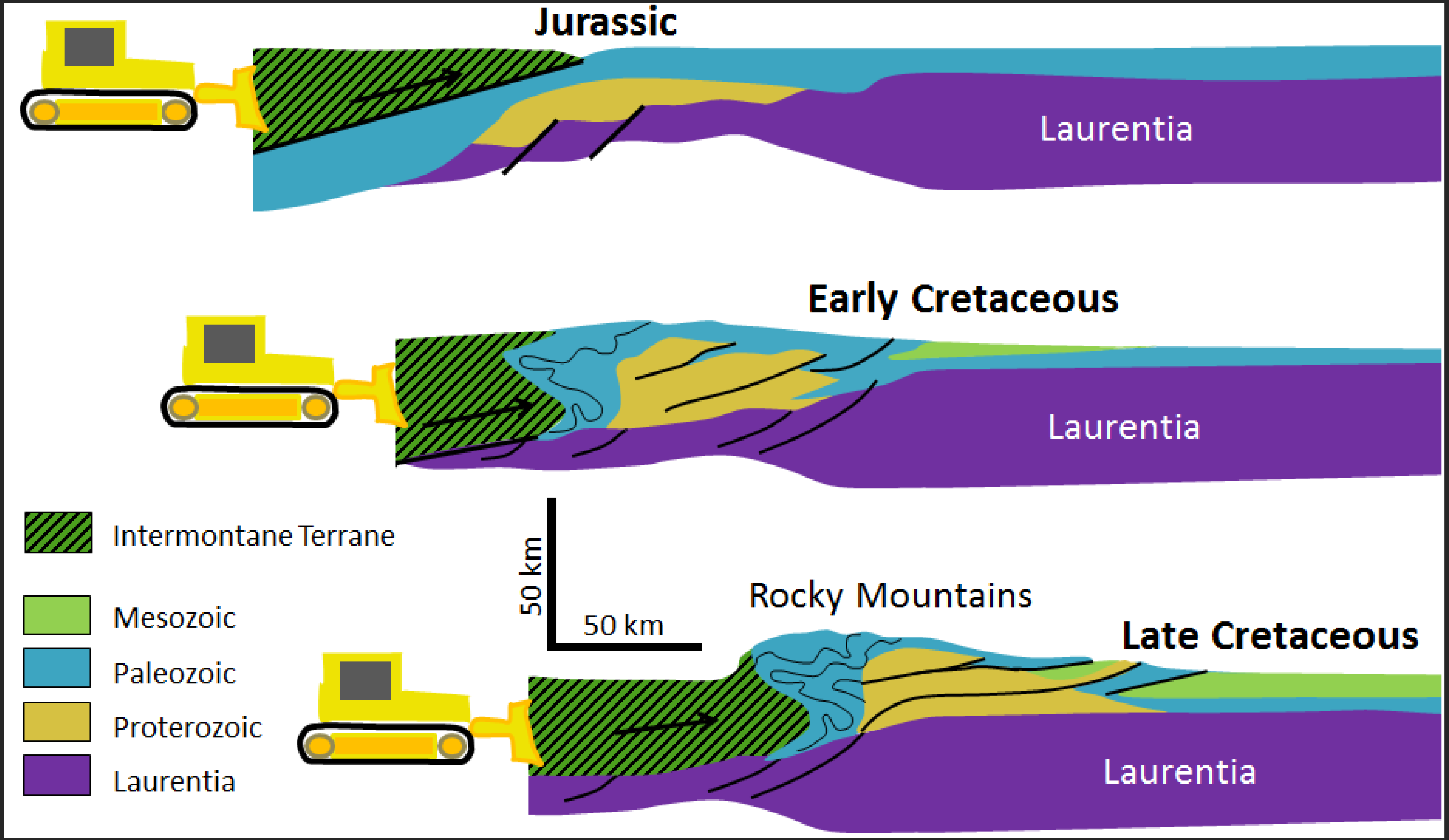
more Quesnellia

- **Fossils** ("McCloud fauna," seafloor invertebrates) and **paleomagnetism** have it originally away from continent and south, hundreds of km
- Volcanic arcs are red dots
- Back-arc seafloor between Quesnellia and North America became Slide Mountain terrane
- Quesnellia was attached to Stikinia (St) and Slide Mountain terranes by time it all accreted to North America as Intermontane superterrane

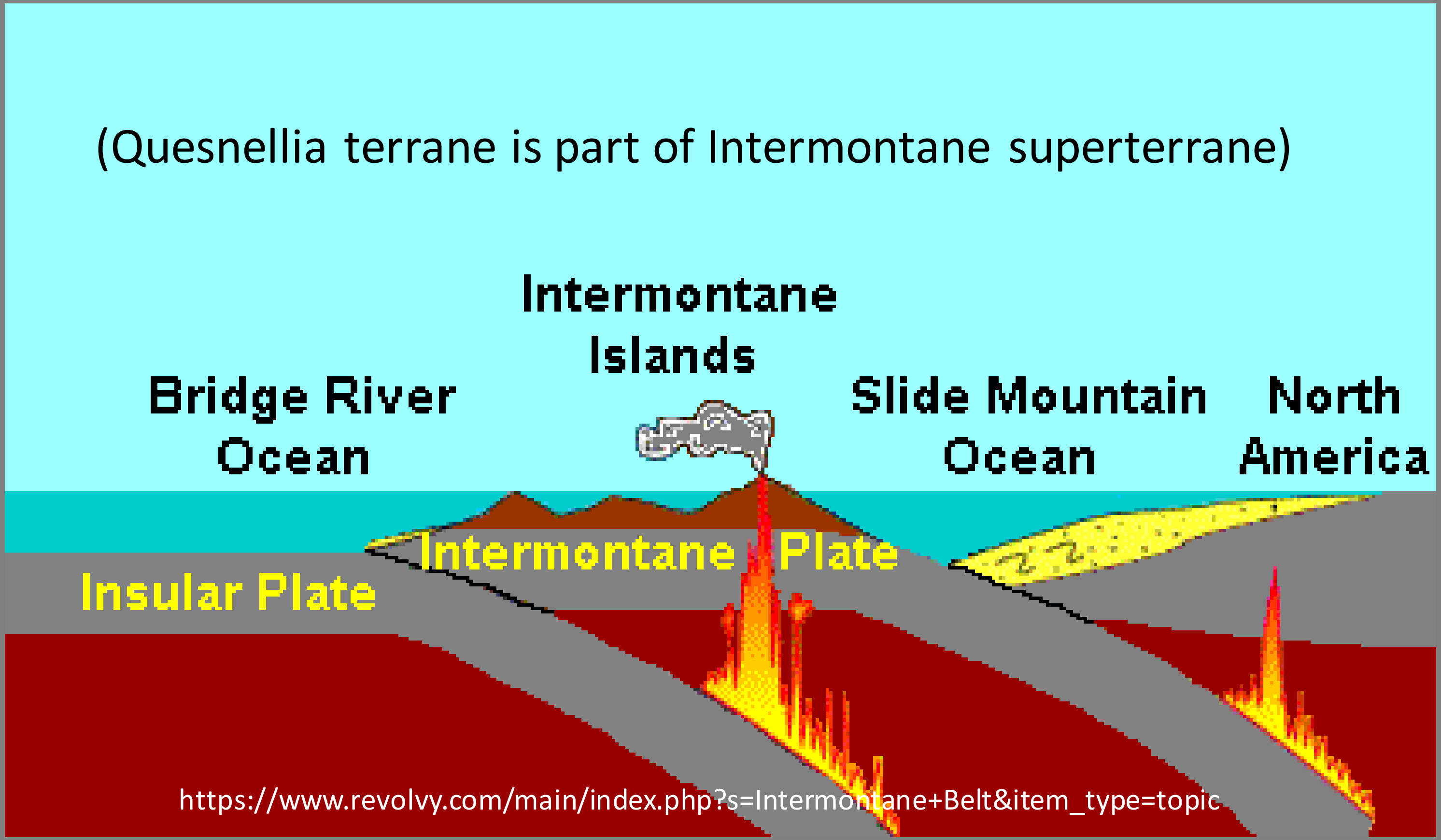
Quesnellia terrane, as part of Intermontane superterrane

Was thrust eastward onto leading edge of Laurentia (North America)

diagram suggests how old continent (Laurentia) deep crust ended up beneath Quesnellia



https://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/08/accretion-of-the-Intermontane-Superterrane.png



terrane puzzle: partly solved, partly not

We know Quesnellia

- came from out in ocean
- consists of island arc crust
- merged w/other Intermontane terranes
- accreted during Jurassic period

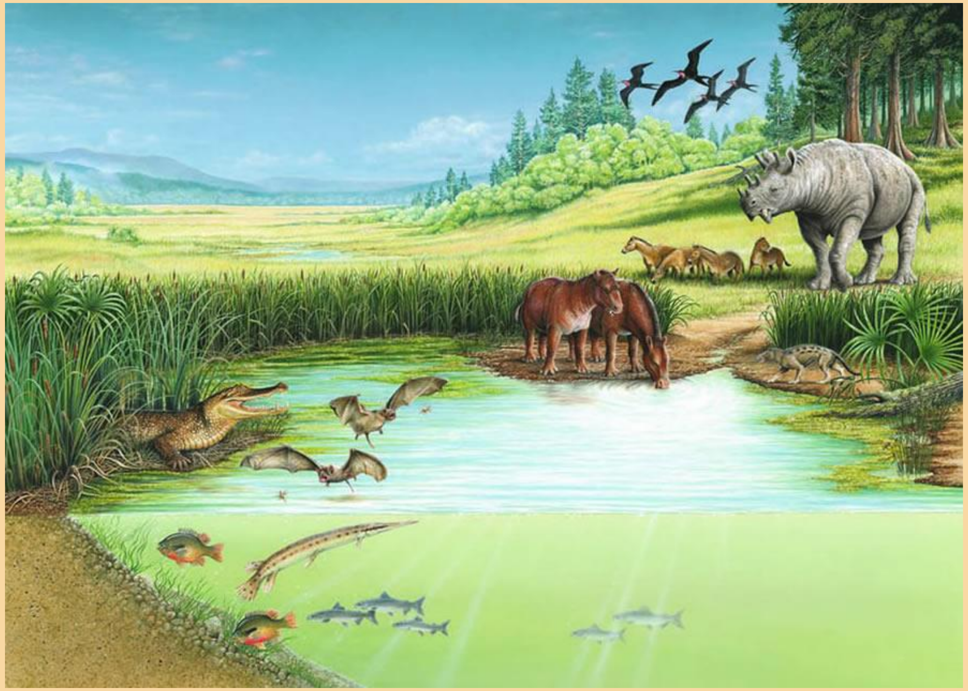
but

- How did Intermontane superterrane get thrust far eastward onto North American margin?
- Which way were the subduction zone(s) facing?

etc.

