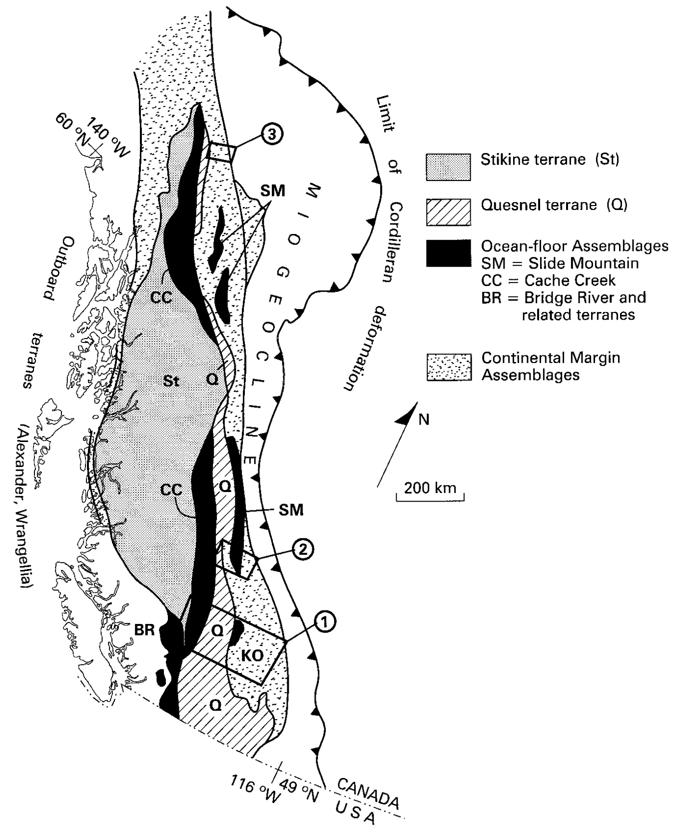
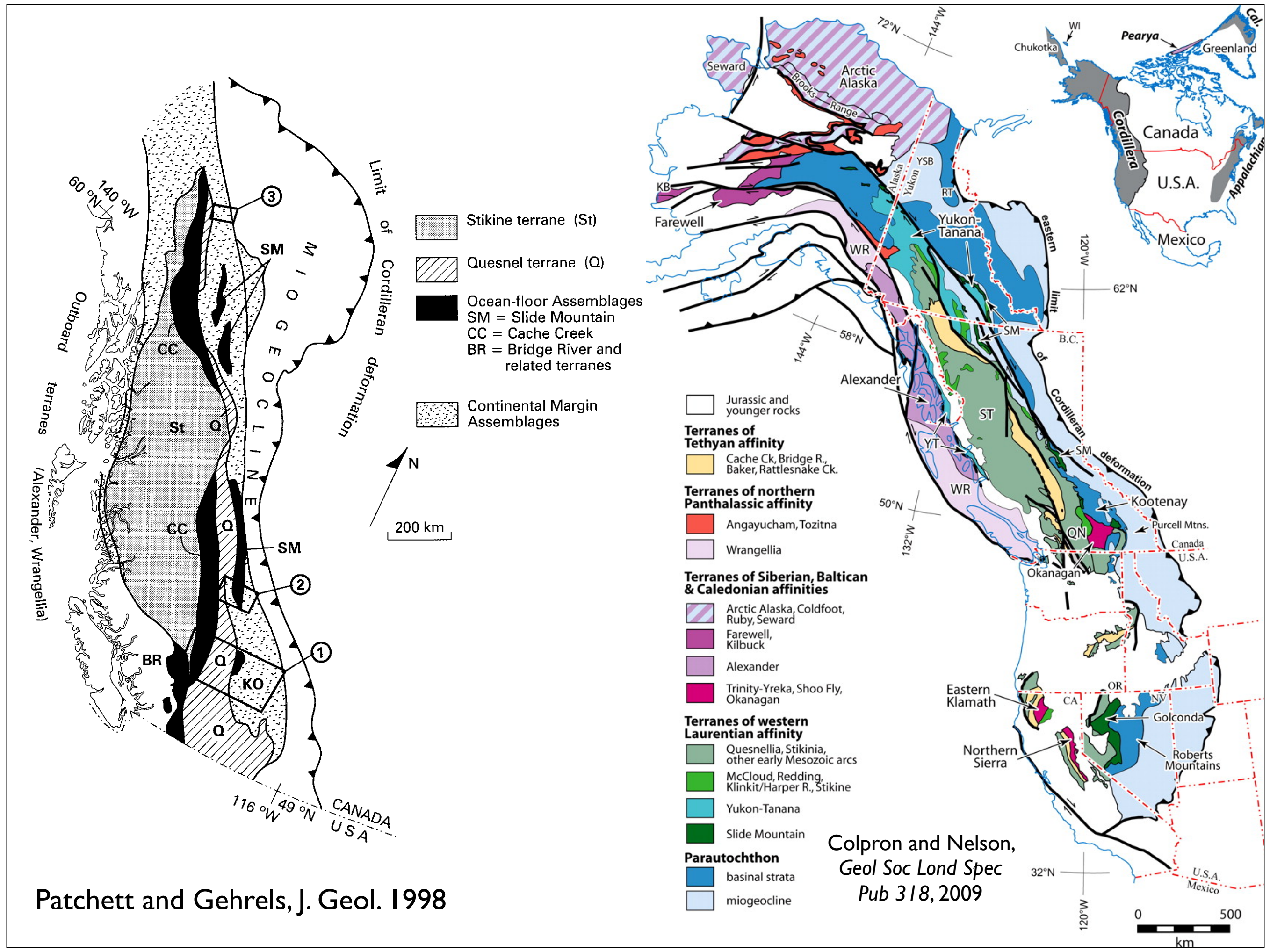
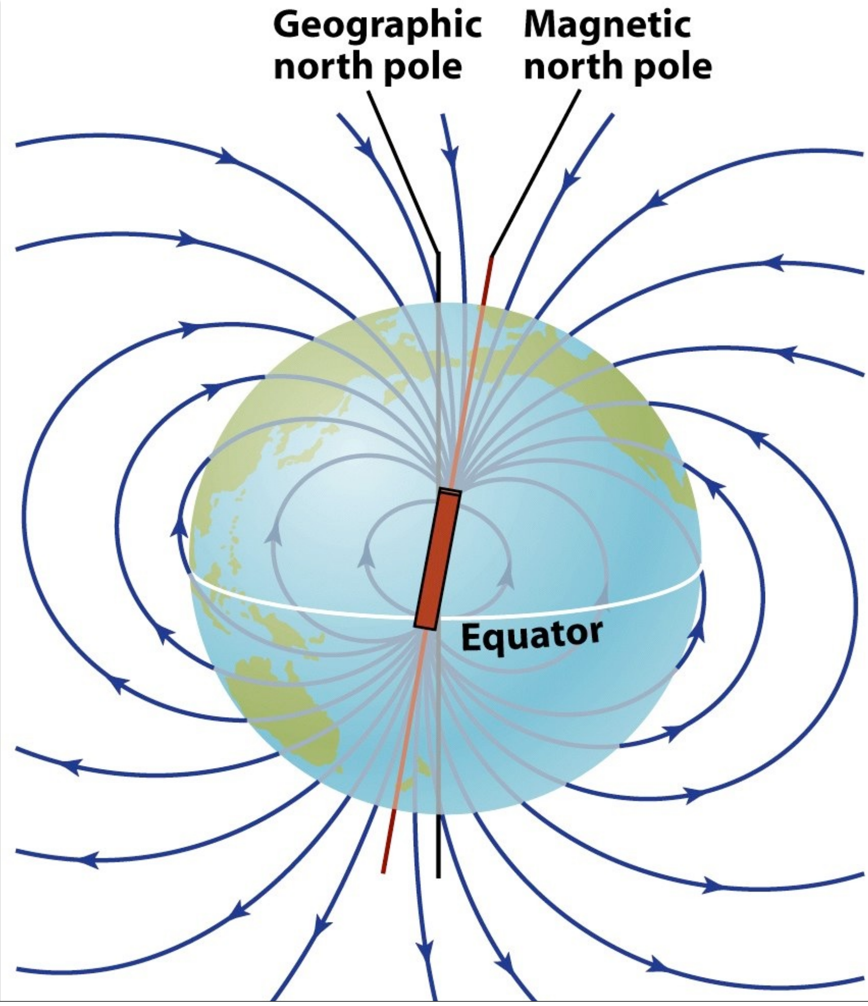
Figure 1. The Canadian Cordillera showing terranes studied here. Rectangles denote sampling regions: 1—southeastern British Columbia for Cache Creek, Quesnel, and Kootenay samples (KO = Kootenay terrane proper); 2—Wells-Barkerville region for Quesnel, Slide Mountain and Kootenay/Cassiar-equivalent samples; 3—Nisutlin assemblage at Little Salmon Lake, Yukon.



Patchett and Gehrels, J. Geol. 1998



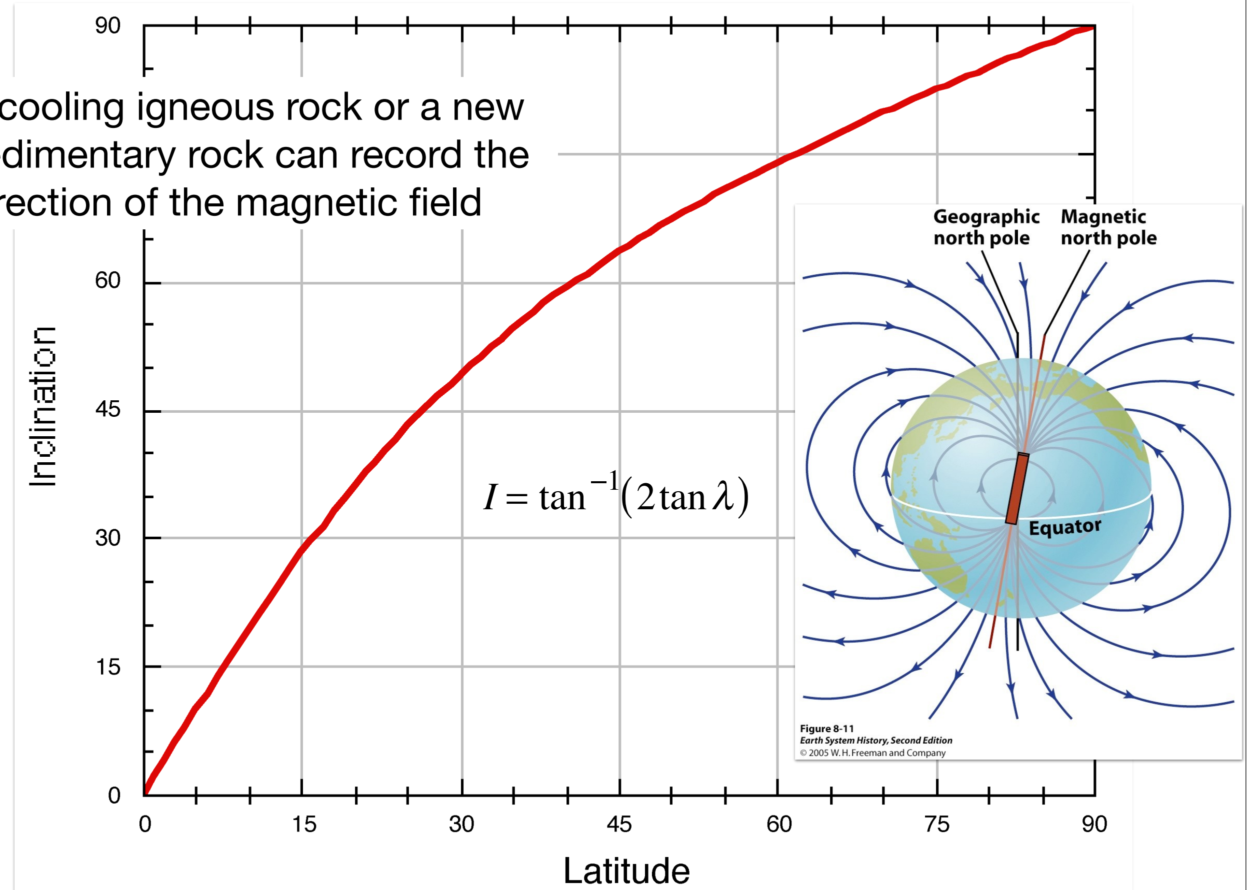
Most terrane maps focus on Canada; map at right extends this into US

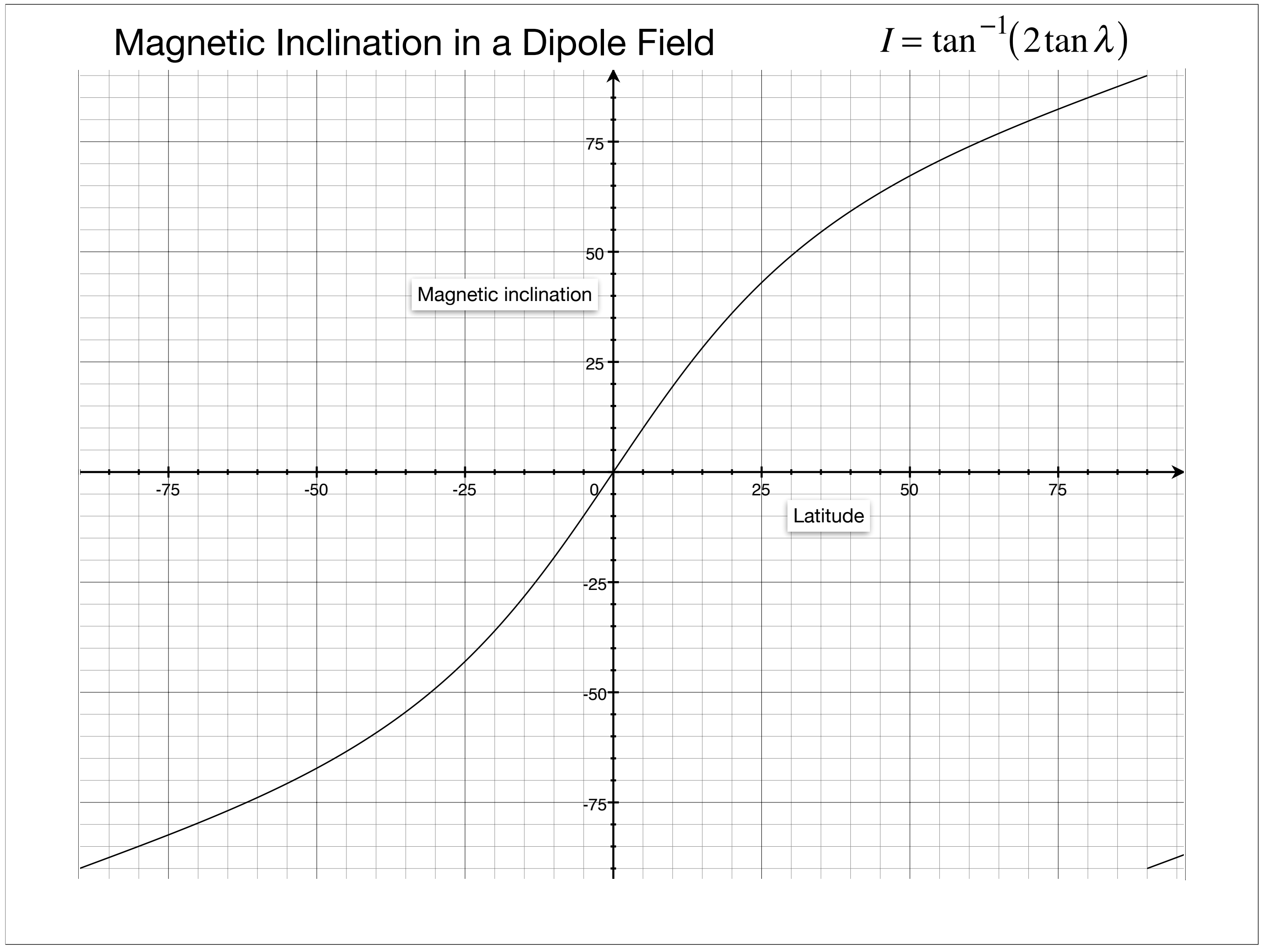

Geographic north pole
Magnetic north pole
Equator

Paleomagnetism and latitude

A cooling igneous rock or a new sedimentary rock can record the direction of the magnetic field

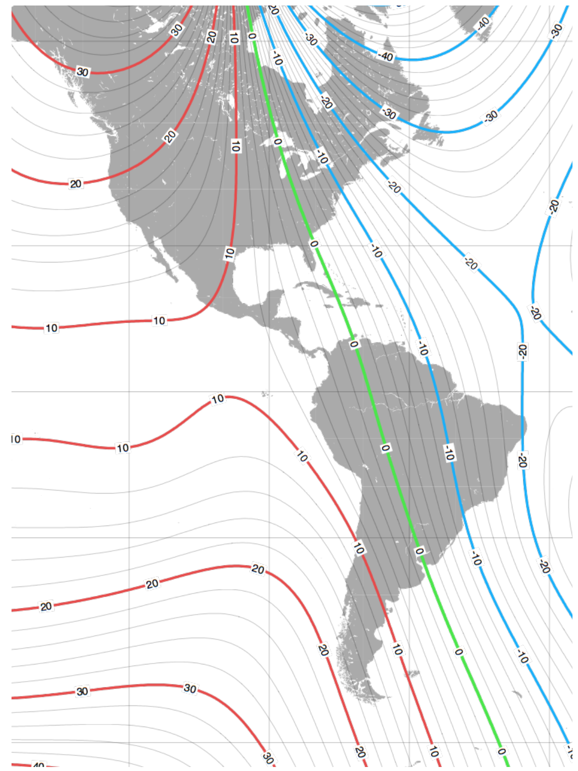
$$I = \tan^{-1}(2\tan\lambda)$$



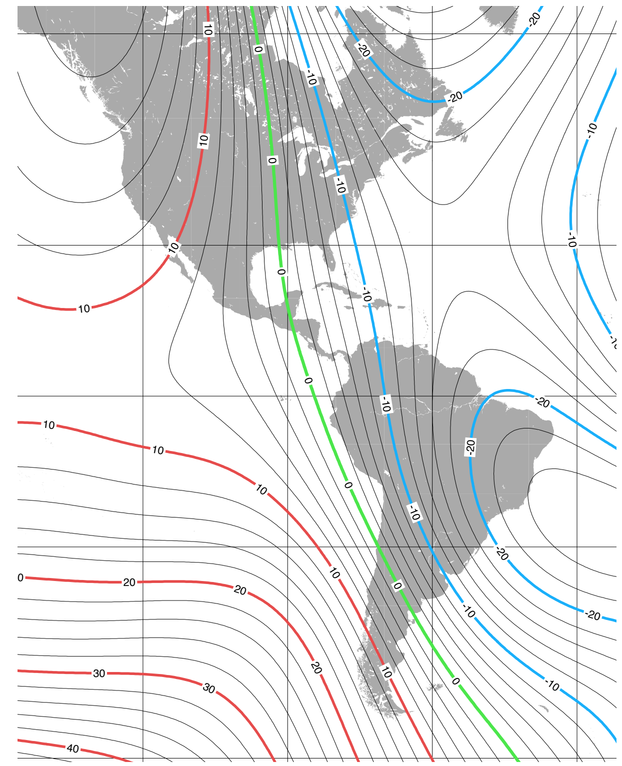

Magnetic Inclination in a Dipole Field
$I = \tan^{-1}(2\tan\lambda)$
Magnetic inclination
Latitude
75
50
25
-25
-50
-75
0