Eocene Eccentricity: What was so unusual?

- **Fast and short**
  - **mostly 55-45 million years ago**
- **Rapid crustal extension & thinning**
  - **metamorphic core complexes and grabens**
- **Challis Arc volcanics**
  - **not from normal subduction**

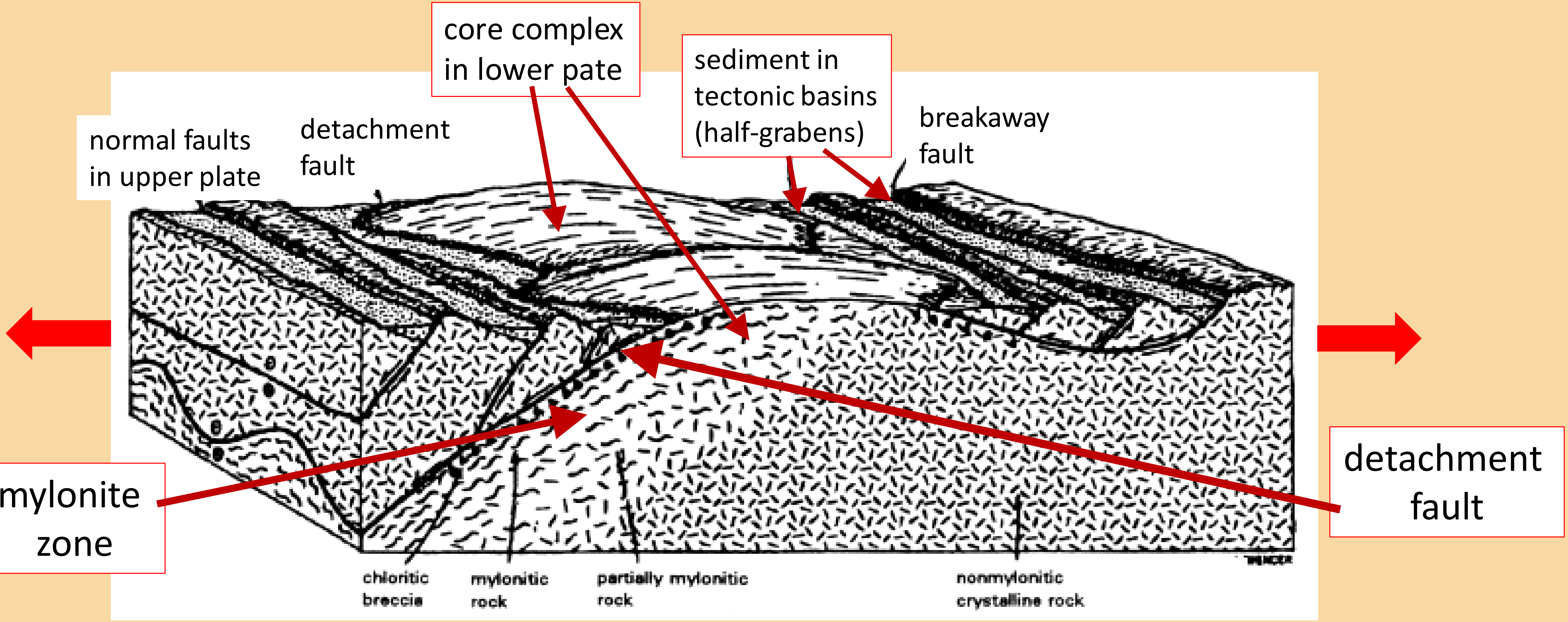


Eocene scene: Artist's rendition
(may not match Okanogan's Eocene)
Artist: Kim Thompson
http://www.kimthompsonartist.com/SingleImages/Eocene.html

This is when the Okanogan Highlands formed.

What are metamorphic core complexes (gneiss domes)?

Here is a model of a metamorphic core complex



After Spencer & Reynolds, 1989. Copied from https://www.nap.edu/read/4939/chapter/4.

Examples of mylonite

Below: along SR 20 east of Tonasket, WA

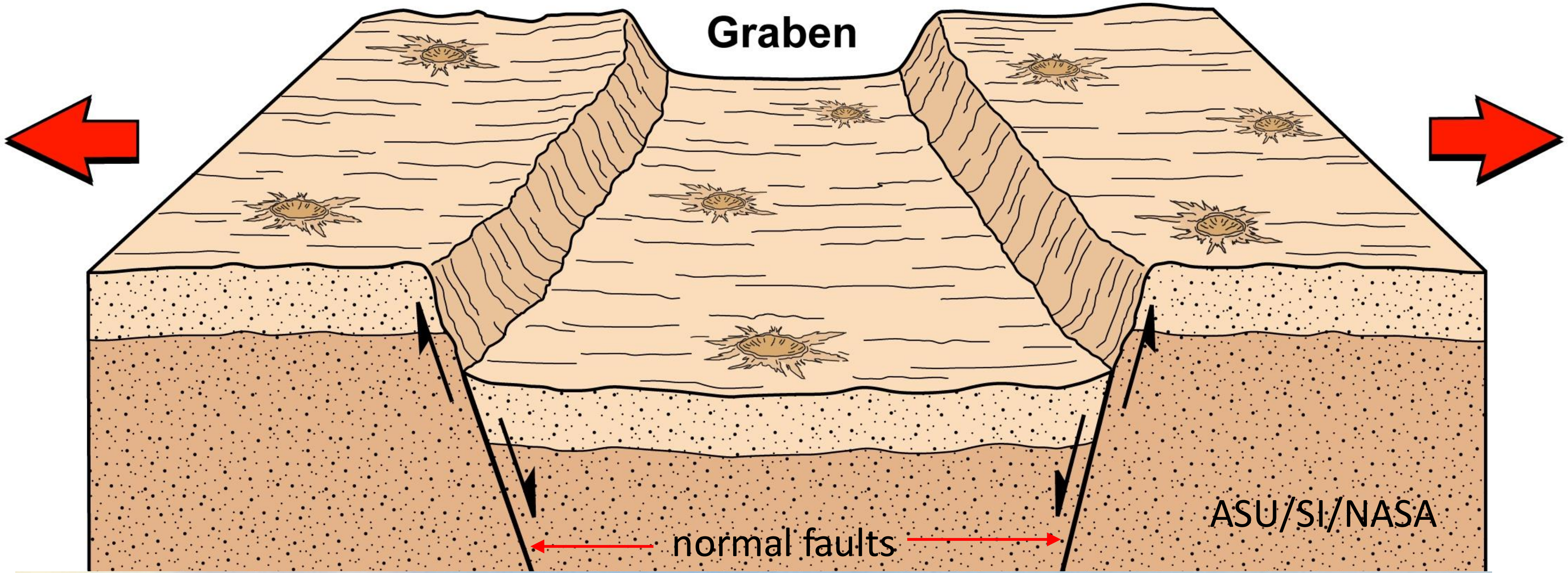
Above: from a core complex in Death Valley, CA

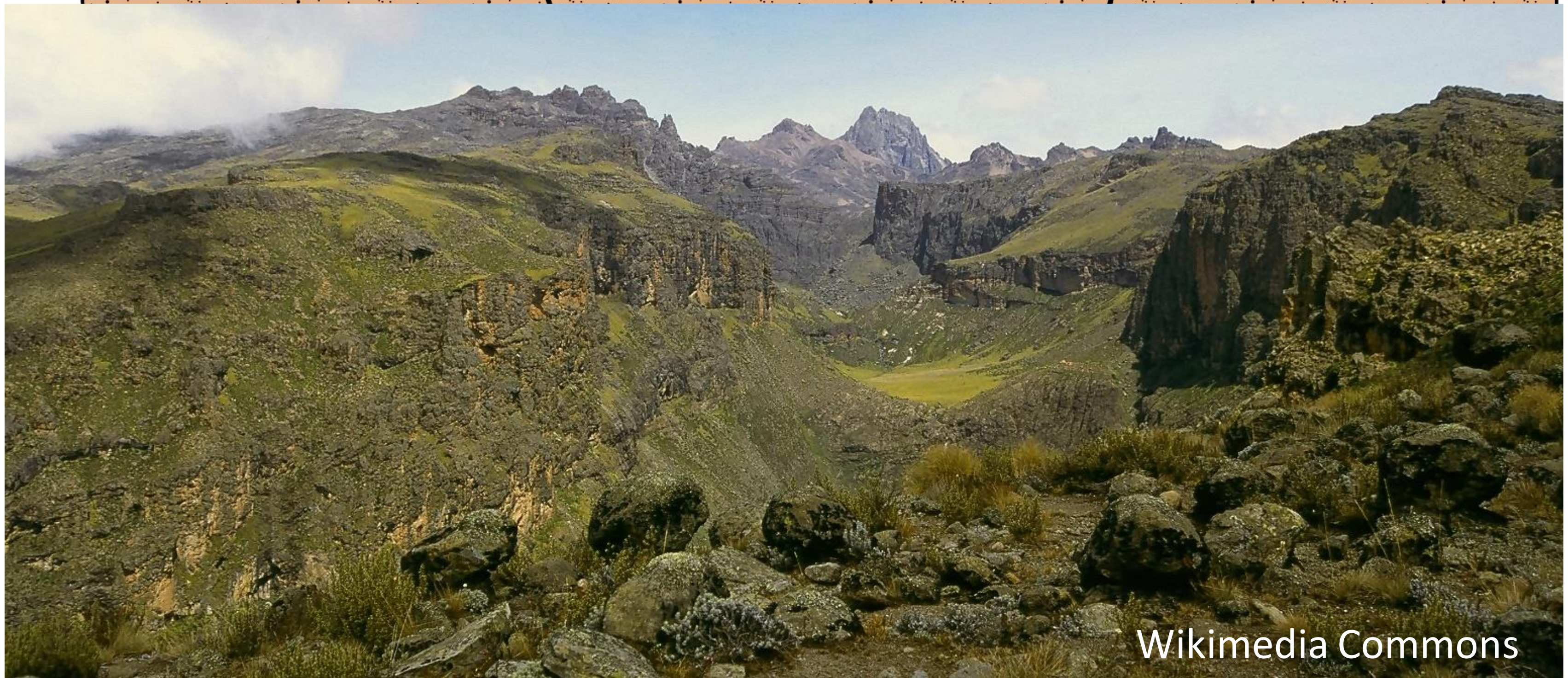
Pictures by Marli Miller, http://geologypics.com/

Grabens

top: graben diagram

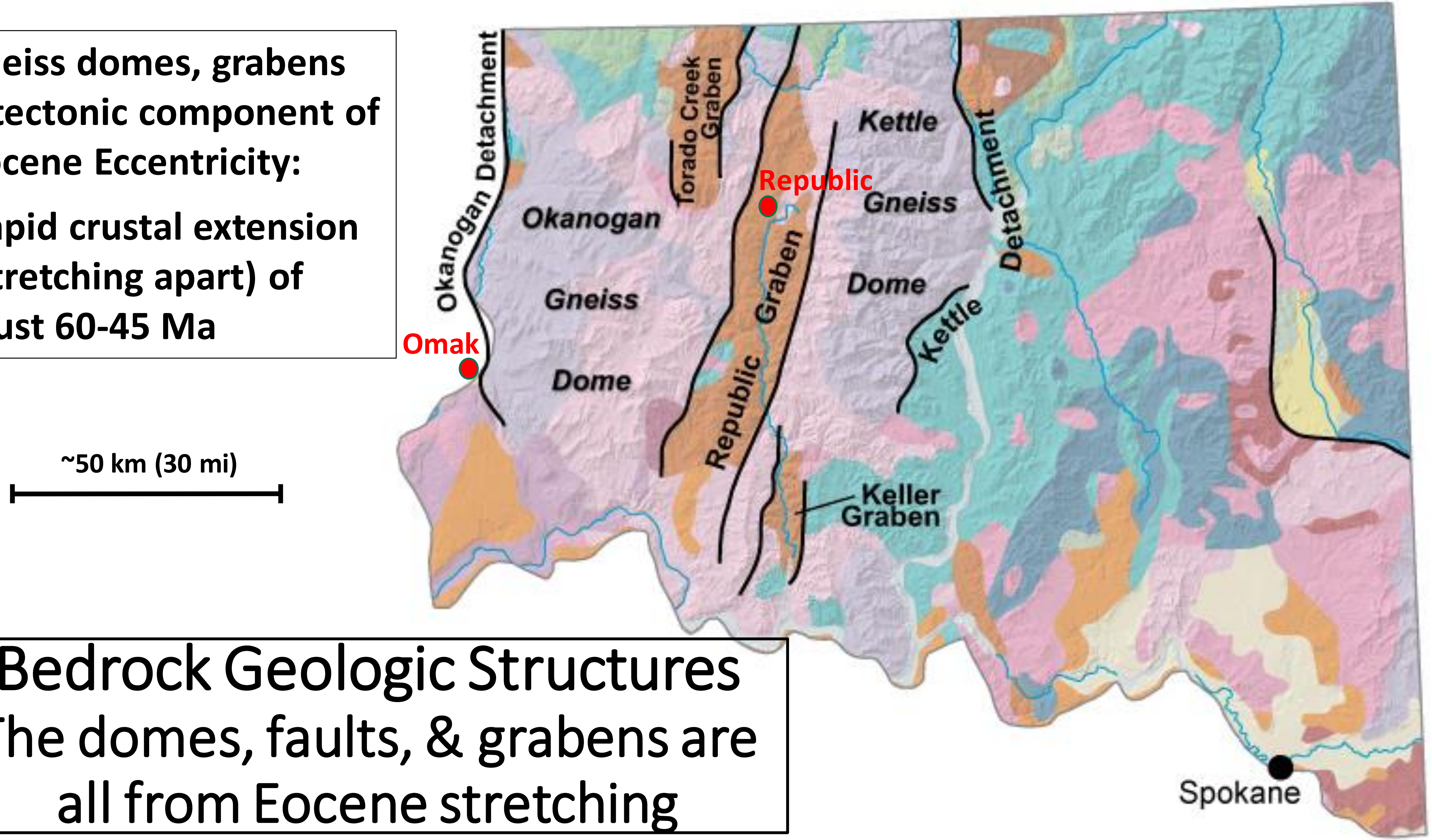
bottom: view up a graben (rift valley) in Africa near Mt. Kenya





gneiss domes, grabens = tectonic component of Eocene Eccentricity:

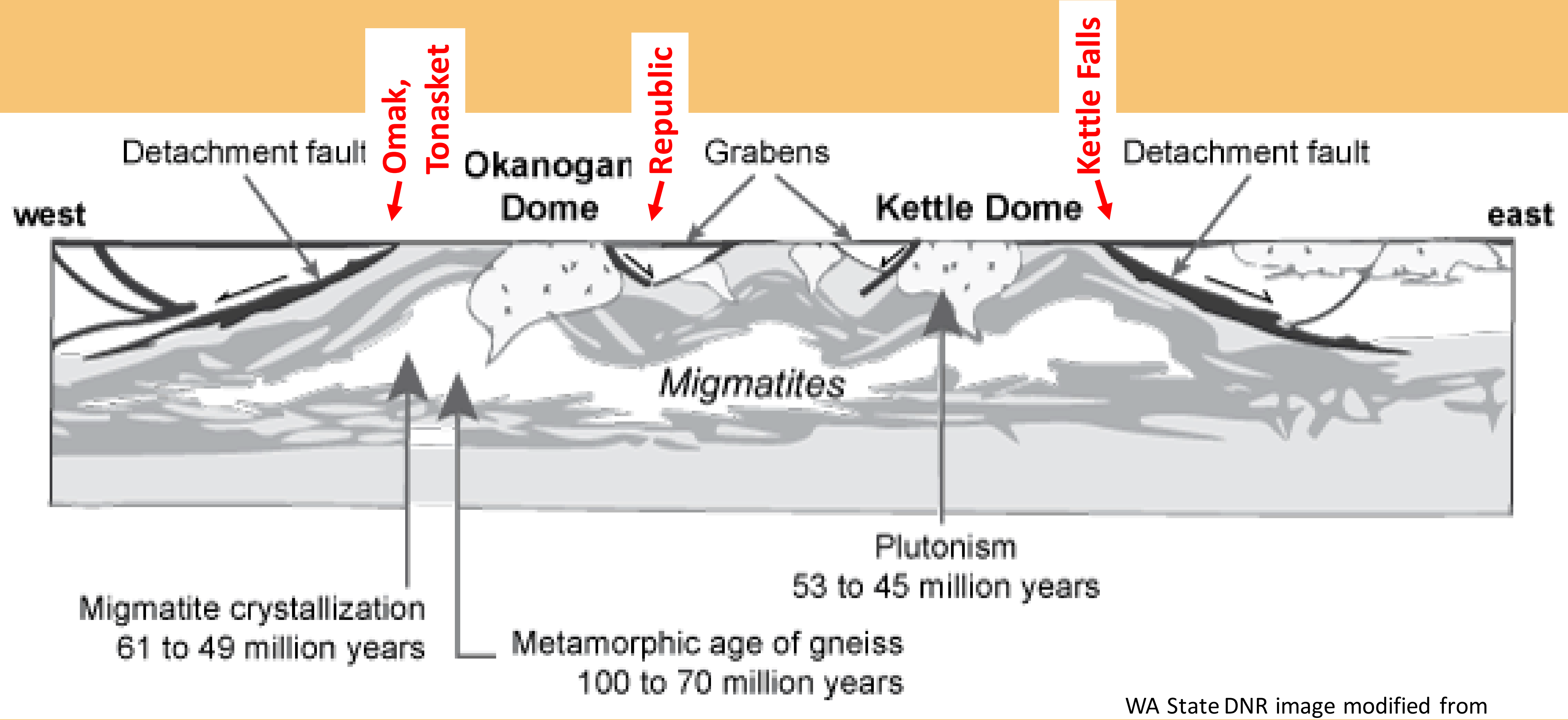
Rapid crustal extension (stretching apart) of crust 60-45 Ma