Magnetic Declination

1945

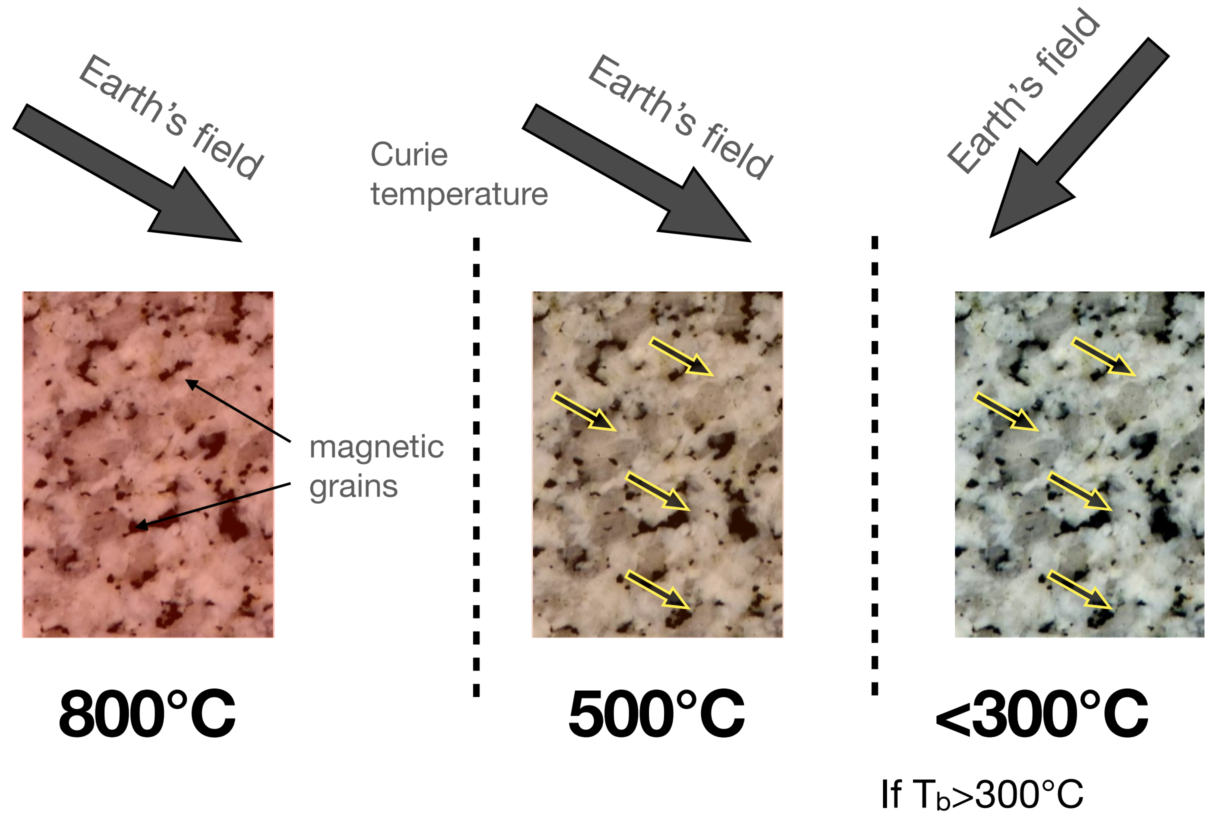


2020

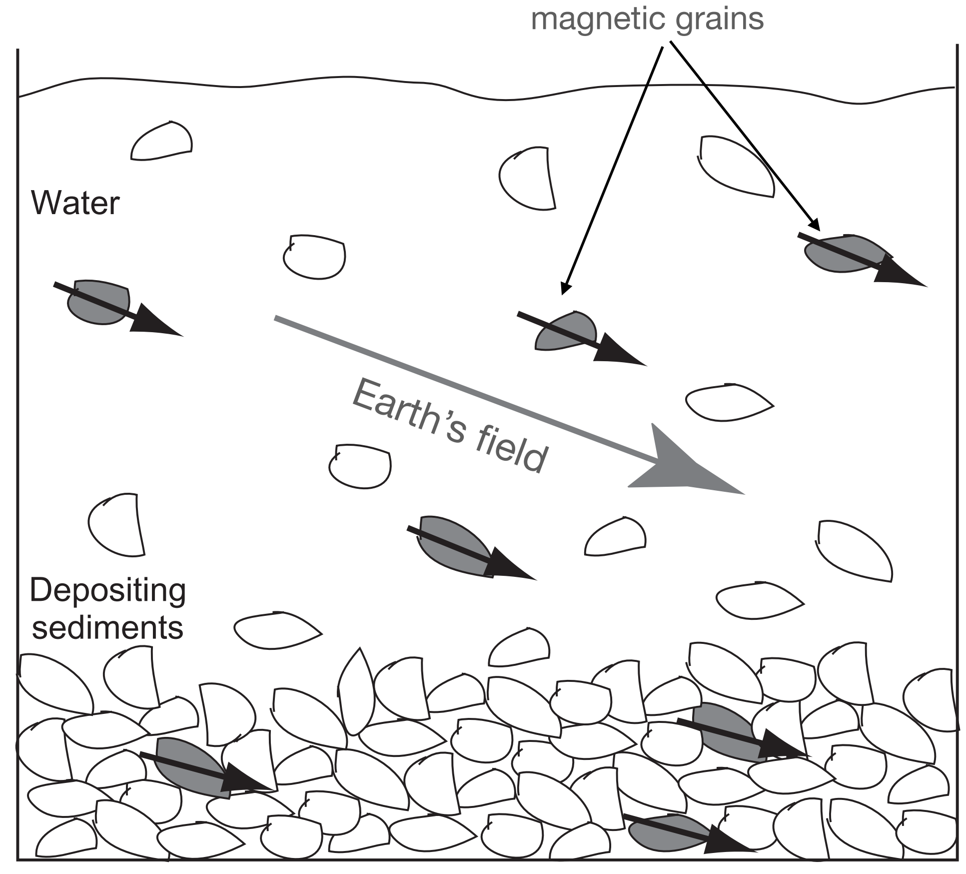


https://www.ngdc.noaa.gov/geomag/data/mag_maps/pdf/

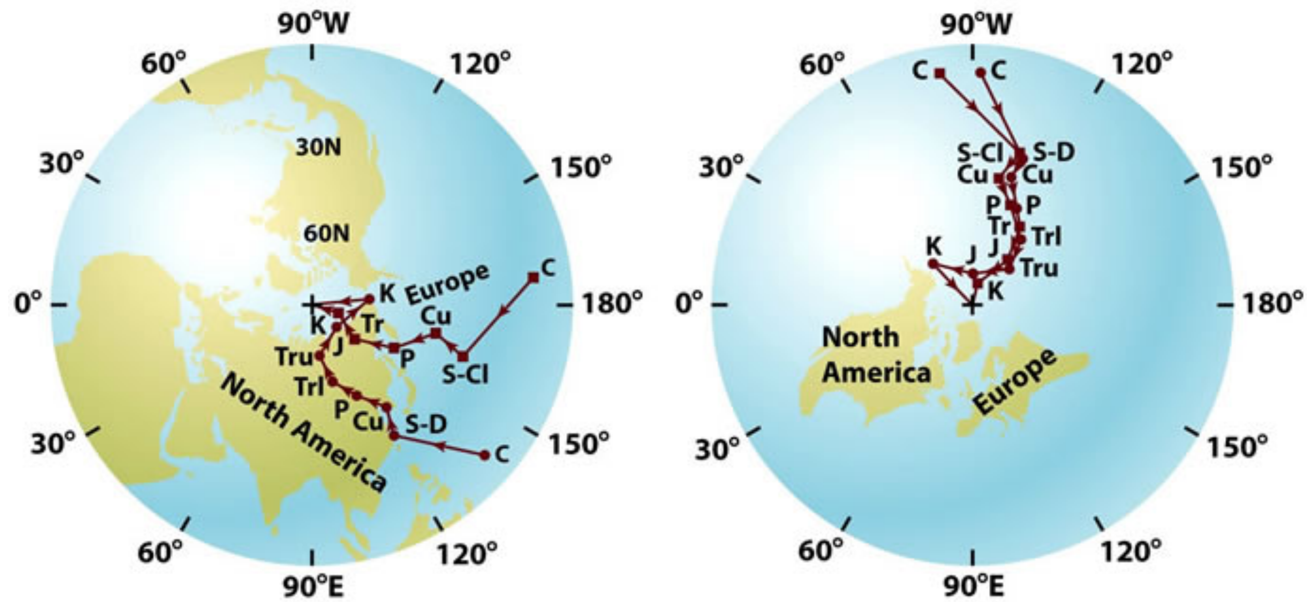
Igneous remanent paleomagnetism



Sedimentary remanent paleomagnetism



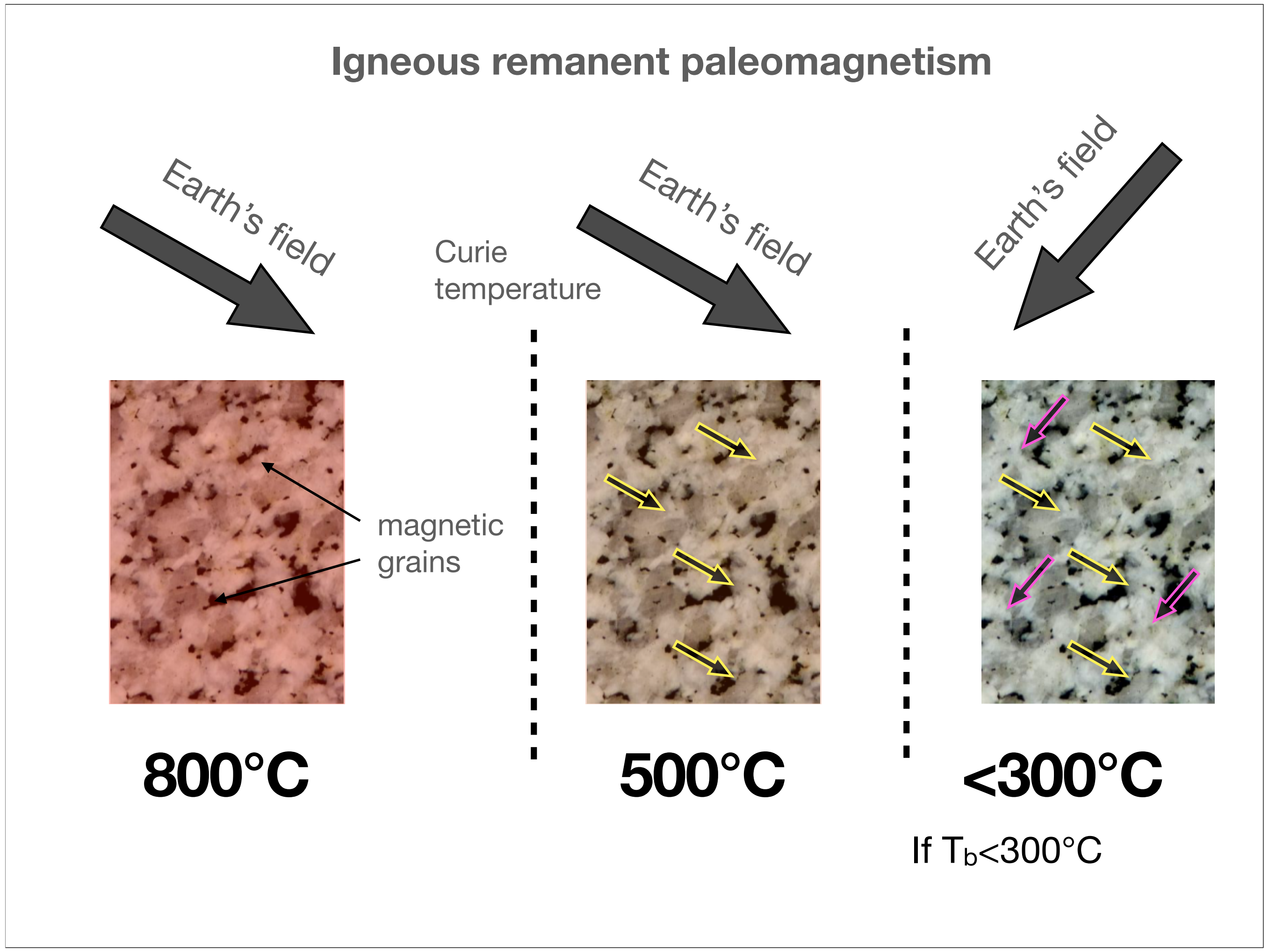
Ziegler and Kodama, *Terrestrial Depositional Systems,* 2017



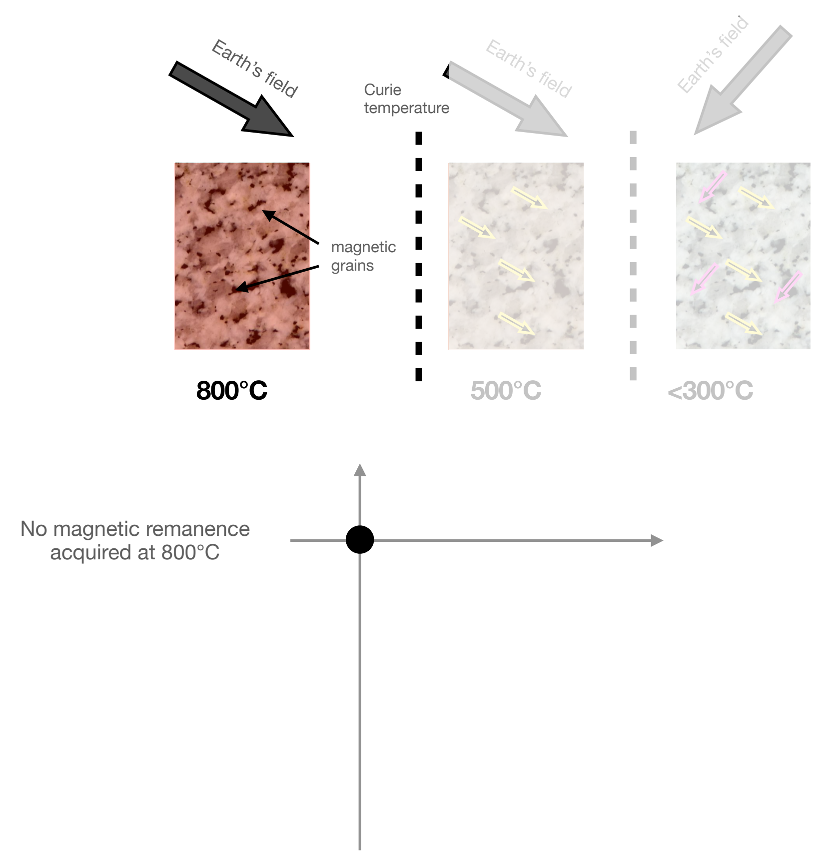
A **B**

Figure 8-12
Earth System History, Second Edition

Mineral	Composition	Curie Point	Origin
Magnetite	Fe_3O_4	580°C	Magmatic, occasional metamorphic and chemical
Titanomagnetite	$Fe_2 Fe_x Ti_{1-x}O_4$	150-580°C	"
Hematite	α-Fe_2O_3	675°C	Often sedimentary, chemical, sometimes magmatic, metamorphic
Maghemite	γ-Fe_2O_3	590-675°C —goes to hematite above 250-750°C	Chemical
Pyrrhotite	FeS_{1+x}, $0<x\leq 0.14$	320°C	Magmatic, chemical
Goethite	α-FeOOH	120°C (dehydrates 100-300°C)	Chemical (weathering)
Lepidocrocite	γ-FeOOH	Below room temperature (dehydrates 250°C to maghemite)	Chemical (weathering)
Greigite	Fe_3S_4	~330°C	Chemical (anoxic sediments)


Igneous remanent paleomagnetism
Earth's field
Curie
temperature
Earth's field
Earth's field
magnetic
grains
800°C
500°C
<300°C
If Tb<300°C

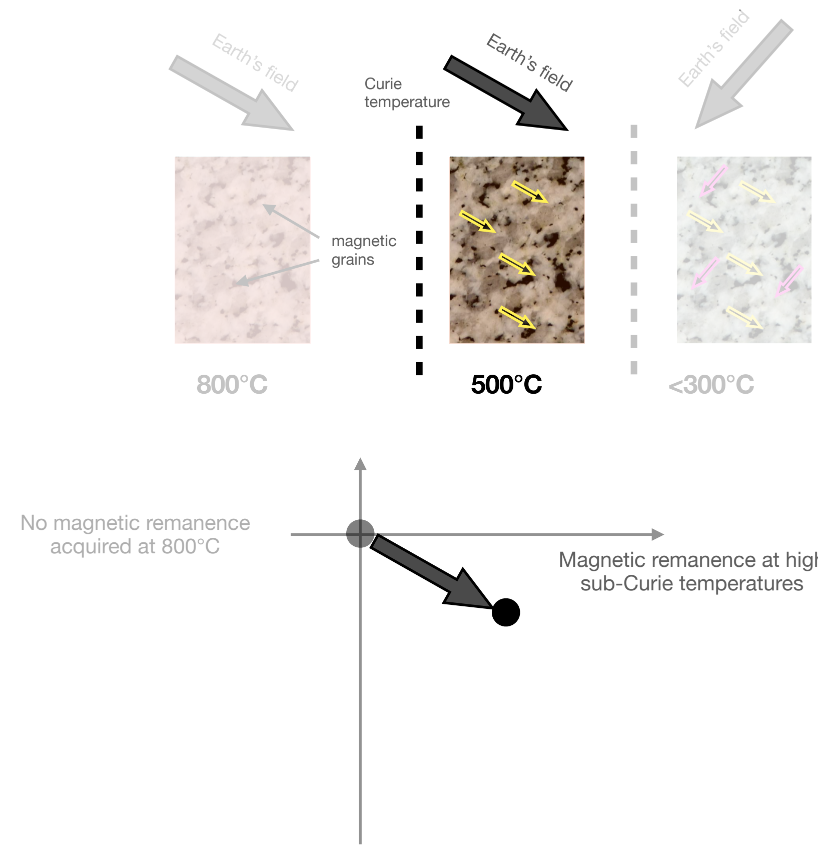
Igneous remanent paleomagnetism



$$M(t) = M_0 e^{-t/\tau}$$

$$\tau = \frac{1}{C} e^{\left(\frac{vK}{kT}\right)}$$

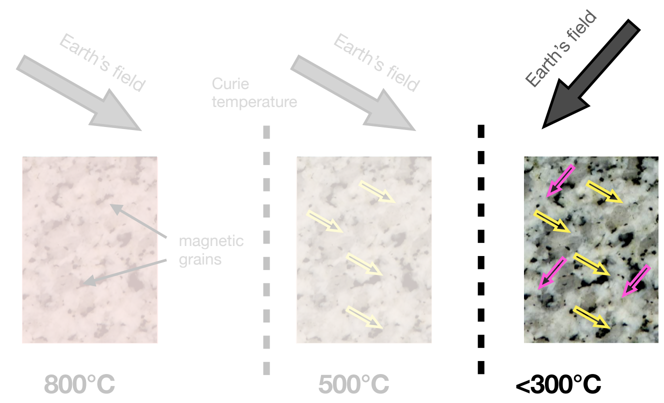
Igneous remanent paleomagnetism



$$M(t) = M_0 e^{-t/\tau}$$

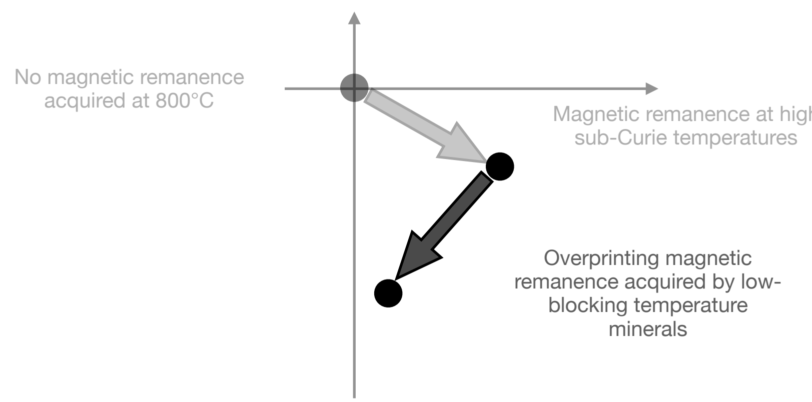
$$\tau = \frac{1}{C} e^{\left(\frac{vK}{kT}\right)}$$