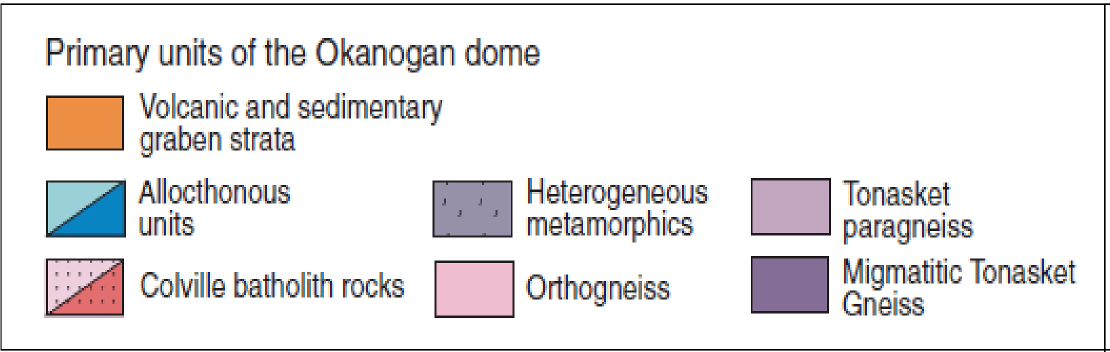
Bedrock Geologic Structures

The domes, faults, & grabens are all from Eocene stretching

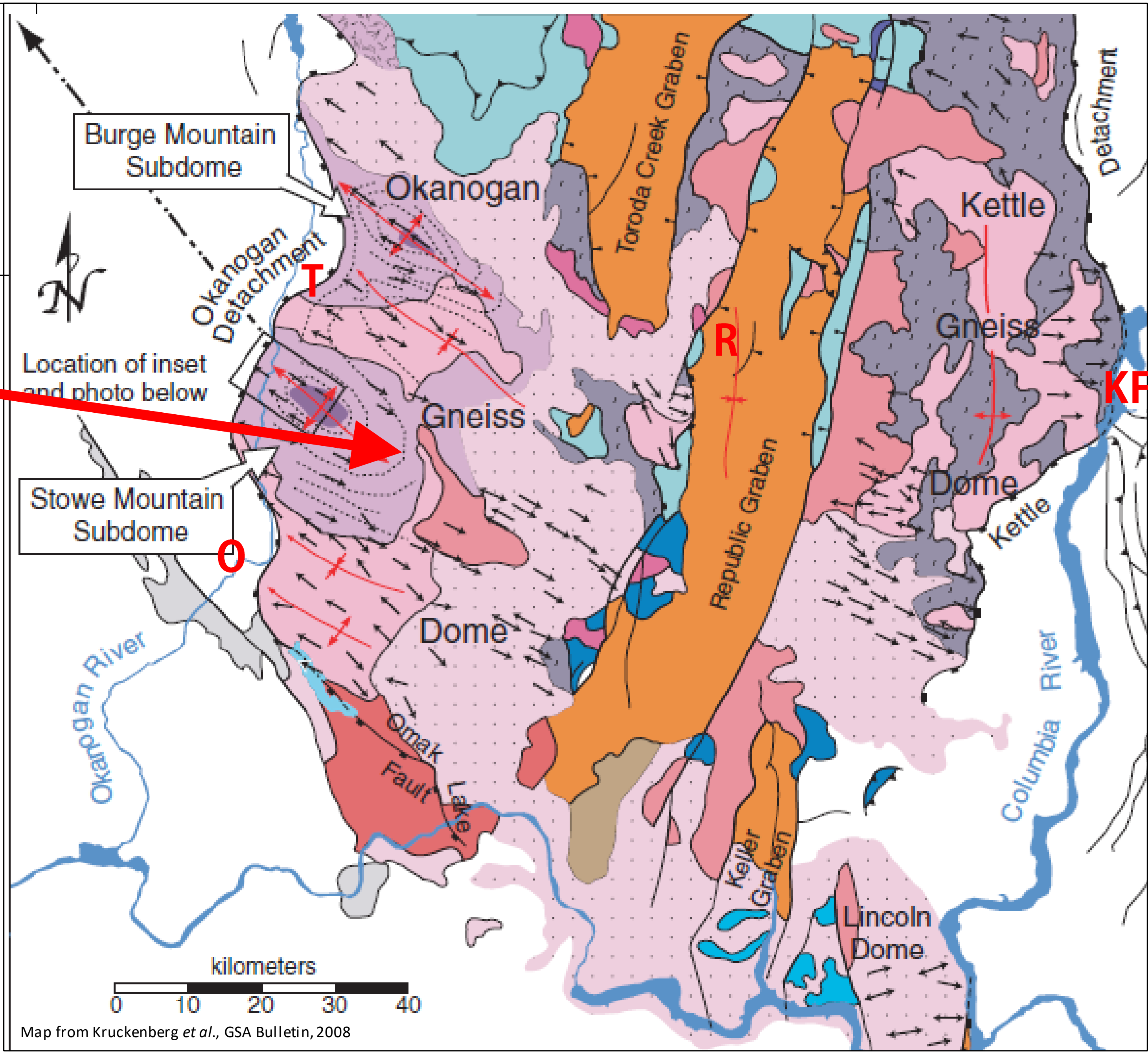
cross-section across Okanogan Highlands



WA State DNR image modified from Kruckenberg *et al.*, 2008, GSA Bulletin



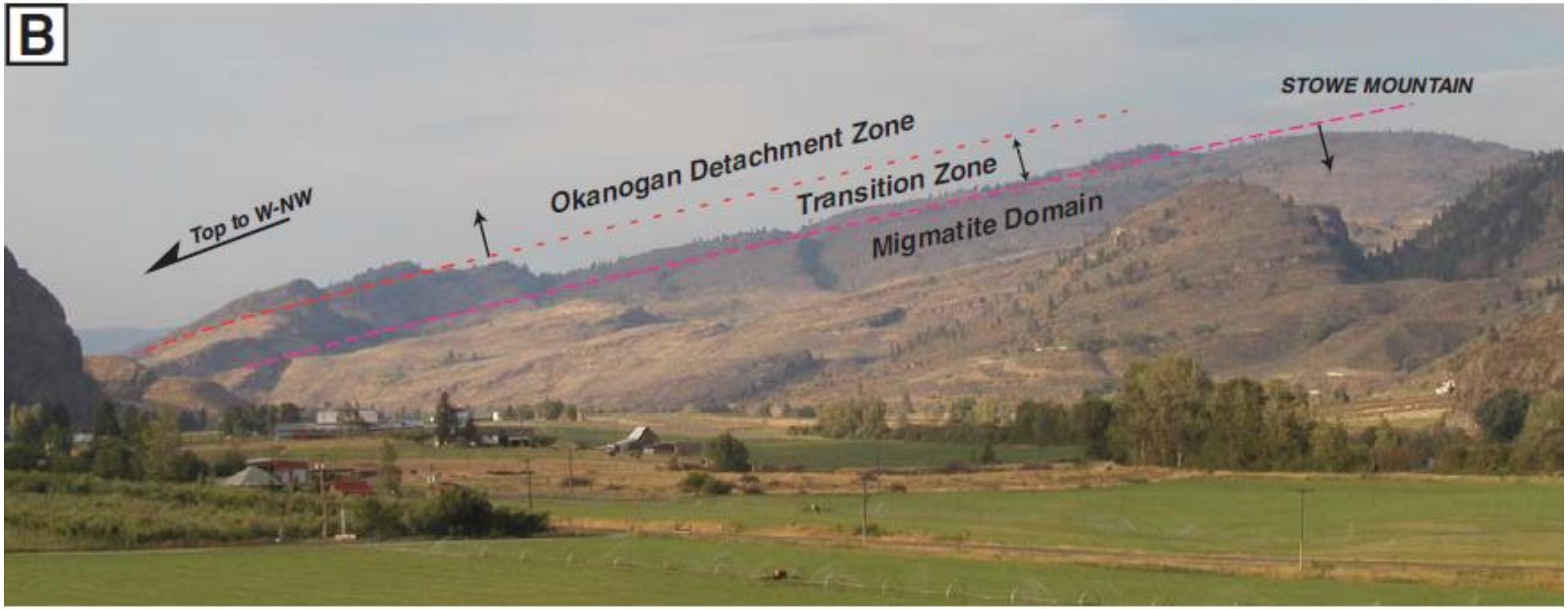
- This type of gneiss dome is a *metamorphic core complex*
- Core complexes & grabens both due to crustal extension, stretching apart of crust
- Stretching lineations (red arrows on map) show direction crust was stretched
- All this 55-45 Ma, during Eocene epoch –
  - Intrusion of granitic magma in core complexes
  - Brittle upper crust sliding off core complexes
  - Grabens formed
  - Total of 100 km (60 mi) of crustal extension
  - Volcanic rock erupting, partly filling grabens
  - Sediment layers accumulating in grabens, preserving abundant plant fossils



Map from Kruckenberg *et al.*, GSA Bulletin, 2008

Total Eocene crustal extension across map area 10-100 (!) km (e.g. Brown *et al.*, 2012)

Looking north from near Riverside along Okanogan fault zone



Bottom image labels geologic structures exposed below Okanogan detachment fault

(from Kruckenberg *et al*., 2008, GSA Bulletin)

The Challis Volcanic Arc:
Igneous side of Eocene Eccentricity

- Reached distant parts of greater Pacific Northwest
- Geography not normal volcanic arc pattern
- Rock chemistry not normal subduction zone volcanic arc chemistry
- Rapid, hot flare-up, die down, ~55-42 Ma

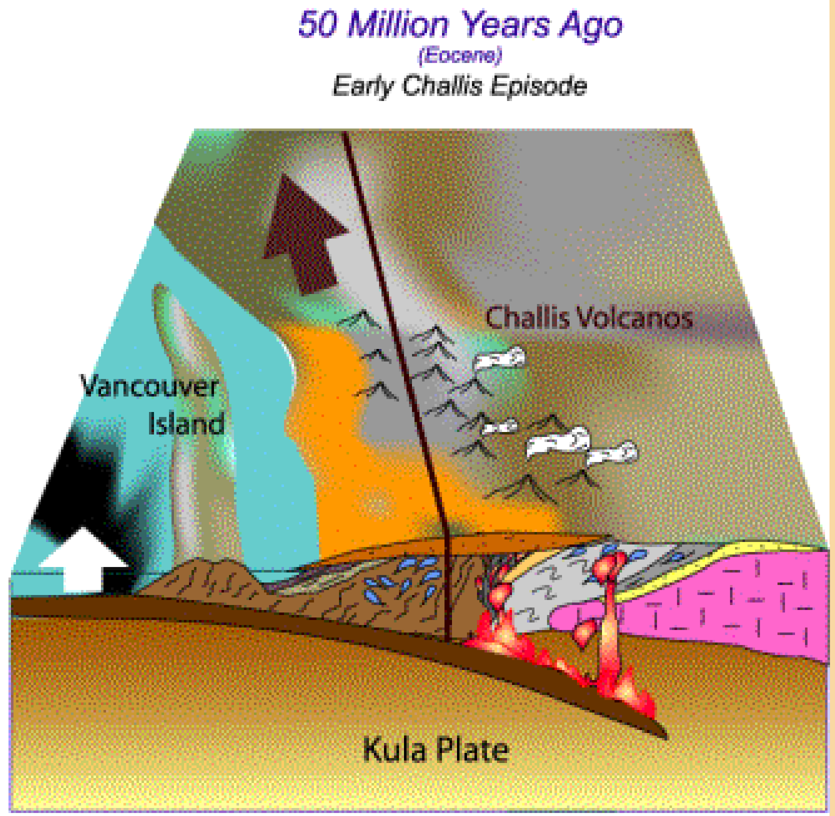
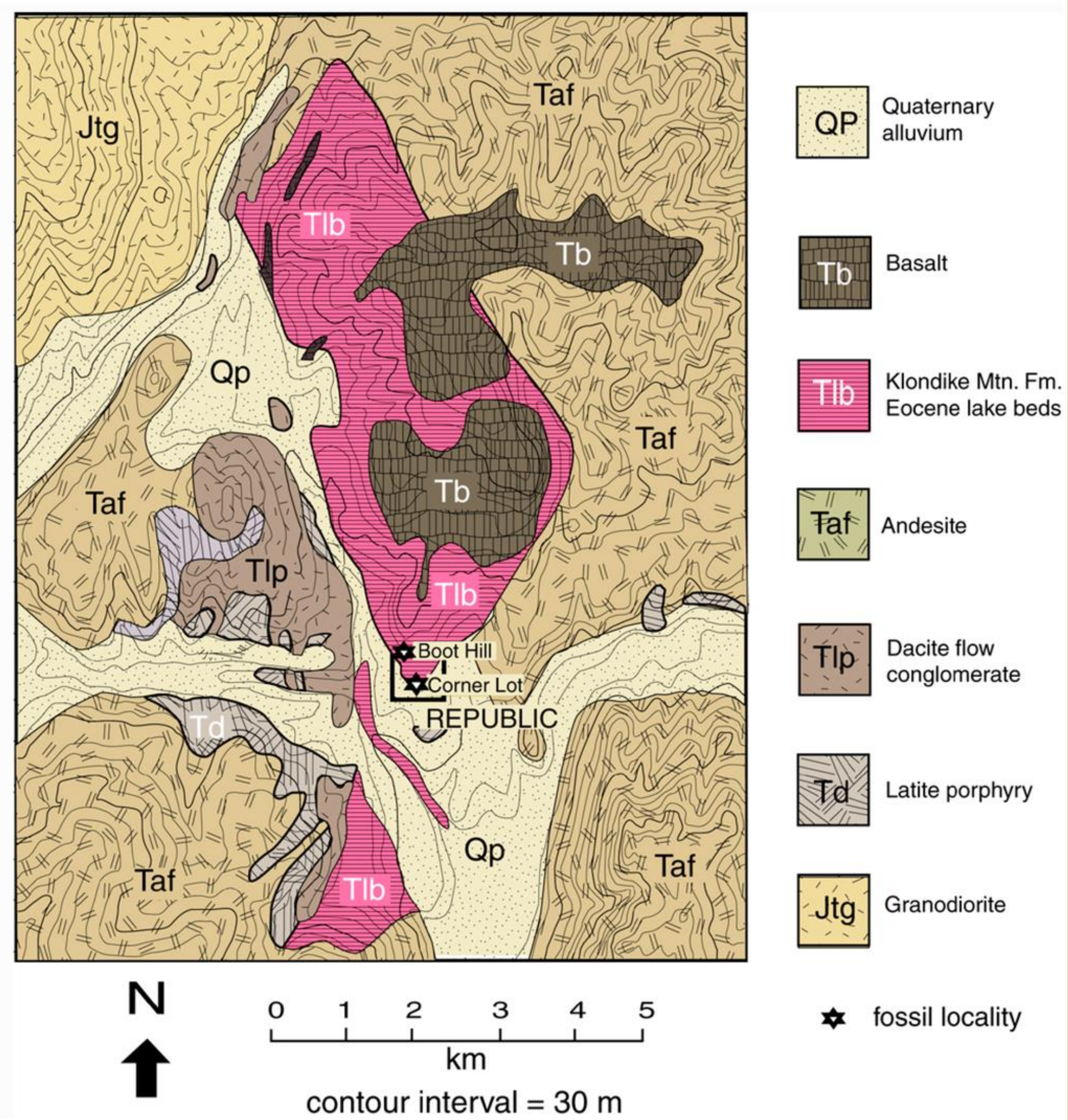


Image from Burke Museum, Seattle
http://www.burkemuseum.org/geo_history_wa/The%20Challis%20Episode.htm

Probably not correct

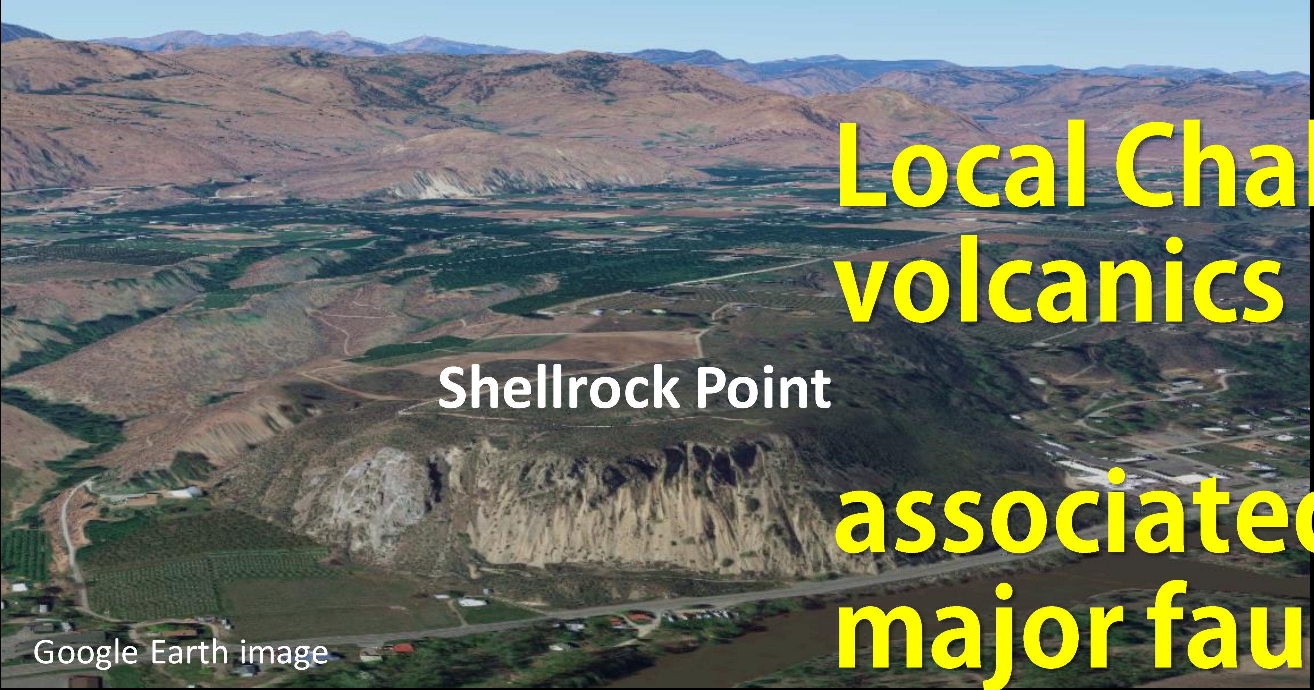
Republic graben largely filled with Eocene Challis arc volcanic rock

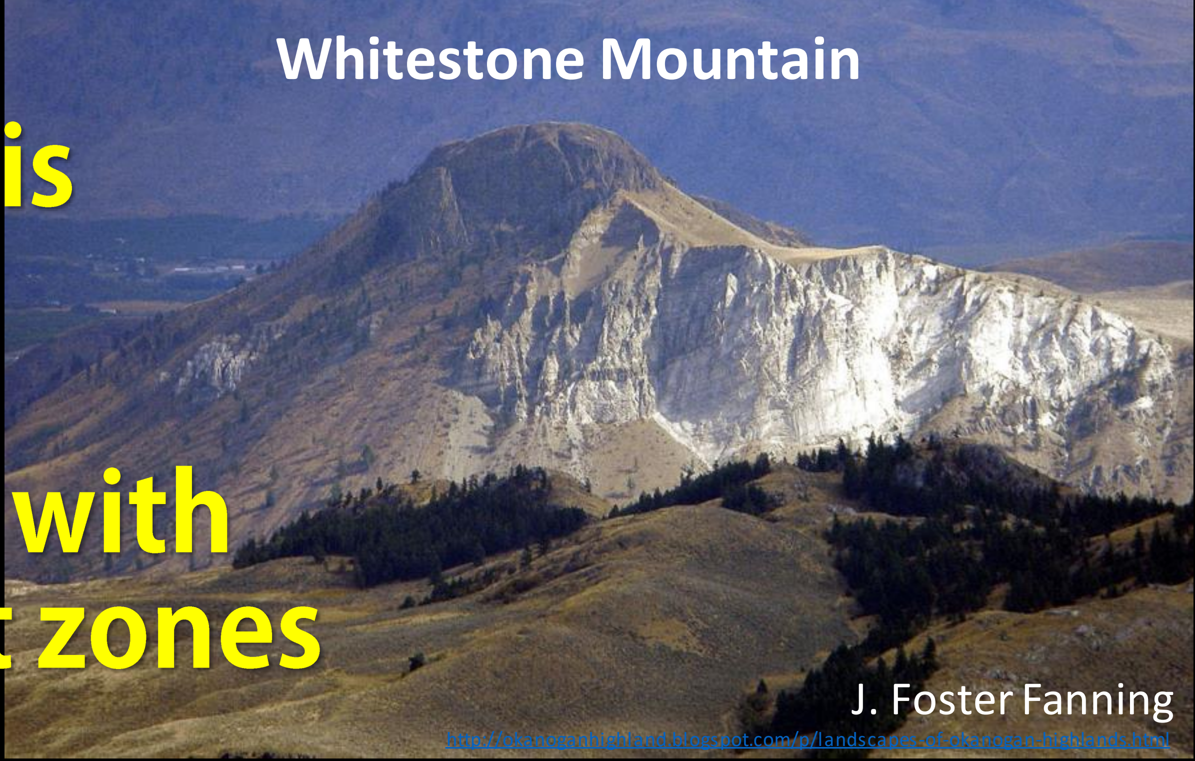
- Erupted same time graben was forming from extensional tectonics
- Volcanic rocks include basalt, andesite, breccia, tuff, etc.
- Volcanic activity also precipitated epithermal ore deposits (gold!)

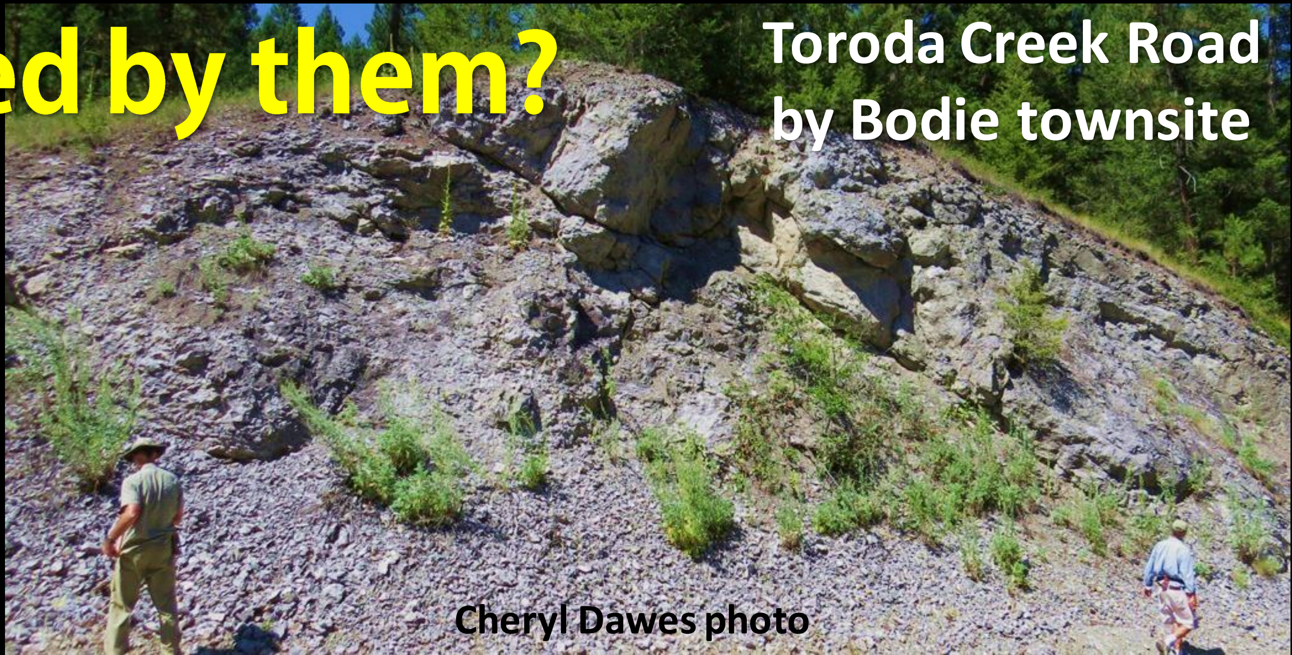


Geologic Map of Republic area
from George Mustoe, 2015, http://www.mdpi.com/2076-3263/5/3/243/htm#B7-geosciences-05-00243

Local Challis volcanics associated with major fault zones channeled by them?