Igneous remanent paleomagnetism

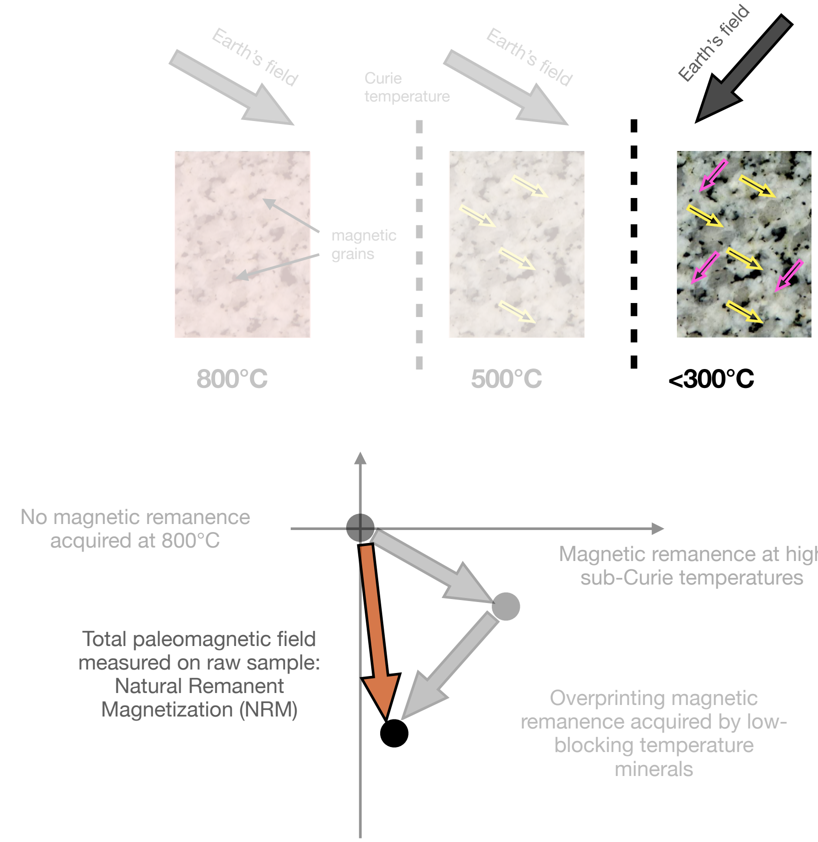


$$M(t) = M_0 e^{-t/\tau}$$

$$\tau = \frac{1}{C} e^{\left(\frac{vK}{kT}\right)}$$



Igneous remanent paleomagnetism



$$M(t) = M_0 e^{-t/\tau}$$

$$\tau = \frac{1}{C} e^{\left(\frac{vK}{kT}\right)}$$

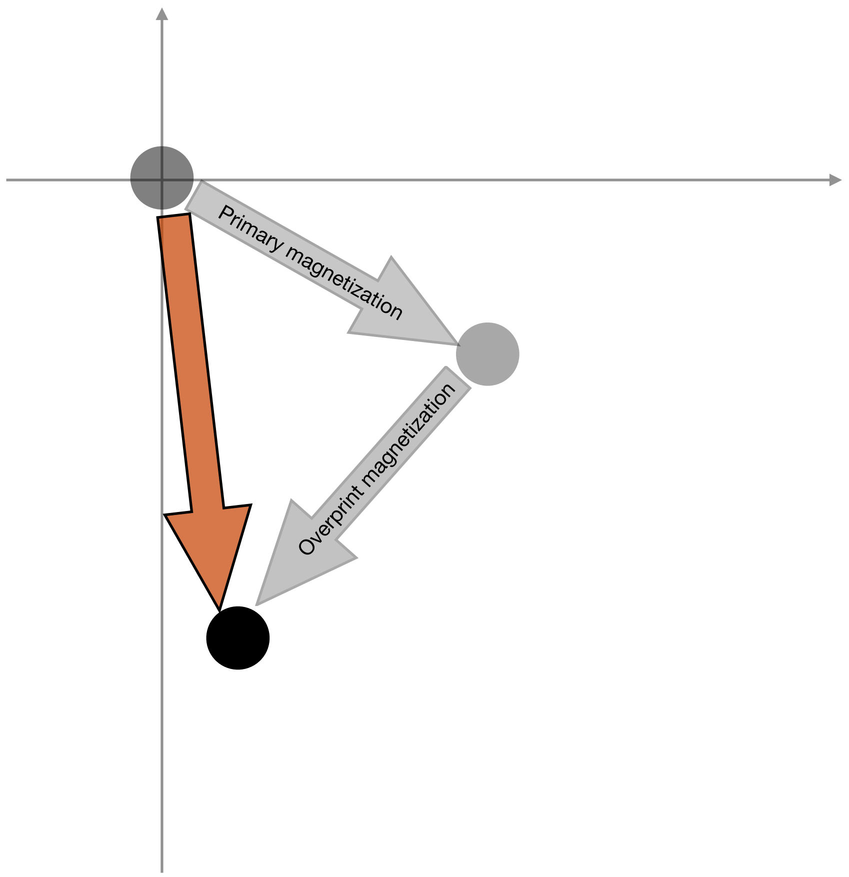
Igneous remanent paleomagnetism

So raw measurements of rocks rarely reveals the “original” primary magnetization.

Demagnetization seeks to run the acquisition of magnetization backwards…

Thermal demagnetization is perhaps most intuitive

$$T_1 \ln C\tau_1 = T_2 \ln C\tau_2$$



Igneous remanent paleomagnetism

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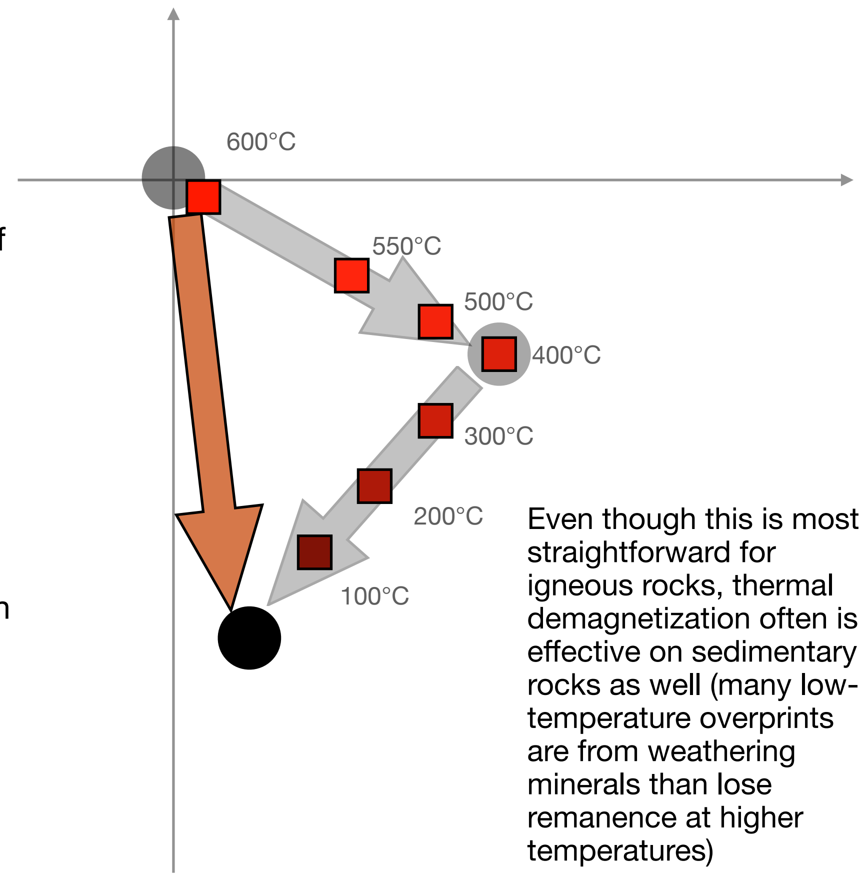
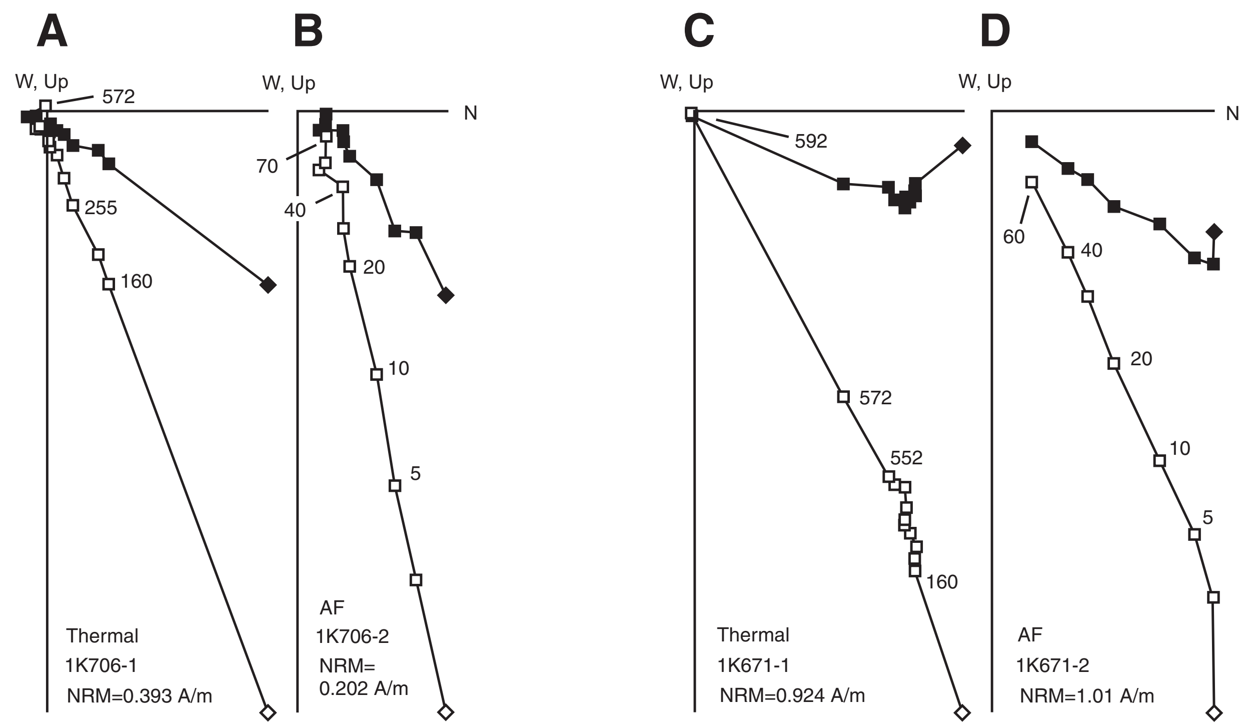
$$T_1 \ln C\tau_1 = T_2 \ln C\tau_2$$



Even though this is most straightforward for igneous rocks, thermal demagnetization often is effective on sedimentary rocks as well (many low-temperature overprints are from weathering minerals than lose remanence at higher temperatures)

Demagnetization Curves

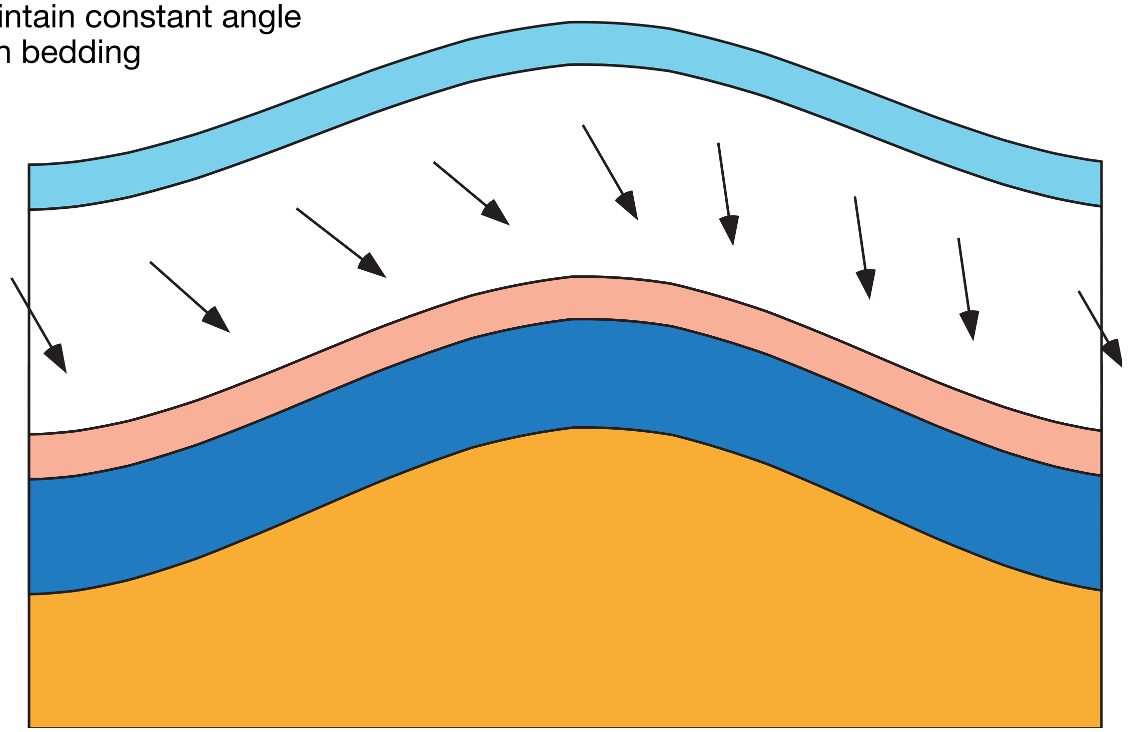


Rusmore et al., *Lithosphere*, 2013
Solid are horizontal projection, open are vertical.

Paleomagnetism tests

Fold test:

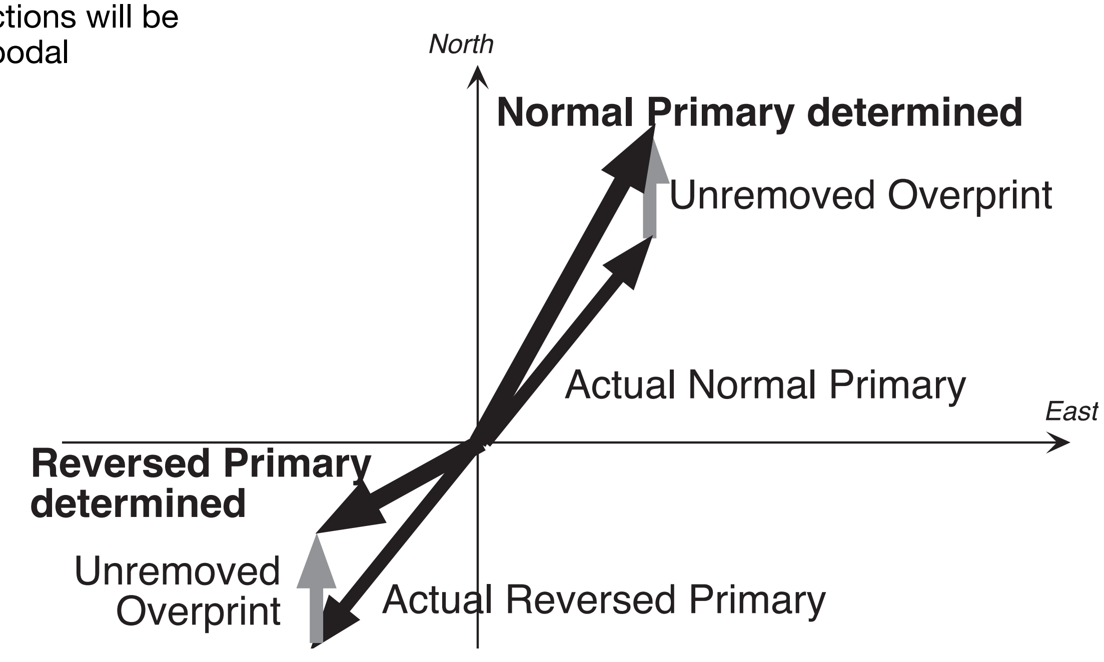
Magnetization acquired at deposition will maintain constant angle with bedding



Paleomagnetism tests

Reversal test:

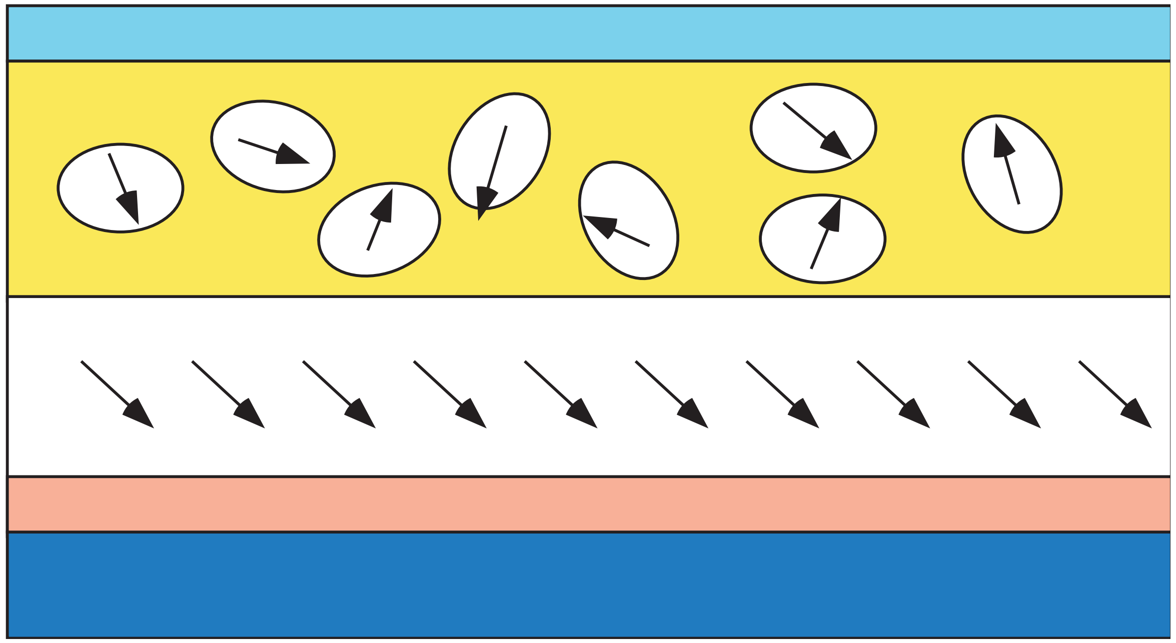
Normal and reversed directions will be antipodal



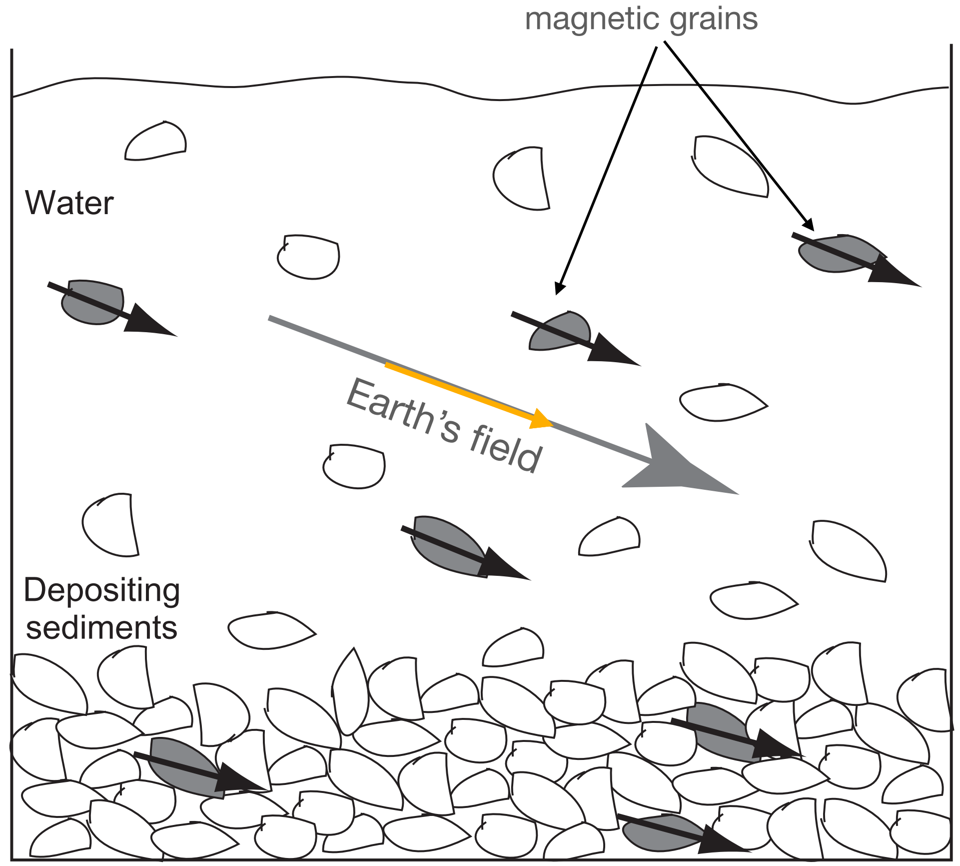
Paleomagnetism tests

Conglomerate test:

Magnetization in cobbles will be random if not overprinted

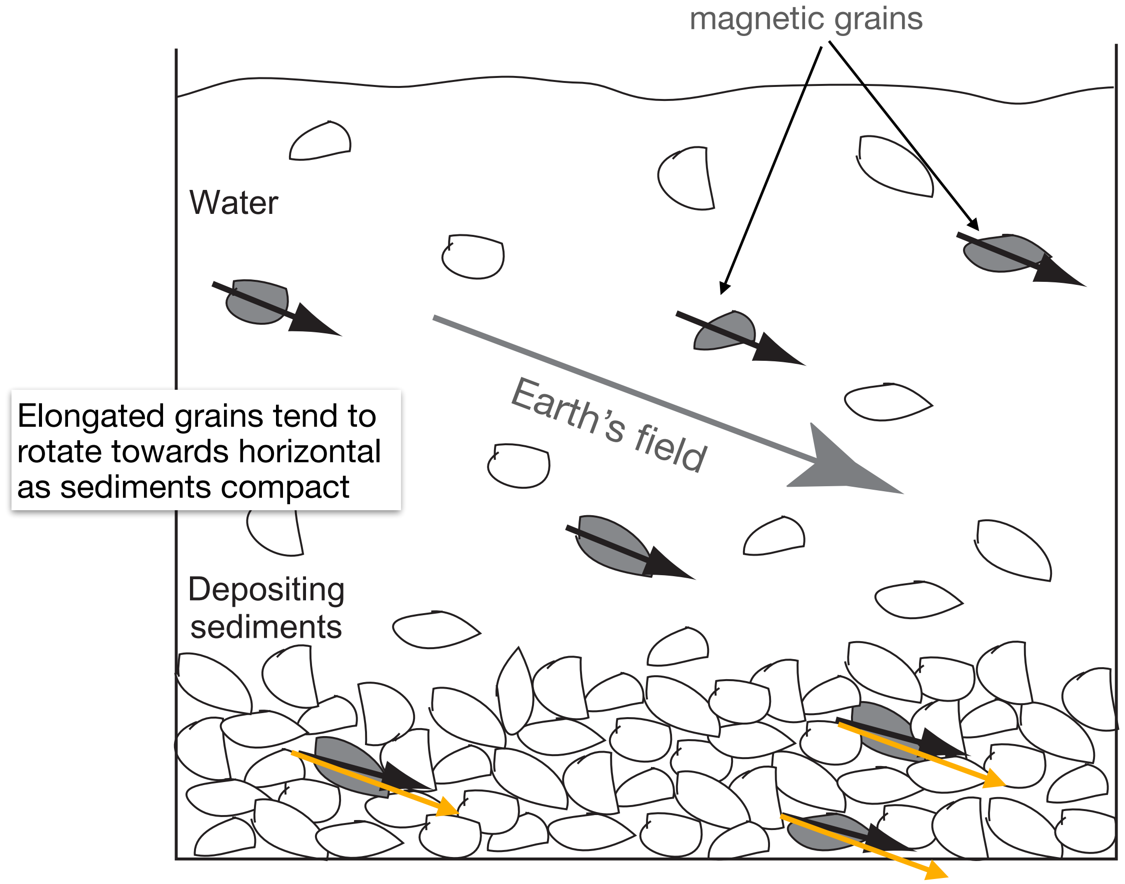


Sedimentary remanent paleomagnetism: Flattening



Ziegler and Kodama, *Terrestrial Depositional Systems,* 2017

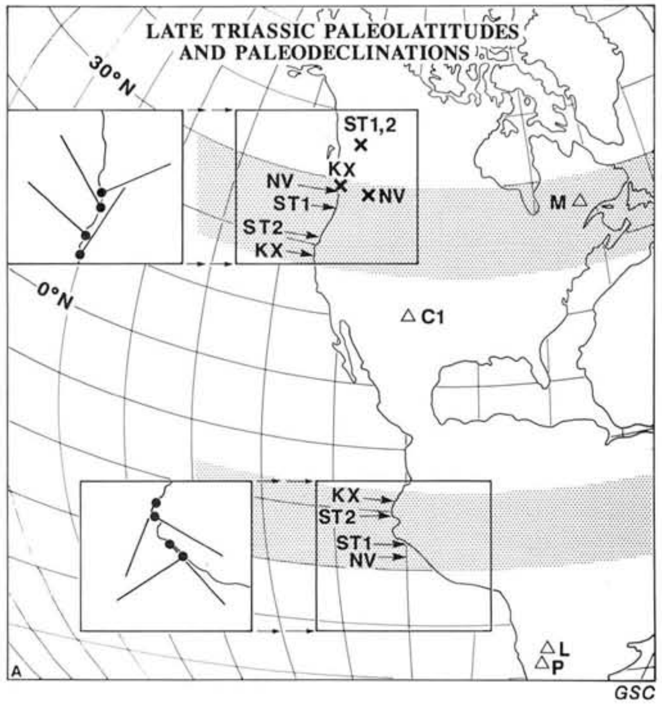
Sedimentary remanent paleomagnetism: Flattening



Ziegler and Kodama, *Terrestrial Depositional Systems,* 2017

Remanent paleomagnetism: Hemispheric ambiguity

In tectonically active areas, large rotations about a vertical axis are possible, so could be in either hemisphere.



Irving and Wynne, DNAG v. G-2, 1991

Igneous remanent paleomagnetism: Paleohorizontal ambiguity

AGUE AND BRANDON

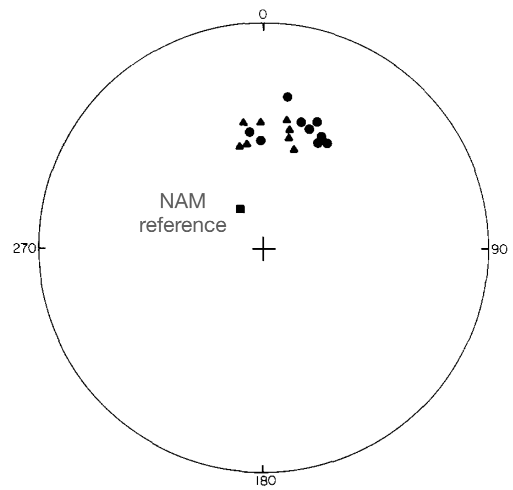
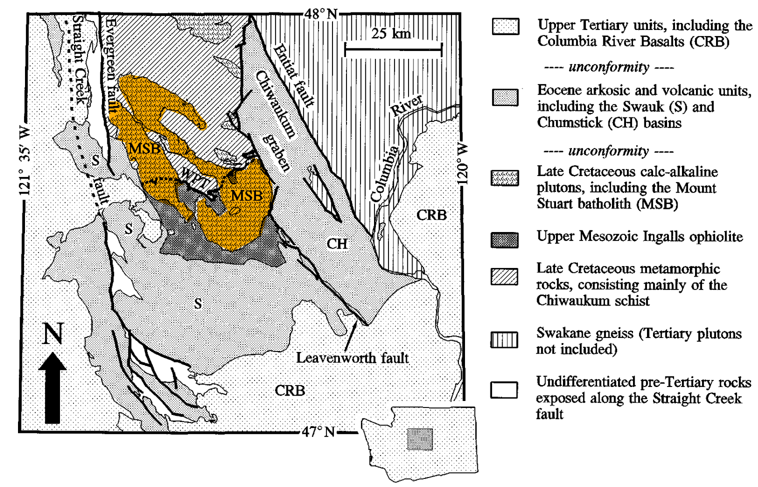


Fig. 3. Equal-area projection on the lower hemisphere, showing site-mean directions of magnetism for the Mt. Stuart batholith. Symbols are keyed to Fig. 4; eastern sites are shown by triangles, western sites by circles. The solid square represents the Cretaceous expected direction at the present latitude and longitude of the Mt. Stuart rocks, calculated from Mankinen [19].

Beck et al., EPSL, 1981



Ague & Brandon, GSA Bull, 1996

Attention focused on one pluton for what could be wrong in pmag...

Igneous remanent paleomagnetism: Paleohorizontal ambiguity

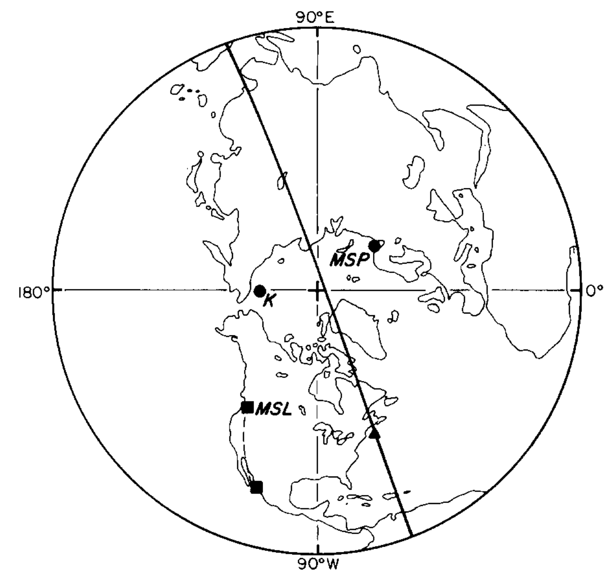


Fig. 5. A tectonic-transport ("microplate") solution. *MSL* = location of Mt. Stuart Batholith; *MSP* = Mt. Stuart paleomagnetic pole; *K* = Cretaceous reference pole for North America. The heavy curve bisects the distance between *K* and *MSP* and therefore is the locus of all possible Euler poles about which *K* can be displaced to *MSP* by a single finite rotation. The triangle shows the unique rotation pole that results from assuming that the Mt. Stuart Batholith originated on the edge of North America. *MSL* is shown rotated back to western Mexico about this pole.

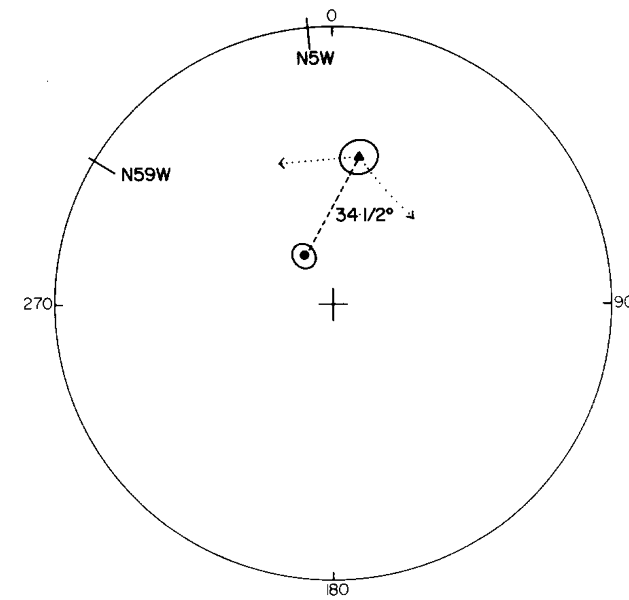
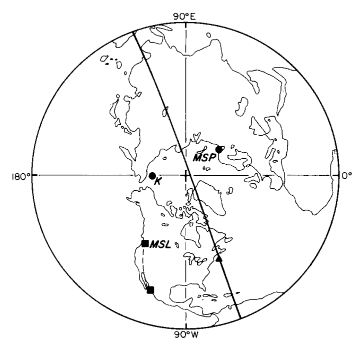


Fig. 6. A tilt solution. Circle is the Cretaceous expected direction, with circle of confidence; triangle is the observed direction for the Mt. Stuart Batholith, also with circle of confidence. A rotation of 34.5° about a fold-axis trending N59W will bring the two into coincidence. Tilt to the southeast or west does not reduce the discordance.

Beck et al., EPSL, 1981

could translate or tilt....

Igneous remanent paleomagnetism: Paleohorizontal ambiguity



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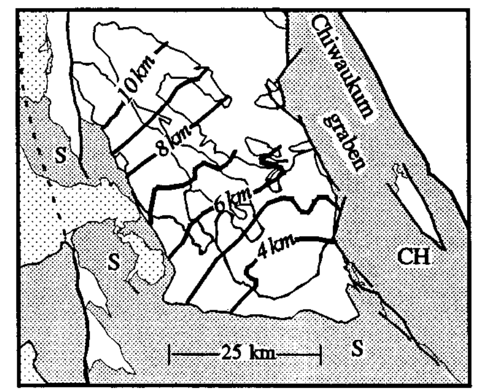


Undifferentiated Upper Tertiary units

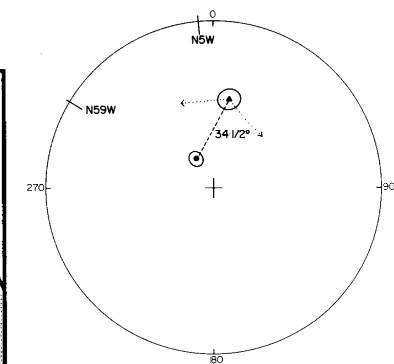
---- *unconformity* ----

Eocene arkosic and volcanic units, including Swauk (S) and Chumstick (CH) basins

---- *unconformity* ----

Undifferentiated pre-Tertiary rocks

Figure 10. Depth contours computed from the best-fit paleosurface by determining the intersection of the present topography with surfaces of constant crystallization depth (cf. text and Fig. 2A).