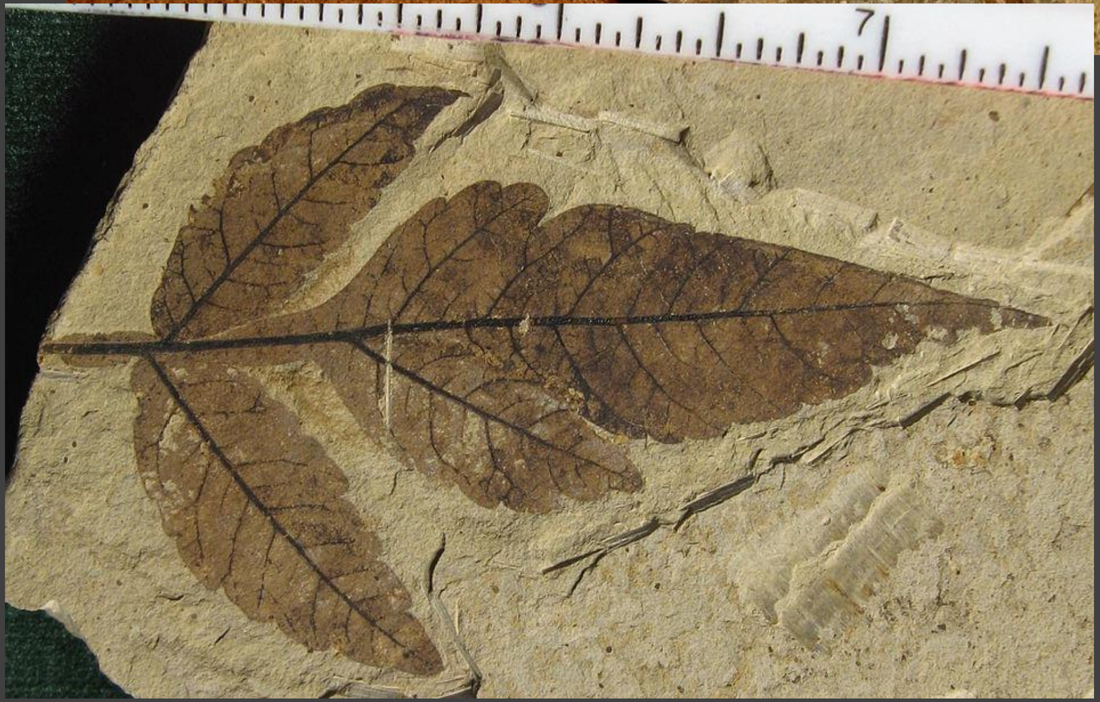






Local basins, grabens and half-grabens, filled with volcanics, sediments, and *fossils*

- Mostly plant fossils, also fish, insects
- In Republic area, Klondike Mountain Formation hosts "Stone Rose" fossils

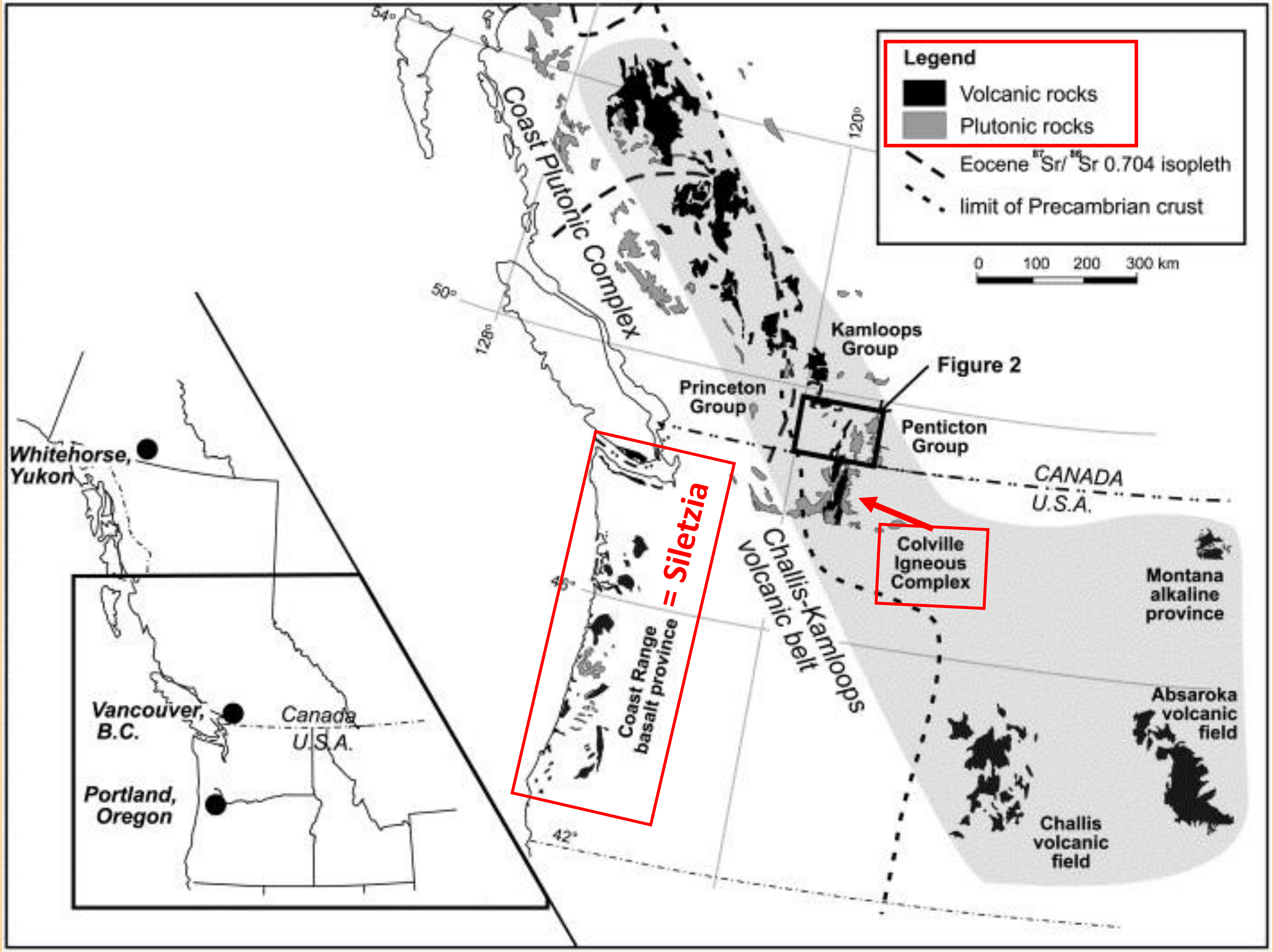


Pictures from Wikipedia article on Klondike Mountain Formation

Eocene Challis “volcanic arc”

No longer thought a standard subduction zone arc

Chemistry, location, timing, point to *hot, upwelling mantle* and *crustal decompression* causing melting



map from Dostal *et al.*, 2003, https://oi:10.1016/S03770273(03)00153-7

Eocene Eccentricity

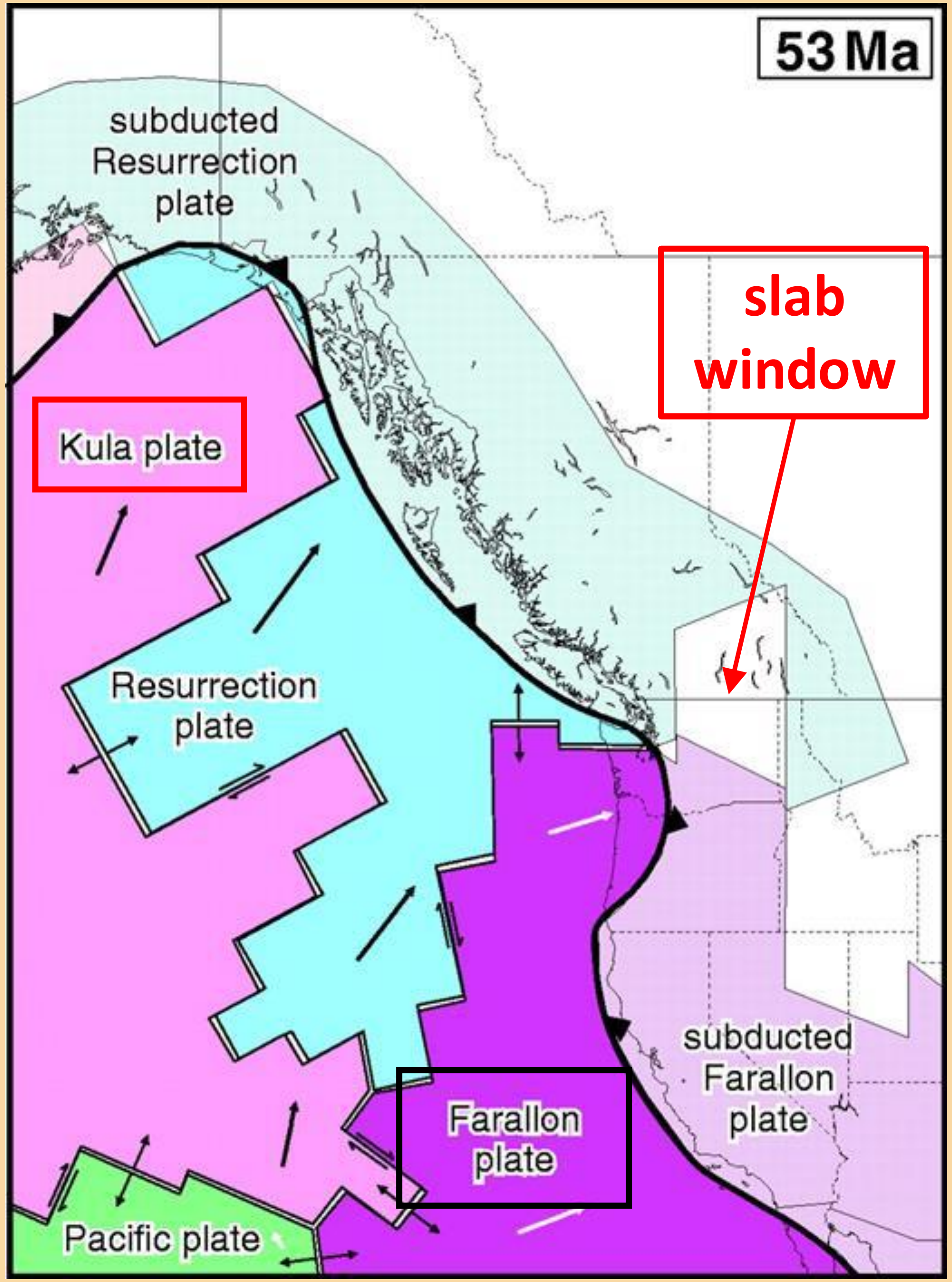
How do we explain:

- Sudden change: compression to extension
- Regional nature: across greater PNW+
- Flare-up: unusual volcanics and intrusions

?