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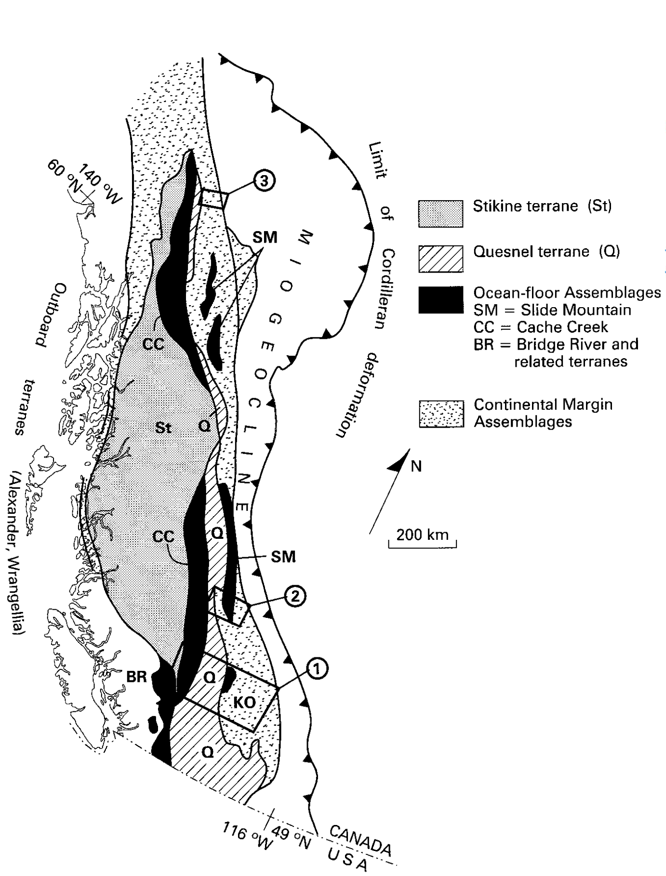
Beck et al., EPSL, 1981

Ague & Brandon, GSA Bull, 1996

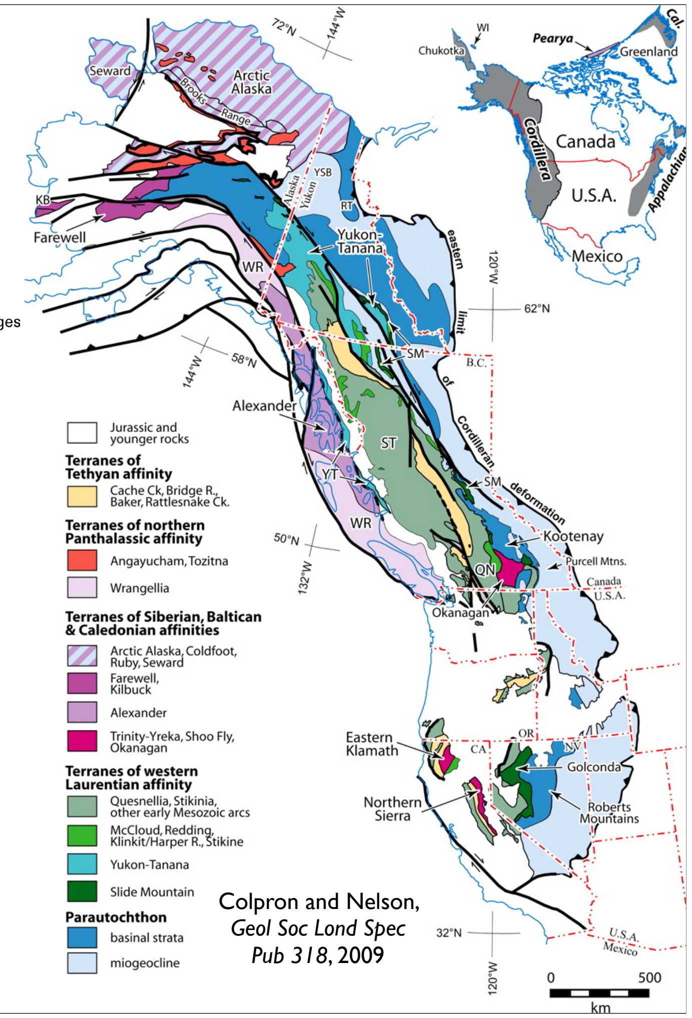
So paleomag can reveal discrepant chunks of crust.

While this has been critical in Baja-BC story (which we'll try not to get too buried in), identification of and determining the history of exotic terranes requires other tools, too.

Let's look at a terrane that has been associated with the Sierra and Klamath rocks, the Alexander terrane.



Patchett and Gehrels, J. Geol. 1998



Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009

Most terrane maps focus on Canada; map at right extends this into US

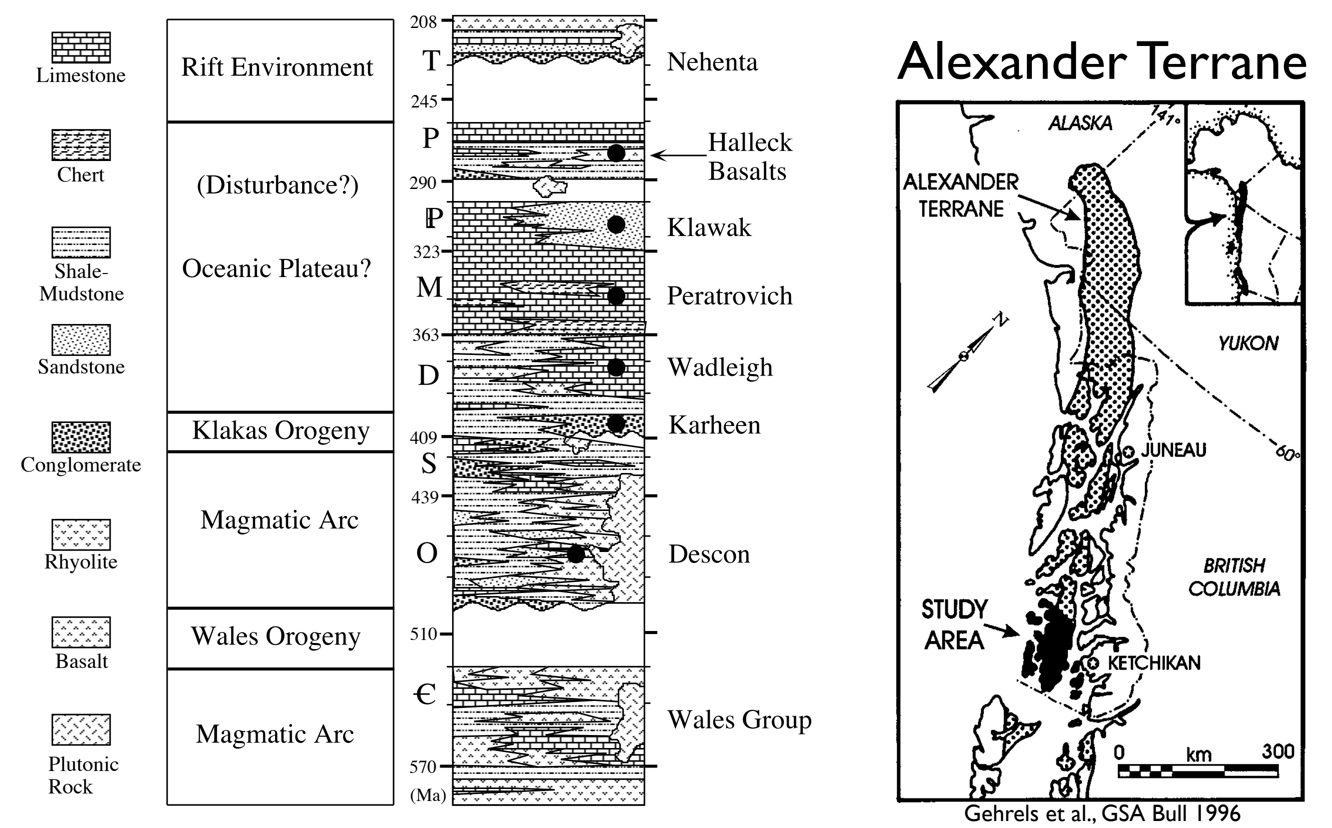


Figure 2. Stratigraphic column of the Alexander terrane in the southern part of southeast Alaska after Gehrels and Saleeby (1987). Filled circles indicate the horizons sampled for paleomagnetic study.

Butler et al., GSA Bull 1997

First, how do we know they are exotic? First big clue (well, maybe second) was very different geologic histories. While many terranes are relatively young, the Alexander terrane has a history going into the pC. Not a WUS history....

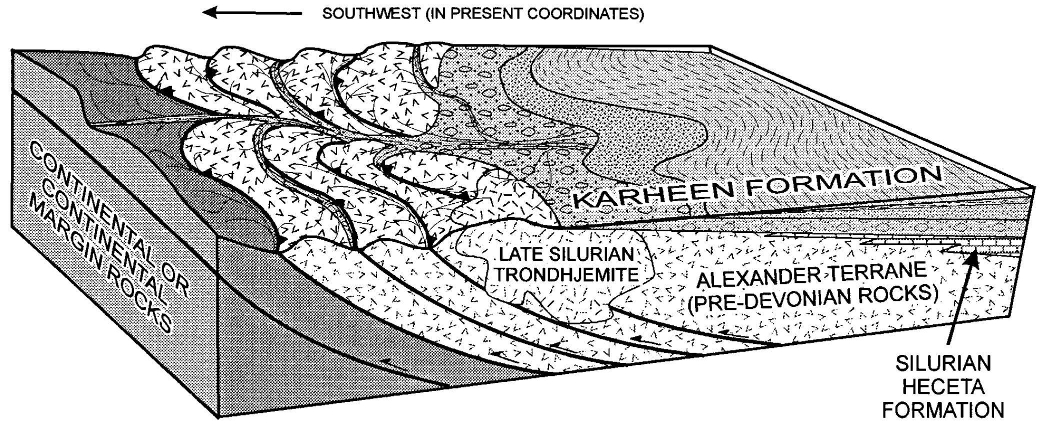
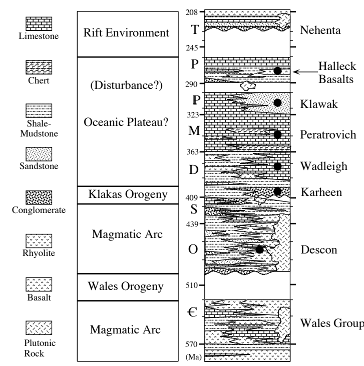


Figure 5. Schematic diagram showing the interpreted juxtaposition of the Alexander terrane with continental or continental-margin rocks during the Middle Silurian–earliest Devonian Klakas orogeny. The Karheen Formation is interpreted to be a clastic wedge shed from this orogen. The unusual geometry of clastic strata accumulating in the hinterland of the thrust system derives from the observations that Klakas-age thrusts are apparently southwest vergent, whereas Karheen strata were shed from source areas to the south or southwest.

Gehrels et al., GSA Bull 1996



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Butler et al., GSA Bull 1997

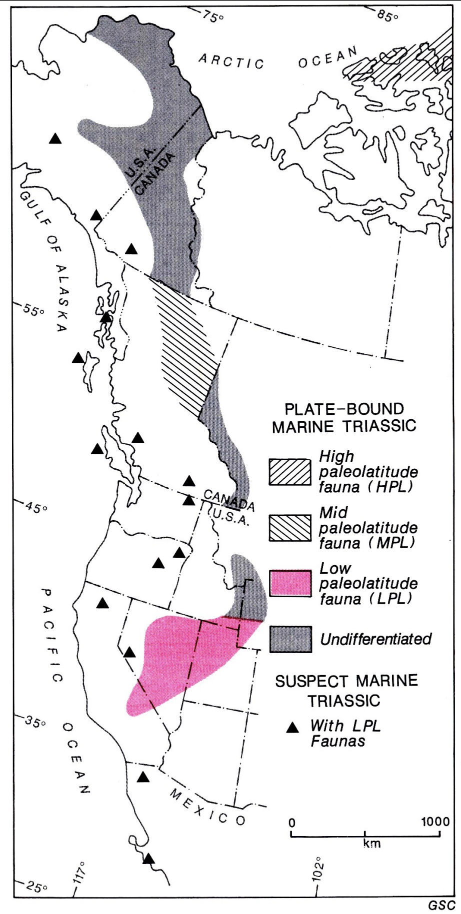
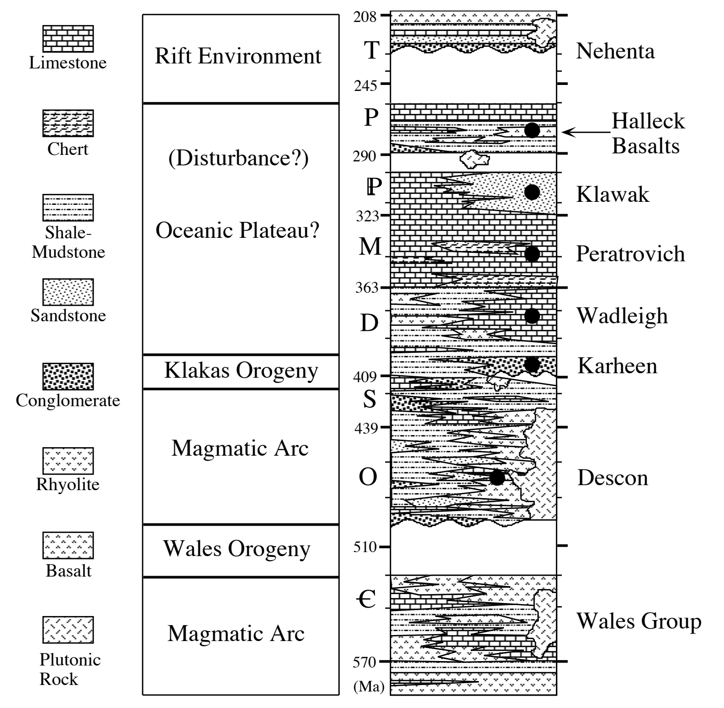


Figure 2.18. Triassic paleobiogeography of western North America (from Tozer, 1982).

Carter et al, DNAG v.G-2, 1991

Second clue fauna--lots of stuff looks wrong



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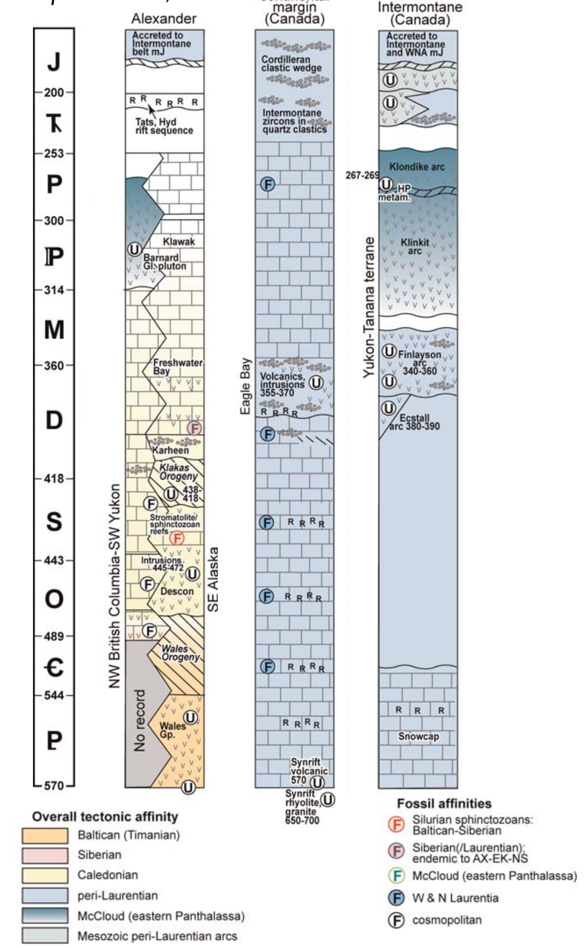
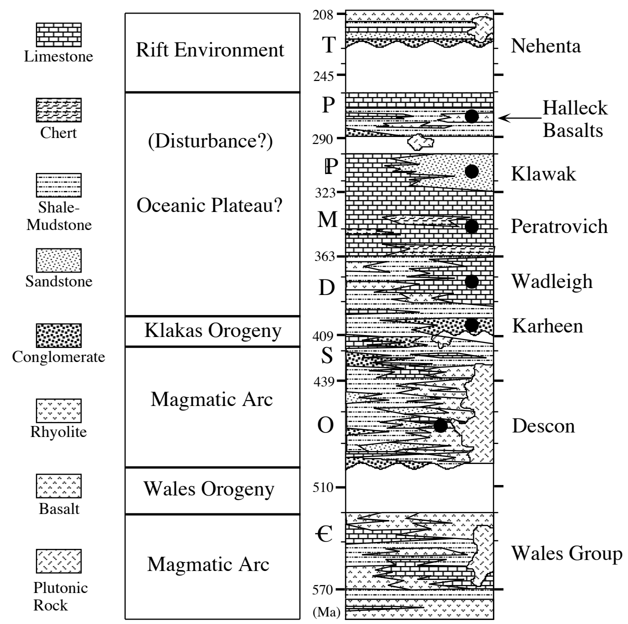
Butler et al., GSA Bull 1997

Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009





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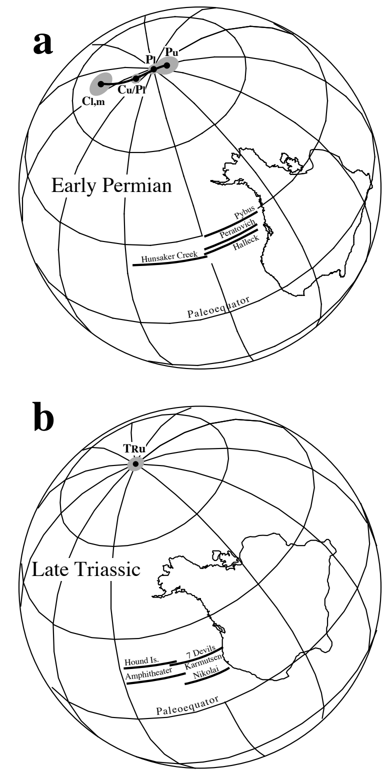
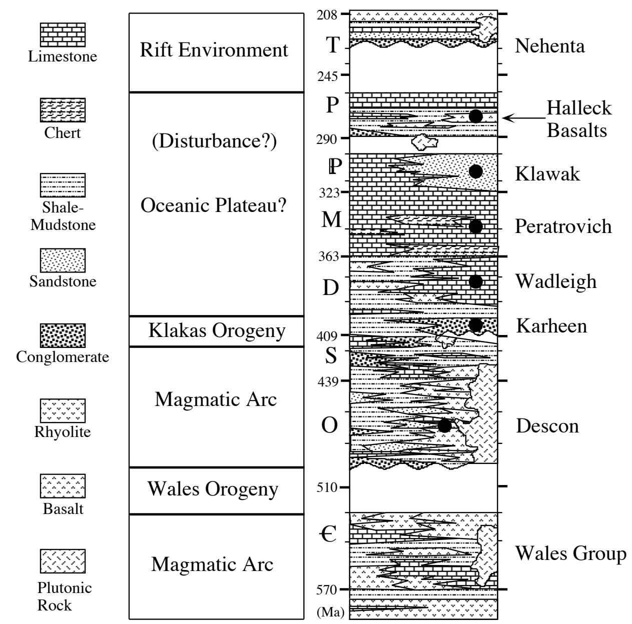


Figure 8. Paleolatitudes determined from (a) Lower Permian and (b) Upper Triassic strata of the Alexander-Wrangellia terrane. Orthographic projections use Early Permian (a) and Late Triassic (b) paleomagnetic reference poles for the axes of the paleogeographic grids (see Table 2 for details). Reference pole designations in (a): Cl, m—Early–Middle Carboniferous mean pole; Cu/Pl—Late Carboniferous–Early Permian mean pole; Pl—Early Permian mean pole; Pu—Late Permian mean pole (Van der Voo, 1993).

Butler et al., GSA Bull 1997

Third clue paleomag--often messed up relative to NAM



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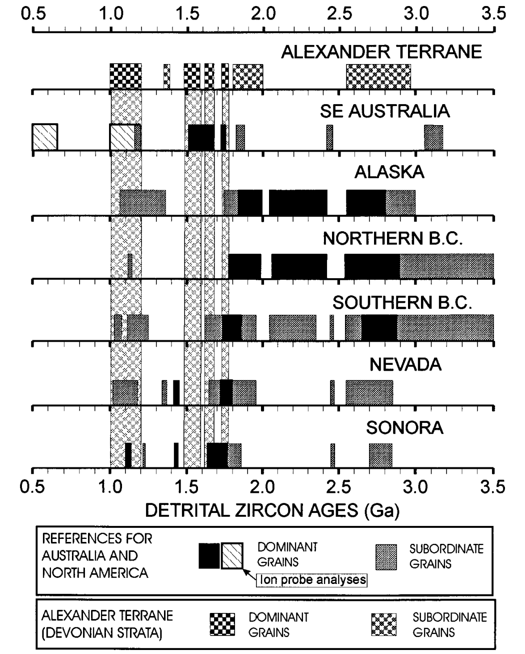
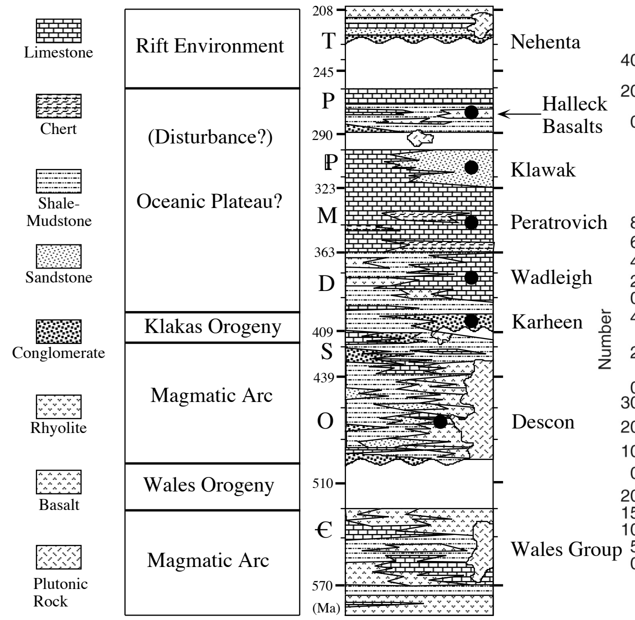


Figure 8. Comparison of Precambrian detrital zircons in the Alexander terrane, miogeoclinal strata of western North America, and eastern Australia. The miogeoclinal reference for western North America is from Gehrels et al. (1995). The Australian age ranges include isotope dilution analyses (from Table 3) and ion probe analyses (from Ireland, 1992; Ireland et al., 1994).

Butler et al., GSA Bull 1997

Gehrels et al., GSA Bull 1996

A more recent approach is our old friend detrital zircons. Here we see a lousy fit to NAM, and not great to Australia (other areas in Aus better)



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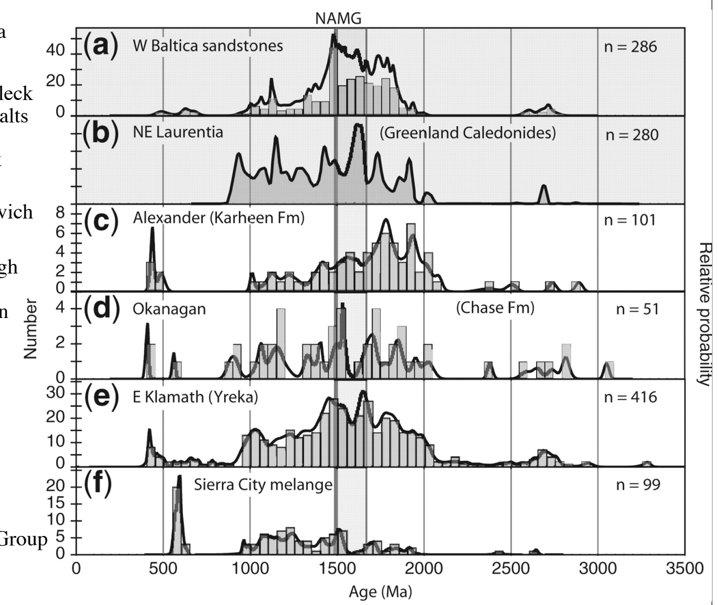
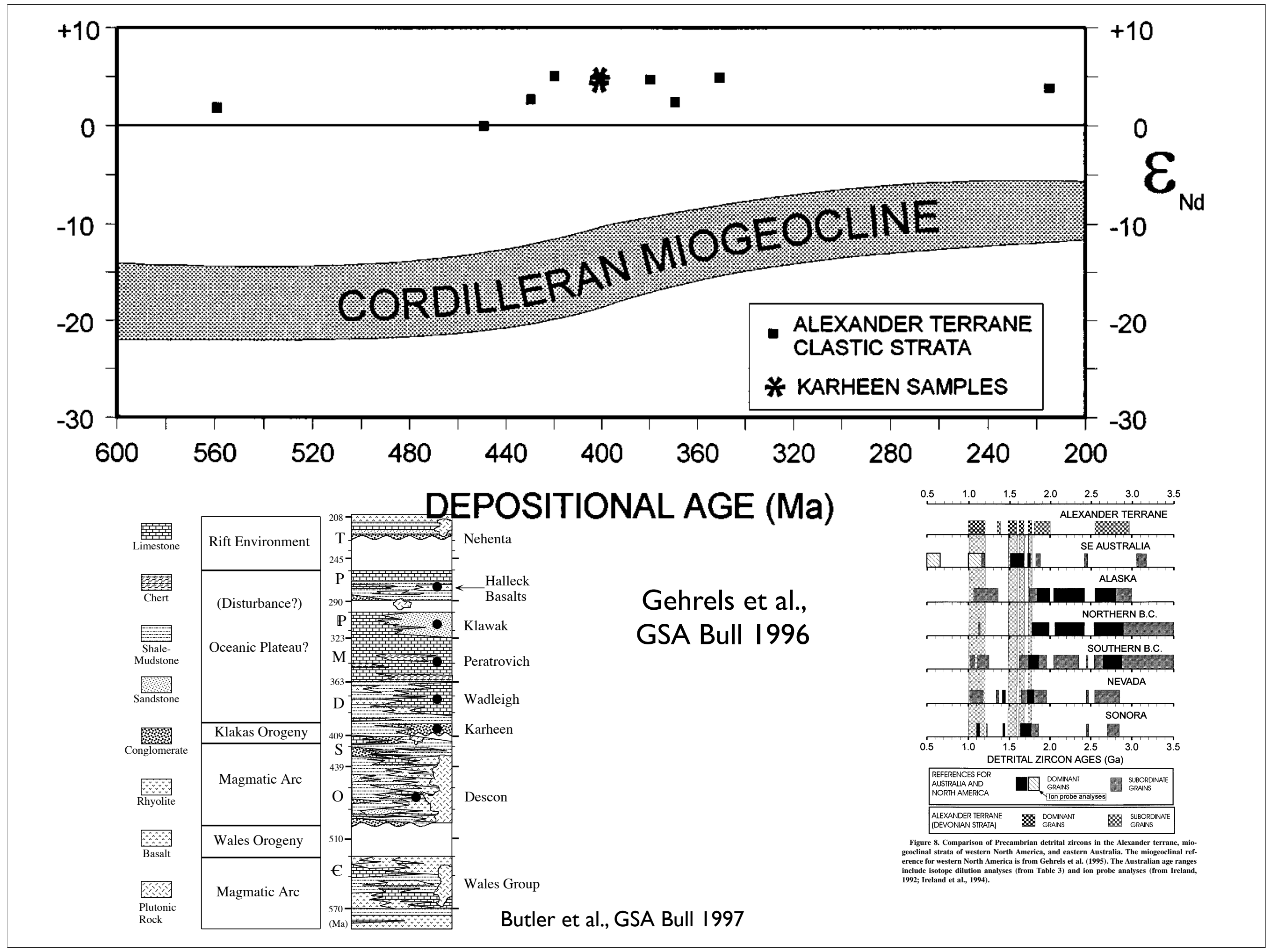


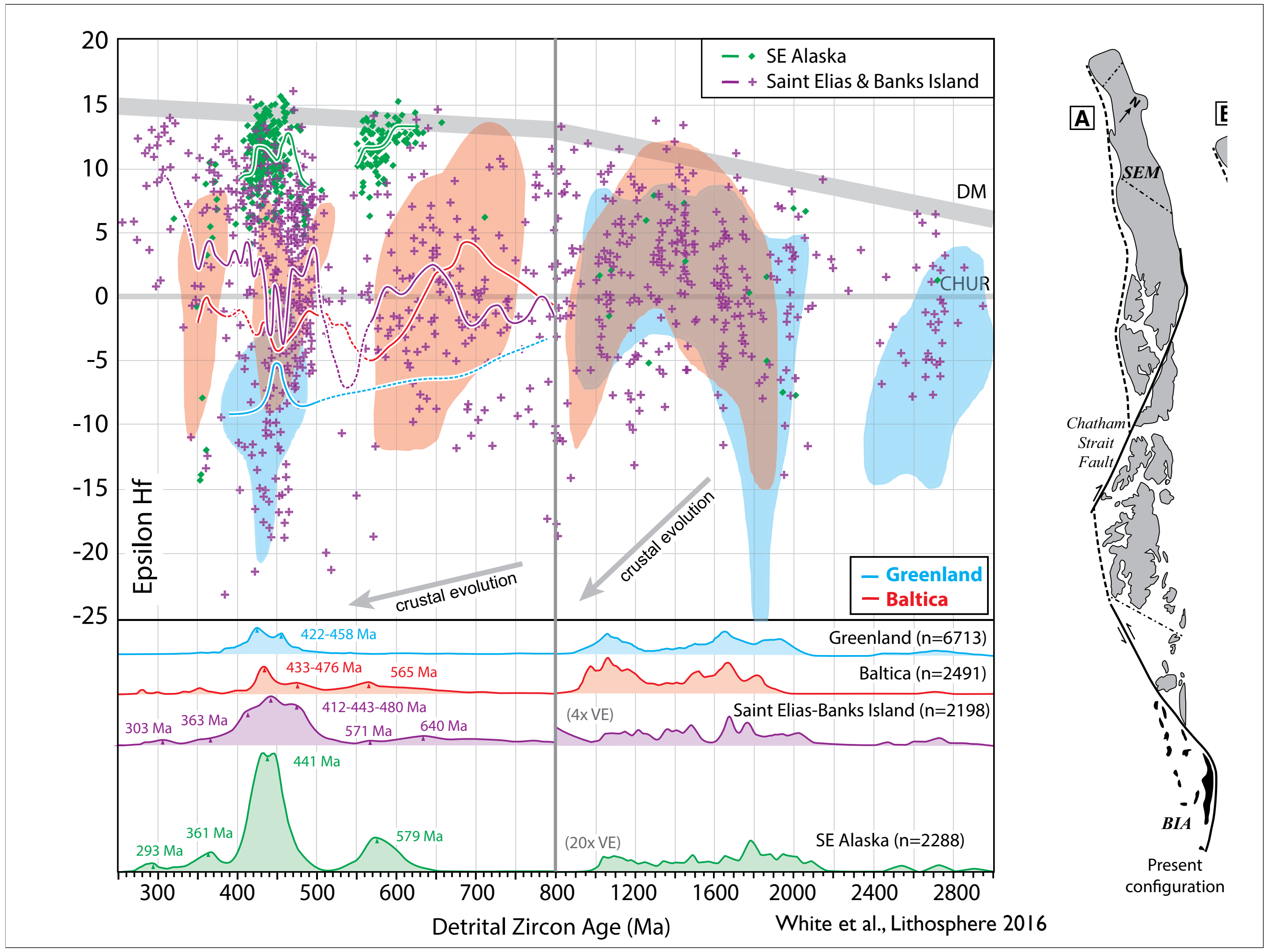
Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009

Butler et al., GSA Bull 1997

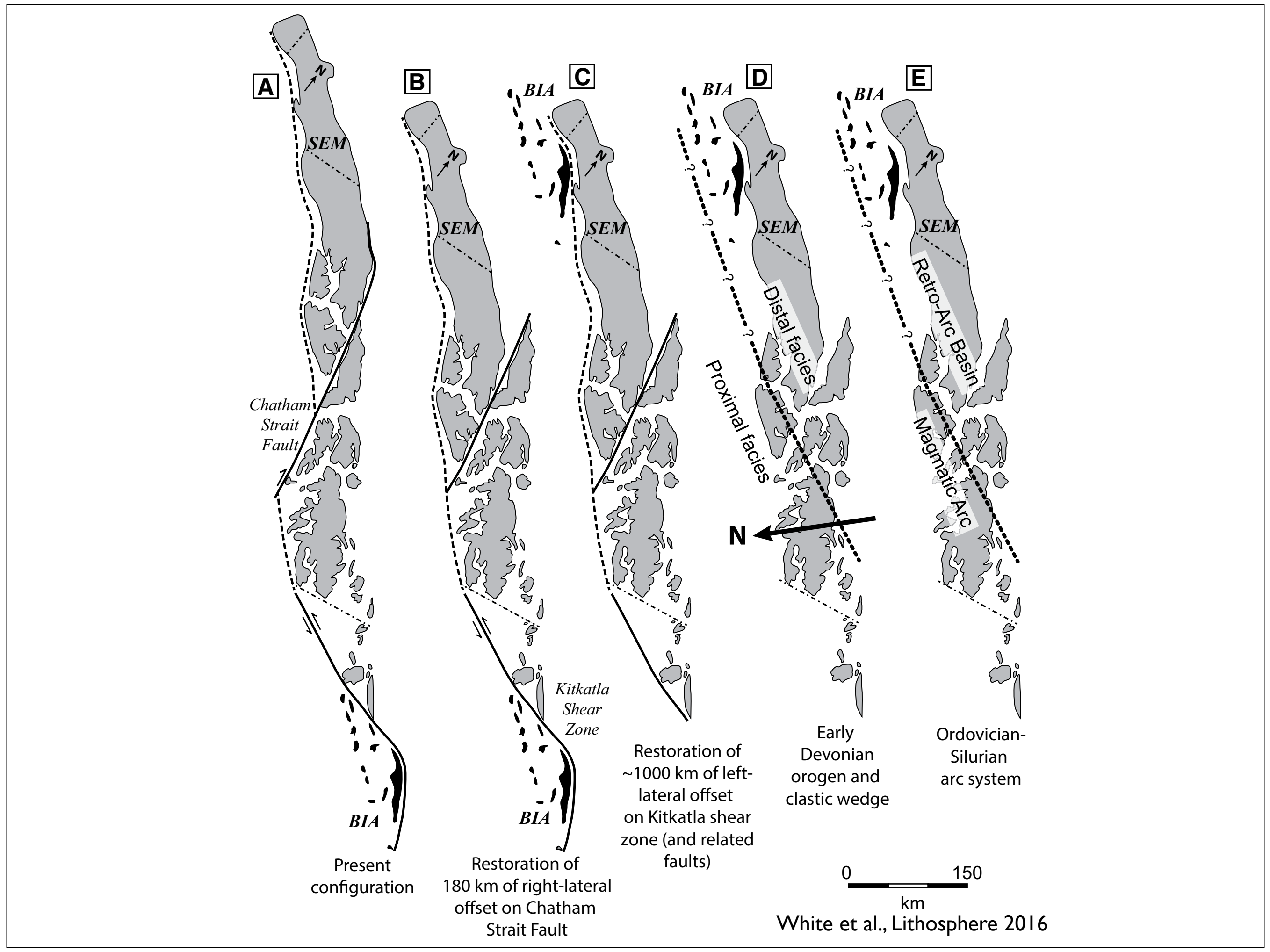
Newer work has focused on Baltica and the northern Calidonides.



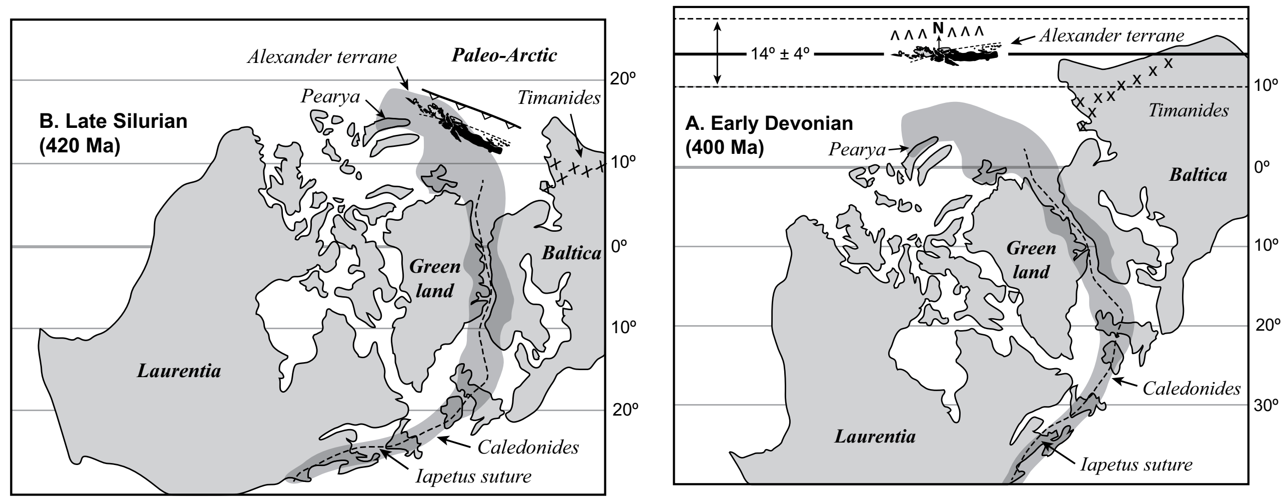
We can also look at other isotopic systems. So here measurements on detrital zircons of E-Nd show that stuff in the Karheen allocthon still don't look North American [which is actually an interesting problem beyond our scope]



Actually quite a range in Alexander Terrane—some very immature stuff in SE Alaska



Retrodeform Alexander Terrane to see what the Paleozoic gradients look like.