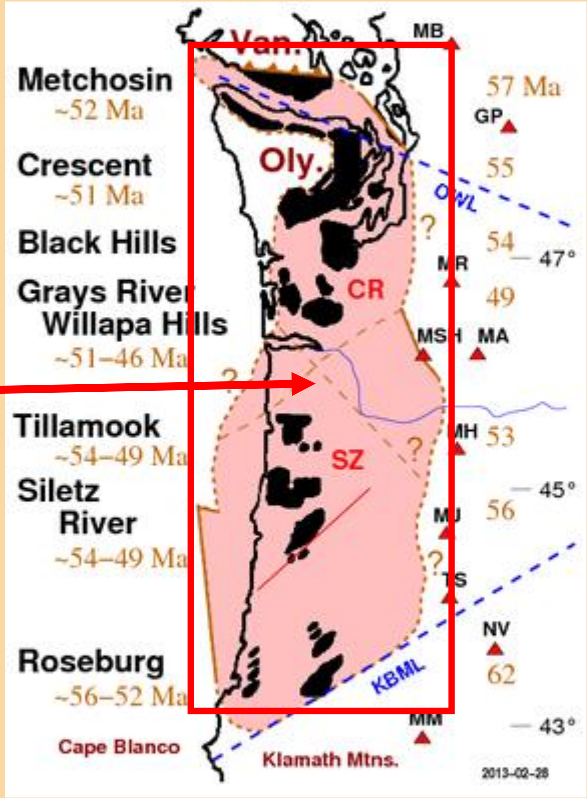
Spoiler Alert: More than the Farallon Plate (now Juan de Fuca Plate) was along PNW coast at that time.

Not just normal subduction!



From Madsen et al., 2006, Geosphere, https://pubs.geoscienceworld.org/gsa/geosphere/article/2/1/11/31116/cenozoic-to-recent-plate-configurations-in-the

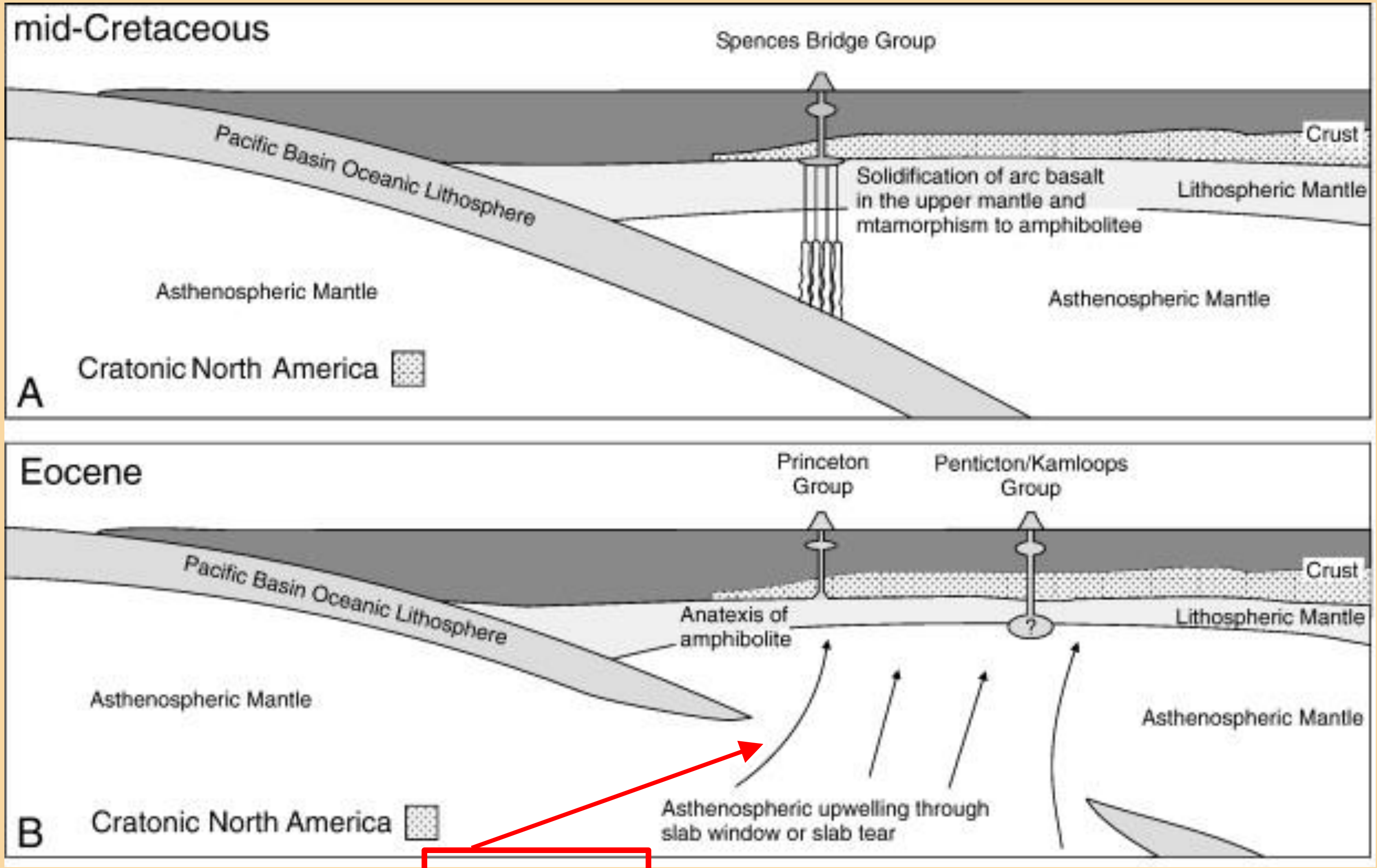
Slab Window ± Hot Spot: possible solution to Eocene eccentricity



Siletzia in red

https://www.wikiwand.com/en/Siletzia

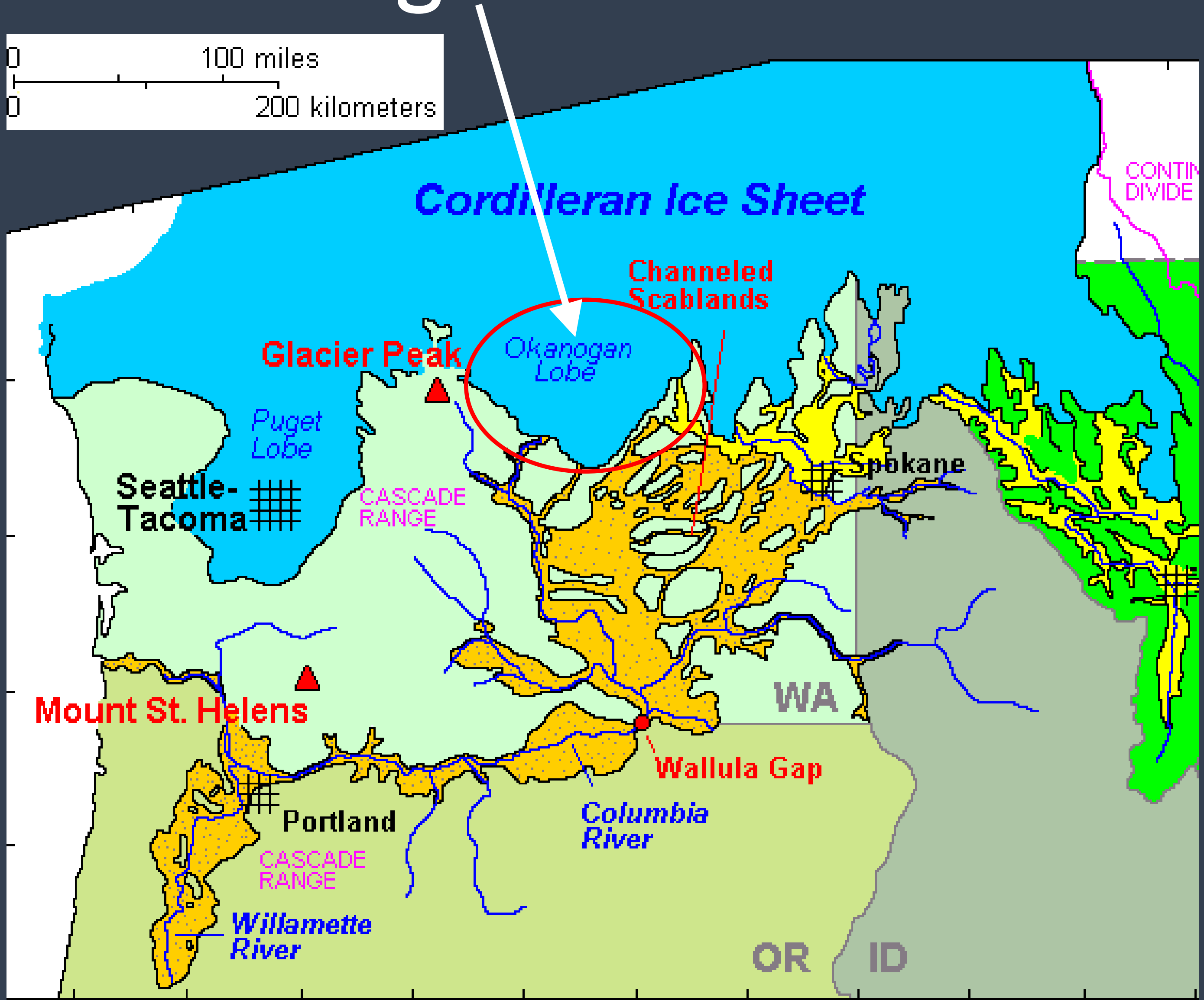
- Siletzia jams trench
- subduction shuts off
- plate boundary transforms
- compression changes to extension
- soft, hot upper mantle upwells, melts, and melts lower crust