White et al., Lithosphere 2016

So early part of history of Alexander Terrane seems to be coming into focus…

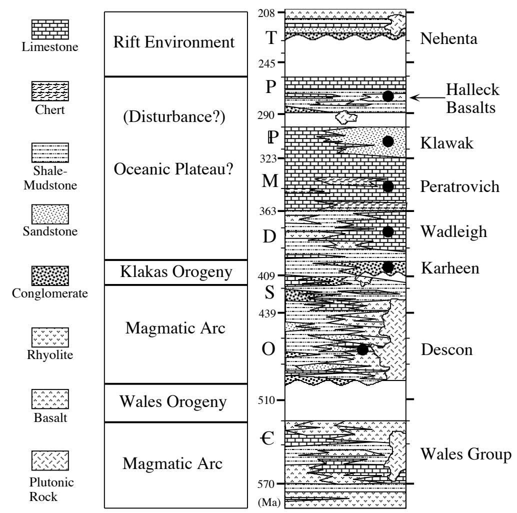
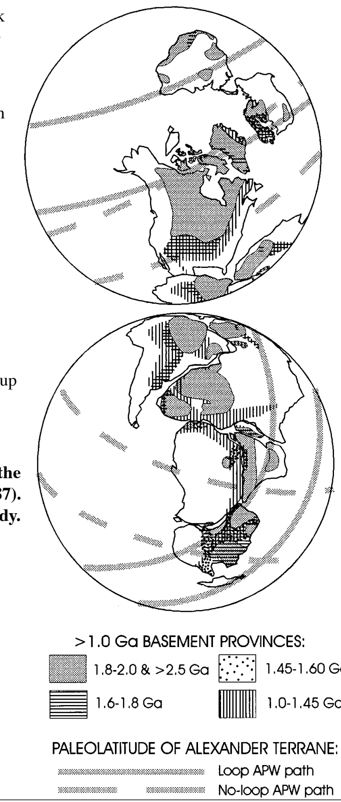


Figure 2. Stratigraphic column of the Alexander terrane in the southern part of southeast Alaska after Gehrels and Saleeby (1987). Filled circles indicate the horizons sampled for paleomagnetic study.

Butler et al., GSA Bull 1997



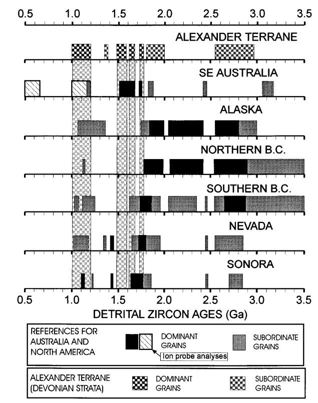


Figure 8. Comparison of Precambrian detrital zircons in the Alexander terrane, miogeoclinal strata of western North America, and eastern Australia. The miogeoclinal reference for western North America is from Gehrels et al. (1995). The Australian age ranges include isotope dilution analyses (from Table 3) and ion probe analyses (from Ireland, 1992; Ireland et al., 1994).

Figure 7. Paleogeographic map showing the distribution of continents during Early Devonian time. Gray bands on the map are the 14° ± 5° paleolatitudes determined from the Karheen Formation (Bazard et al., 1995), assuming both loop-present and no-loop apparent polar wander (APW) paths for North America and Gondwana (Van der Voo, 1990, 1993). Precambrian rocks are shown in the age groupings represented by detrital zircons in the Karheen Formation (compiled from Hoffman, 1989; Goodwin, 1991).

Gehrels et al., GSA Bull 1996

Does this all agree with the paleomag?

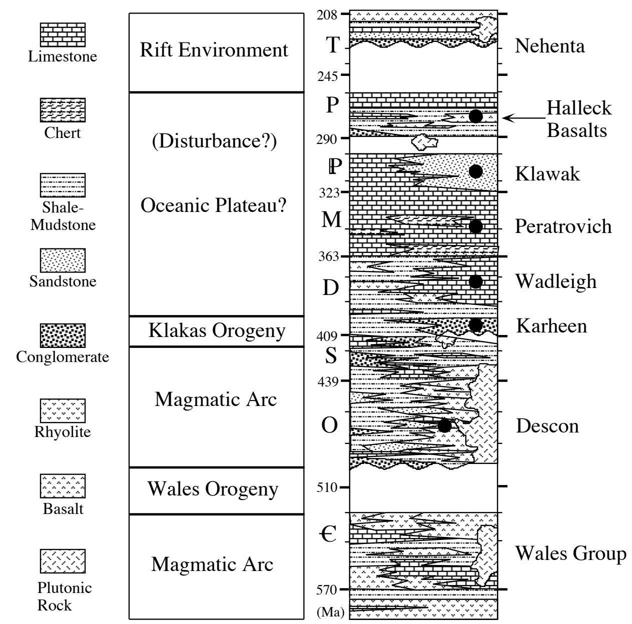


Figure 2. Stratigraphic column of the Alexander terrane in the southern part of southeast Alaska after Gehrels and Saleeby (1987). Filled circles indicate the horizons sampled for paleomagnetic study.

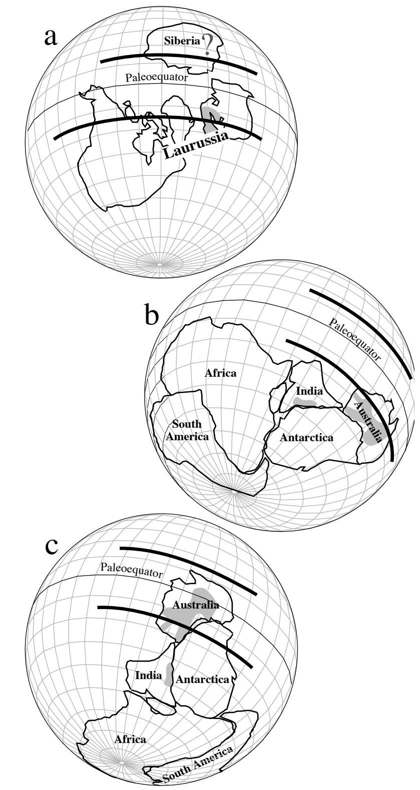
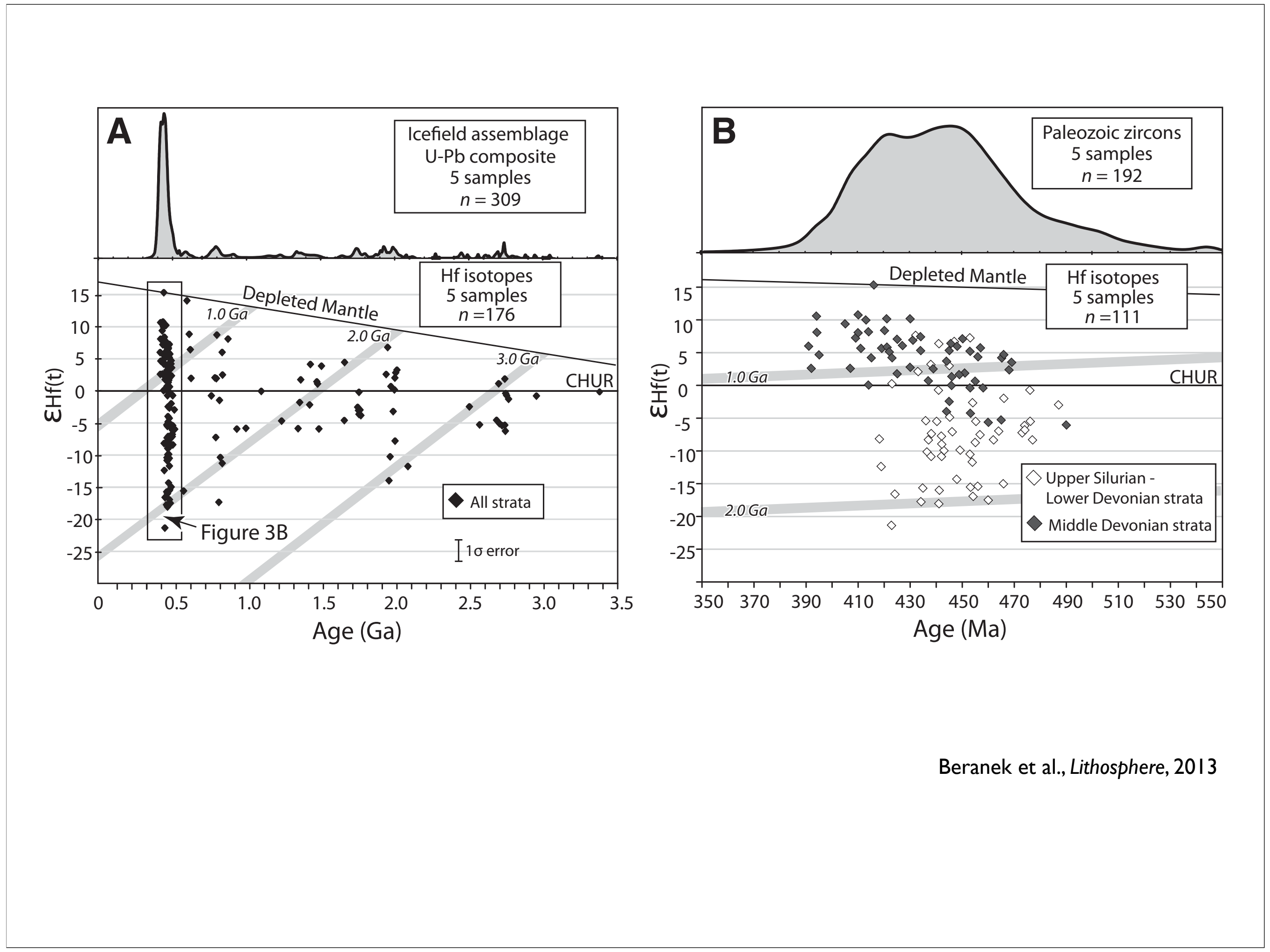


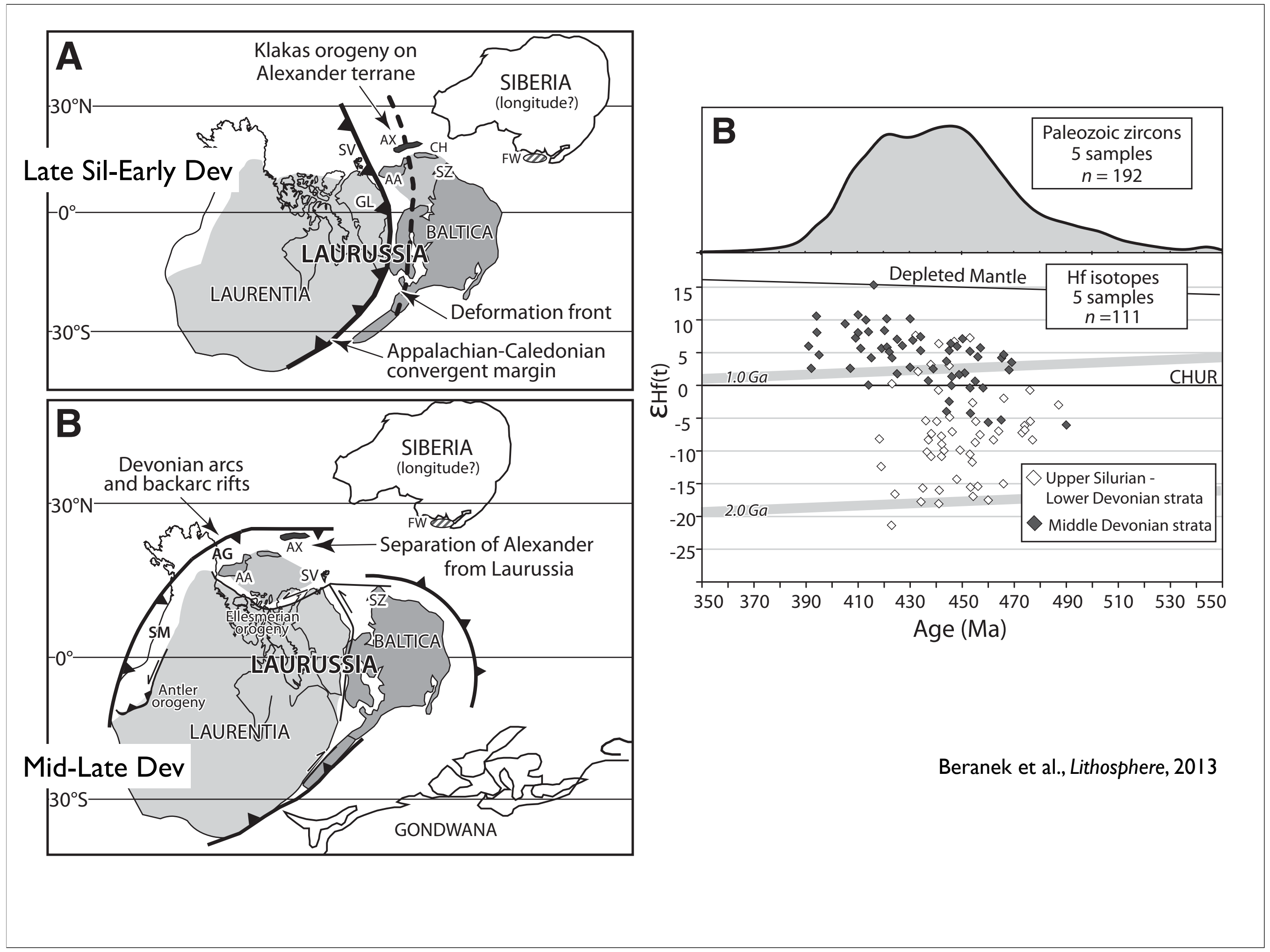
Figure 9. Late Silurian–Early Devonian world paleogeographies. (a) Paleogeography of the northern continents using Late Silurian–Early Devonian mean paleomagnetic pole for North America as axis of paleogeographic grid. (b) Paleogeography for Gondwana in Late Silurian–Early Devonian time using paleomagnetic pole from the Aïr complex as axis of paleogeographic grid. (c) Alternative Late Silurian–Early Devonian paleogeography for Gondwana using an interpolated Late Silurian–Early Devonian pole as axis of paleogeographic grid. Dark bands show 14° paleolatitudes determined for the Karheen Formation. Dark stippled areas are parts of cratons containing rocks within age windows of 1.6–1.8 Ga and 1.45–1.6 Ga. Question mark is placed in Siberia because of uncertain paleogeographic location in Late Silurian–Early Devonian time. See text for discussion.

Butler et al., GSA Bull 1997

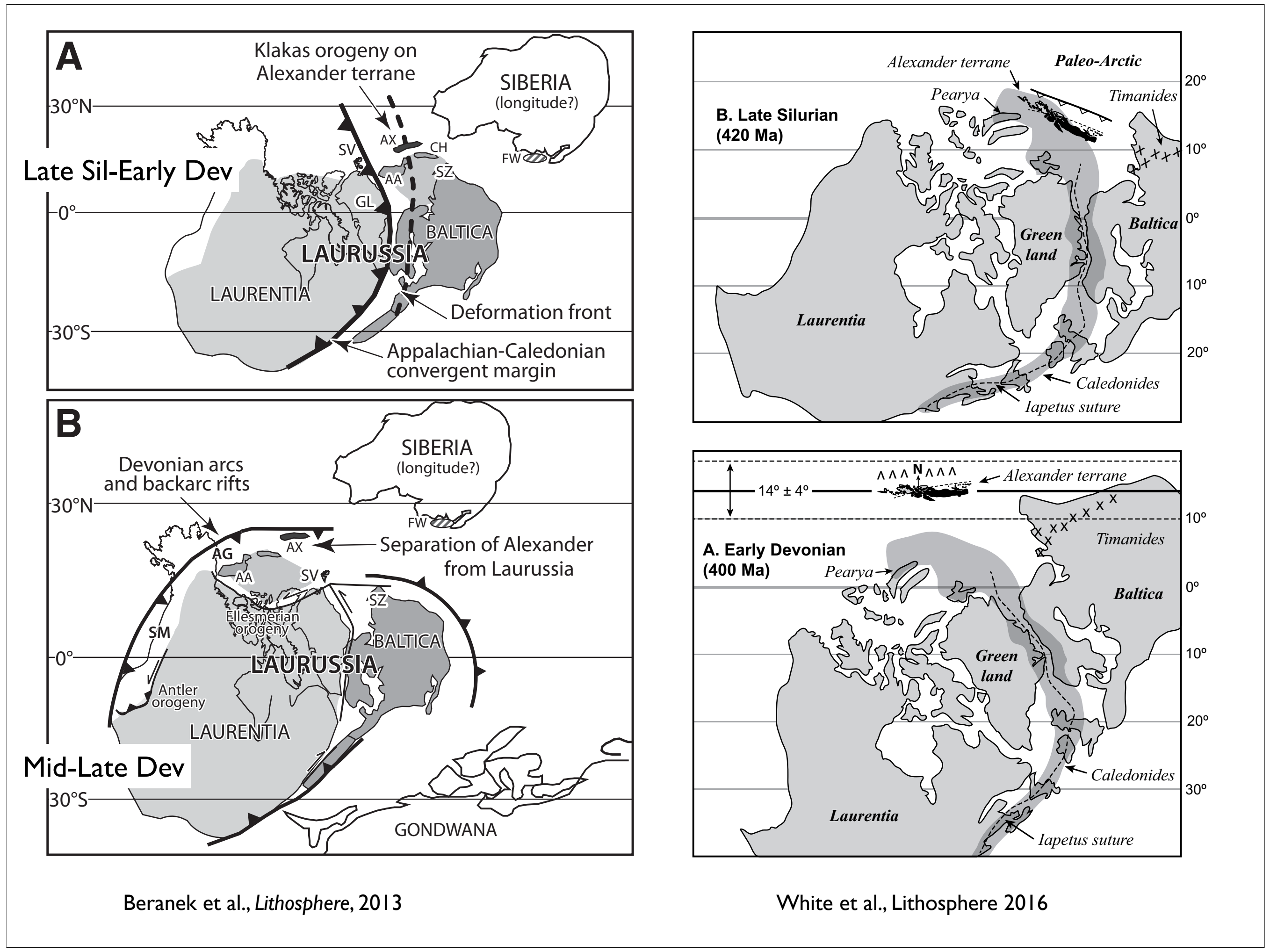
Yes, it does.



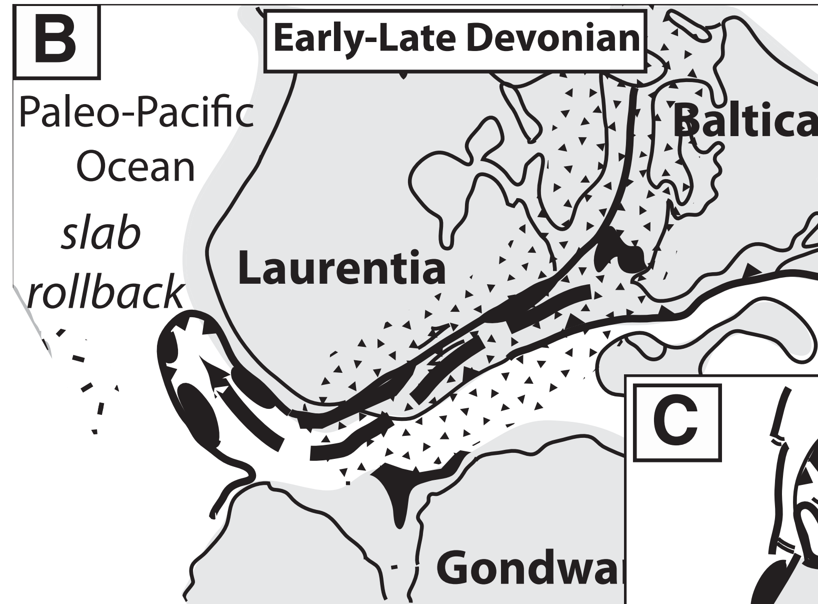
Can start to see when departed. Argue that the big change in epsilon Hf from lower Dev to Mid Dev is departure from scandinavian margin and creation of arc--think this agrees well with Scandinavia [unfortunately this pub lacks a good comparison figure]. Ice field is in St. Elias area.