slab window

Ickert *et al.*, 2009
https://doi.org/10.1016/j.tecto.2007.10.007

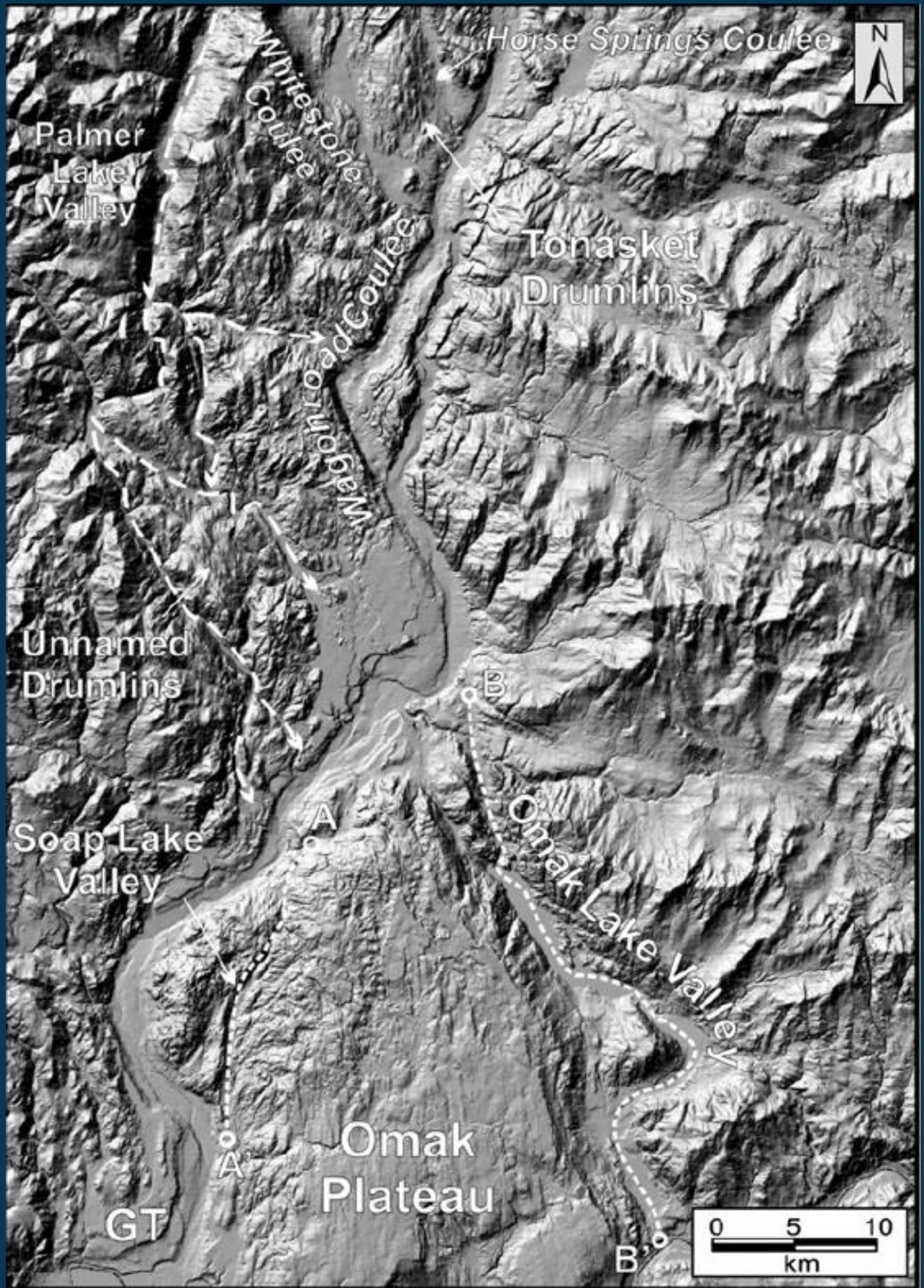
The ice age (Pleistocene epoch glaciations) - all the Highlands were beneath Cordilleran ice sheet



- Giant glacier flowed out of British Columbia interior
- Multiple, repeated glaciations 2.6 million – 12,000 years ago
- Most of Okanogan region's surface shows effects of glaciation, either erosional or depositional

alternative origin of Okanogan's major ice age landforms: huge-volume discharge of pressurized melt water trapped beneath ice sheet

Lesemann, J. E., & Brennand, T. A. (2009). *Regional reconstruction of subglacial hydrology and glaciodynamic behaviour along the southern margin of the Cordilleran Ice Sheet in British Columbia, Canada and northern Washington State,* USA. *Quaternary Science Reviews*, *28*(23-24), 2420-2444. (source of figure on right)



Brennand and Lesemann (2009) hypothesis

All drumlins or drumlin-like features in region are due to turbulent subglacial water flow

All major deep-cut valleys, including Palmer Lake, Omak Lake, and Okanogan River valleys, were cut by turbulent flow of subglacial water

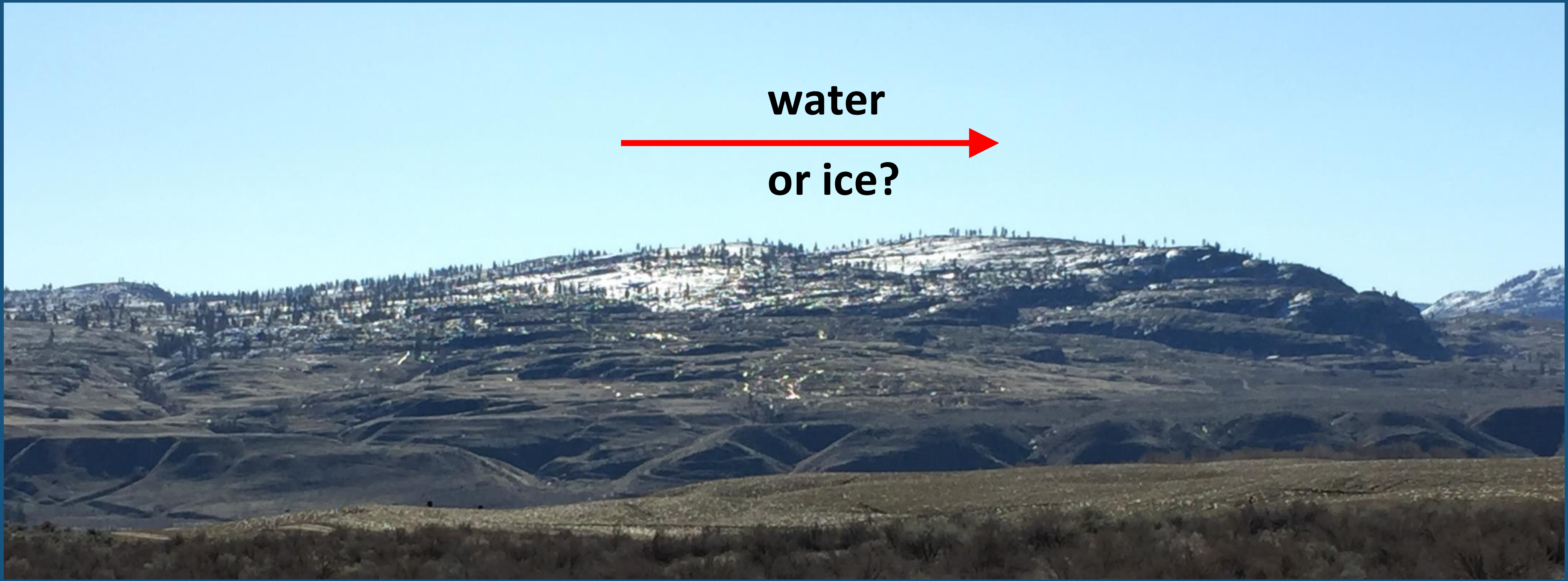
Fig. 13. Southward-looking oblique aerial photograph of Similkameen Valley and Palmer Lake Valley. The modern course of the Similkameen River makes a sharp east-northeast turn in a wetland area north of Palmer Lake. Palmer Lake valley is a bedrock valley with modern underfit and ephemeral streams. It may have operated as a tunnel valley during glaciation. Smaller bedrock coulees like Whitestone Coulee branch off toward Okanogan valley.

From Brennand and Lesemann, 2009

My take: problems with Brennand & Lesemann's (2009) hypothesis

- See my poster
- Talk to me

View E from SR 97 N of Omak



Summary

- Okanogan region geology is special
- Underlies the character of the place
- It spans from old North American to recently accreted terranes
- Classic examples of metamorphic core complexes & grabens
- Eocene volcanics, sediments, and fossils
- All topped by unique array of ice age features

All this without investigating the foundational role of geology to the economy, ecology, and human history of the Okanogan region!

Questions or comments?

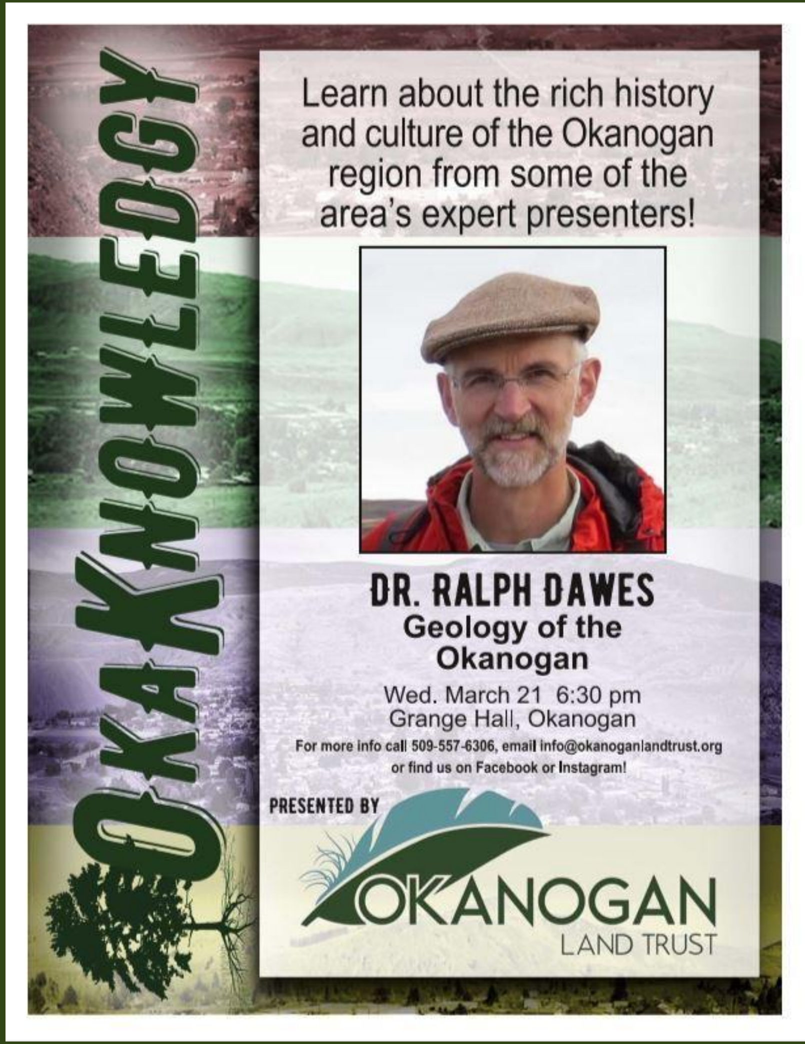
Want me to come check out your local geology?

Contact me:

rdawes@wvc.edu

You can email me pictures of geological finds you question.

Thank you!



I am particularly interested in glacial geomorphology and stratigraphy. In other words, the shapes of the Earth's surface, and the sediments on it:

Random boulders (erratics)

Unsorted mixtures of every grain size, which may be glacial till

Glacial outwash: bedded layers of sediment, spread by meltwater beyond the glacier, not buried and turned into sedimentary rock. Also deformed/convoluted outwash beds

Fine layers of sediment from bottoms of lakes formed by temporary glacial damming of stream or river drainages

Elongate, smooth/streamlined ridges (drumlins or drumlin-like)

Glacial striations (grooves, polish) on bedrock surfaces.