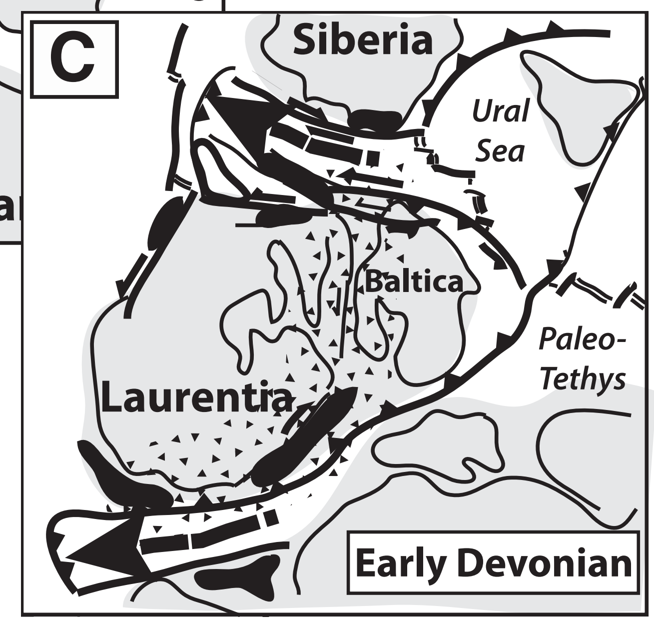
Argue that the big change in epsilon Hf from lower Dev to Mid Dev is departure from scandinavian margin and creation of arc--think this agrees well with Scandanavia [unfortunately this pub lacks a good comparison figure]



Argue that the big change in epsilon Hf from lower Dev to Mid Dev is departure from scandinavian margin and creation of arc--think this agrees well with Scandanavia [unfortunately this pub lacks a good comparison figure]

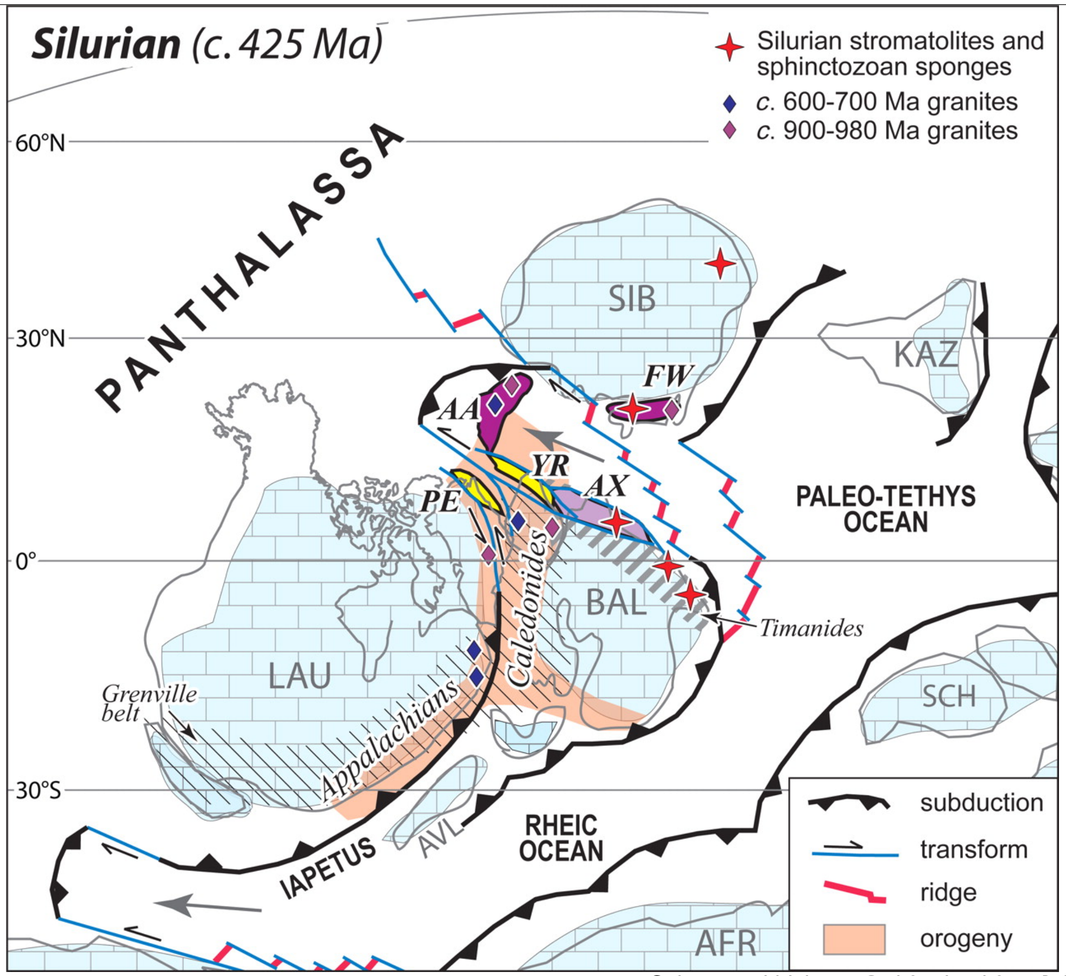


after Colpron and Nelson,
Geol Soc Lond Spec Pub 318,
2009

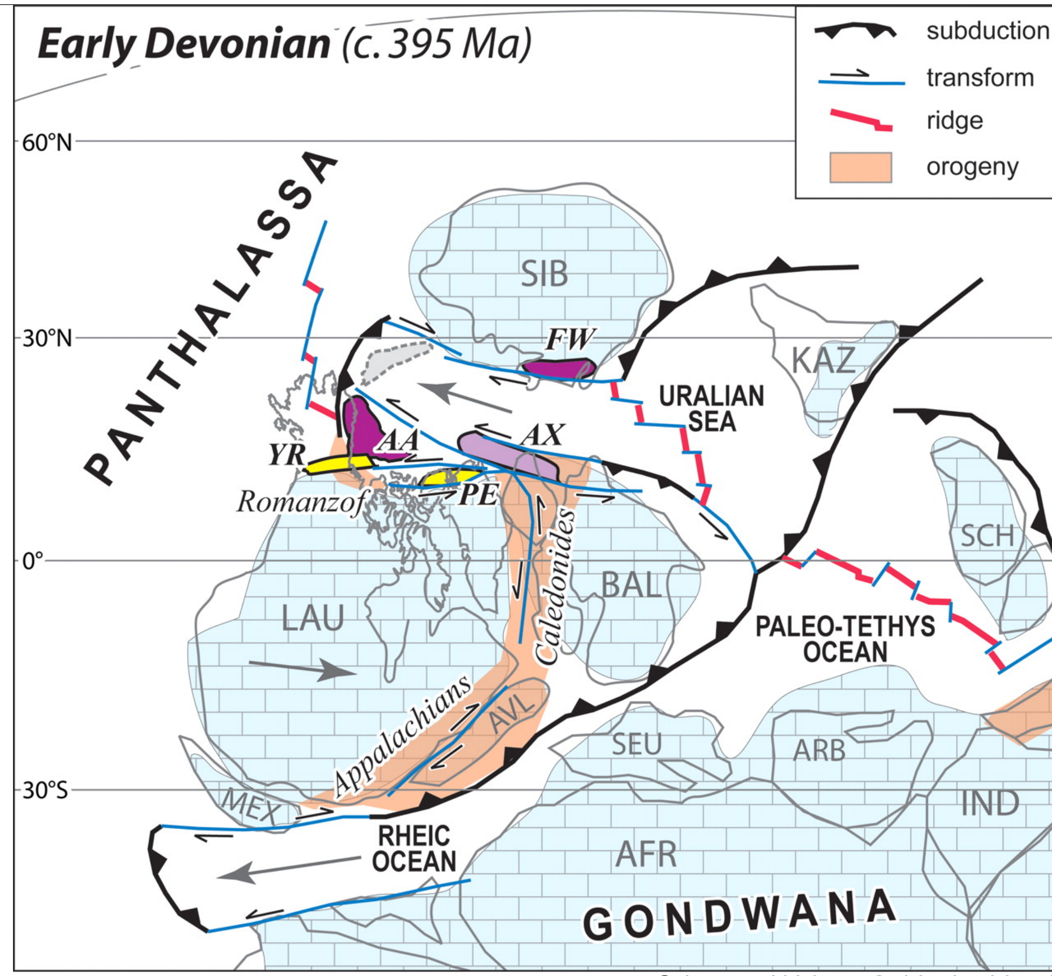


after Wright & Wyld, 2006 GSC SP 45

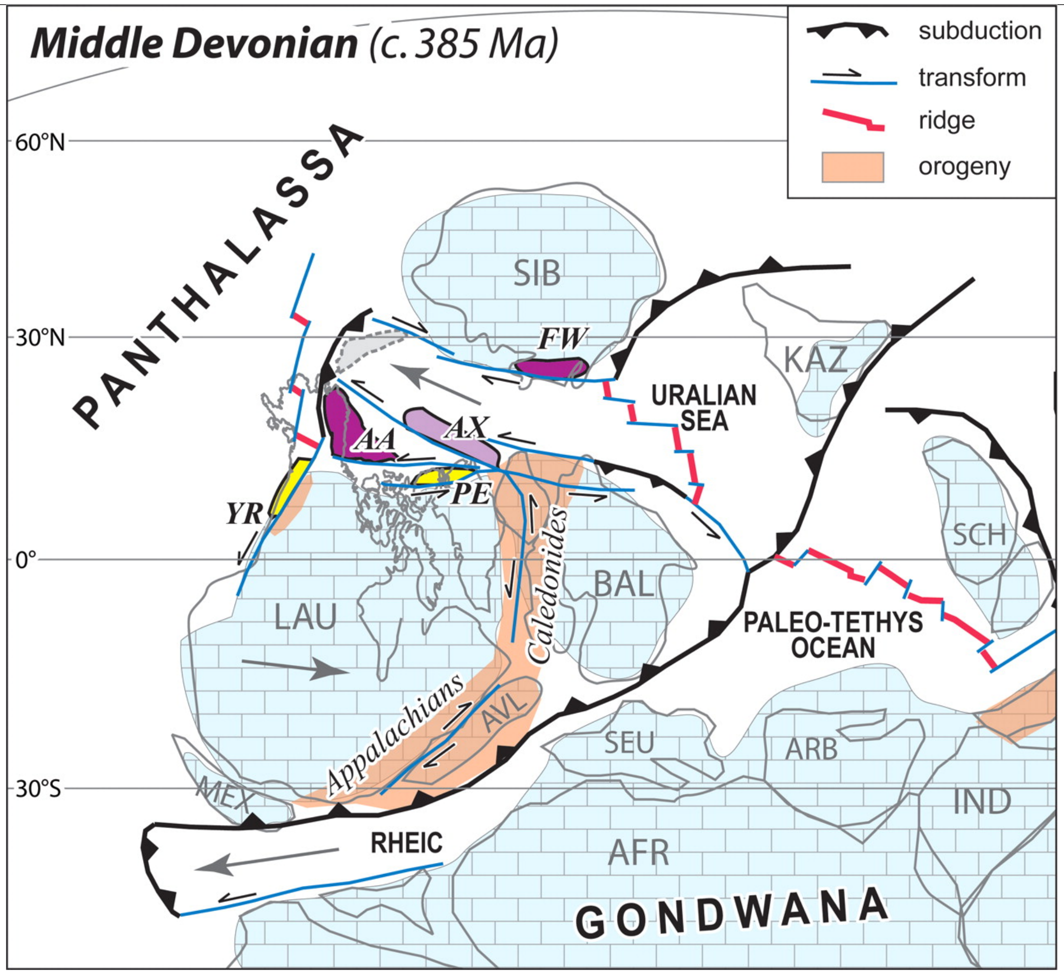
Miller et al., *Geology*, 2011



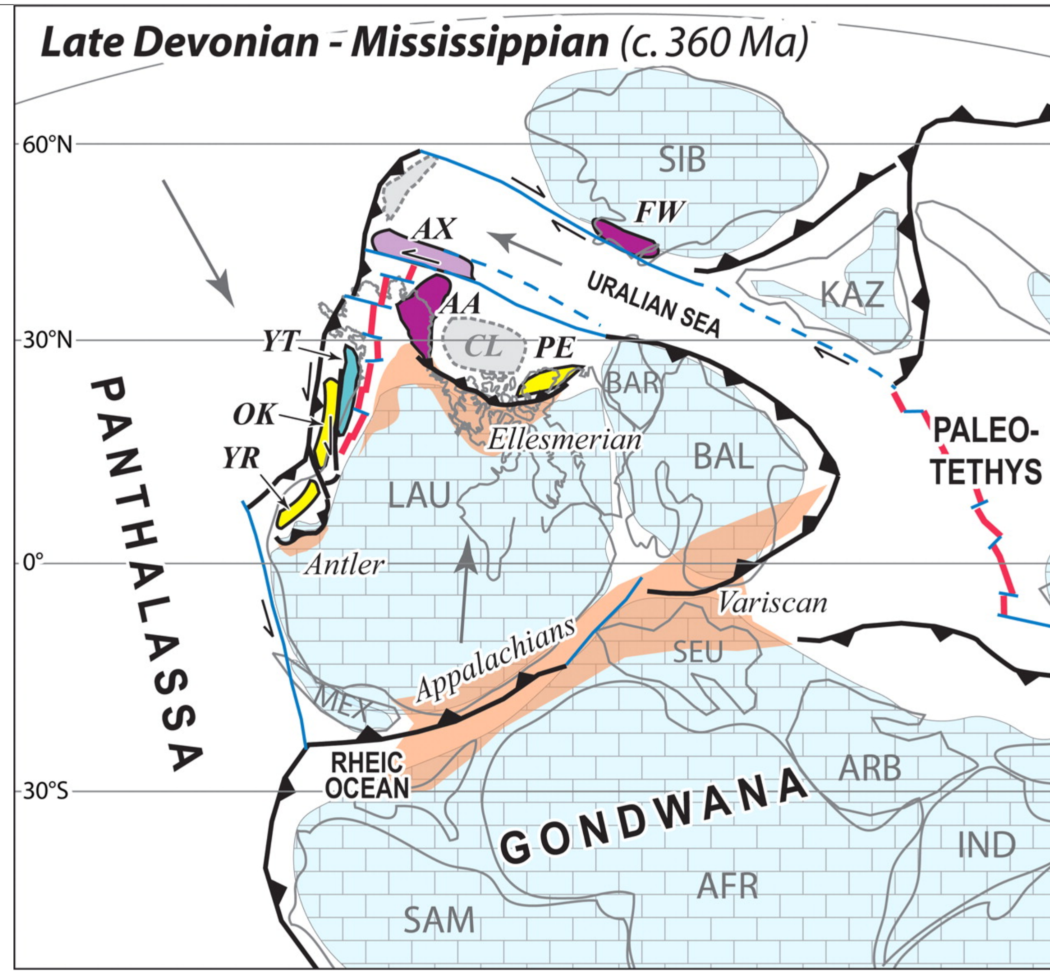
Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009



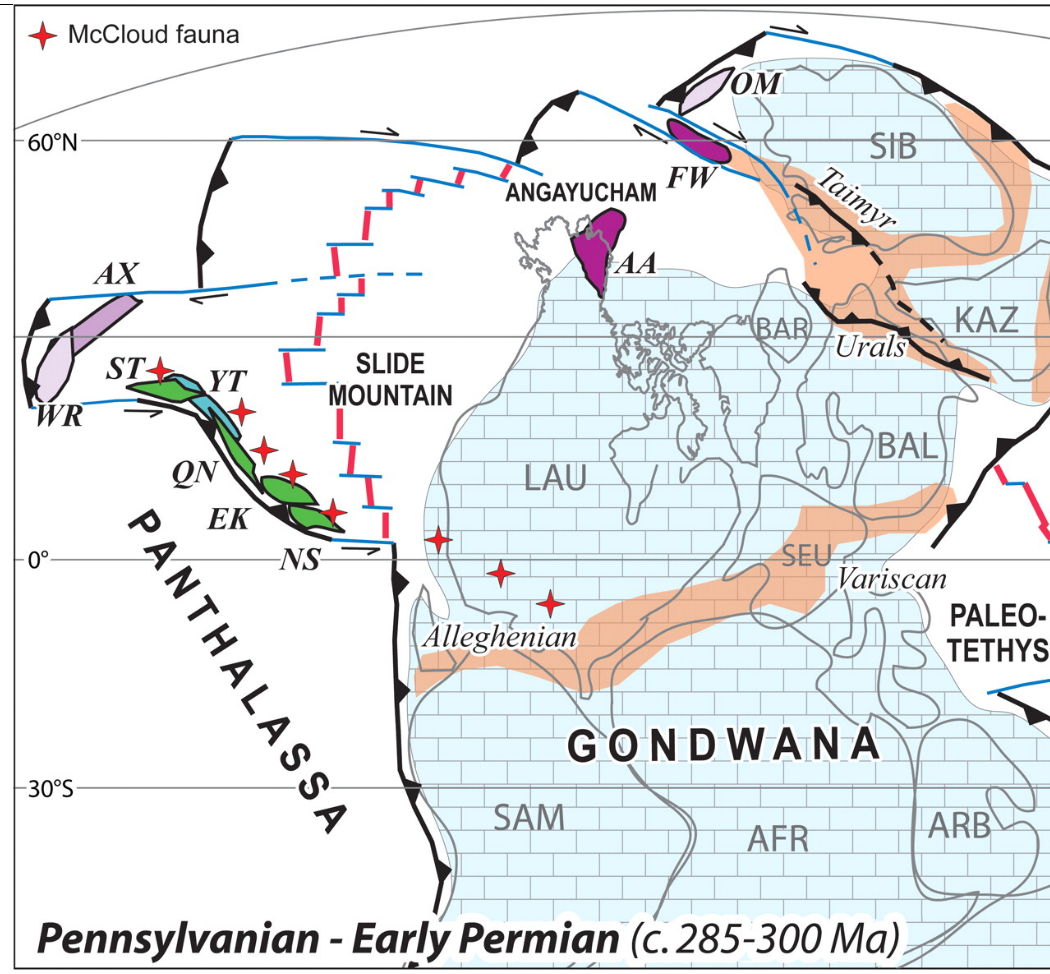
Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009



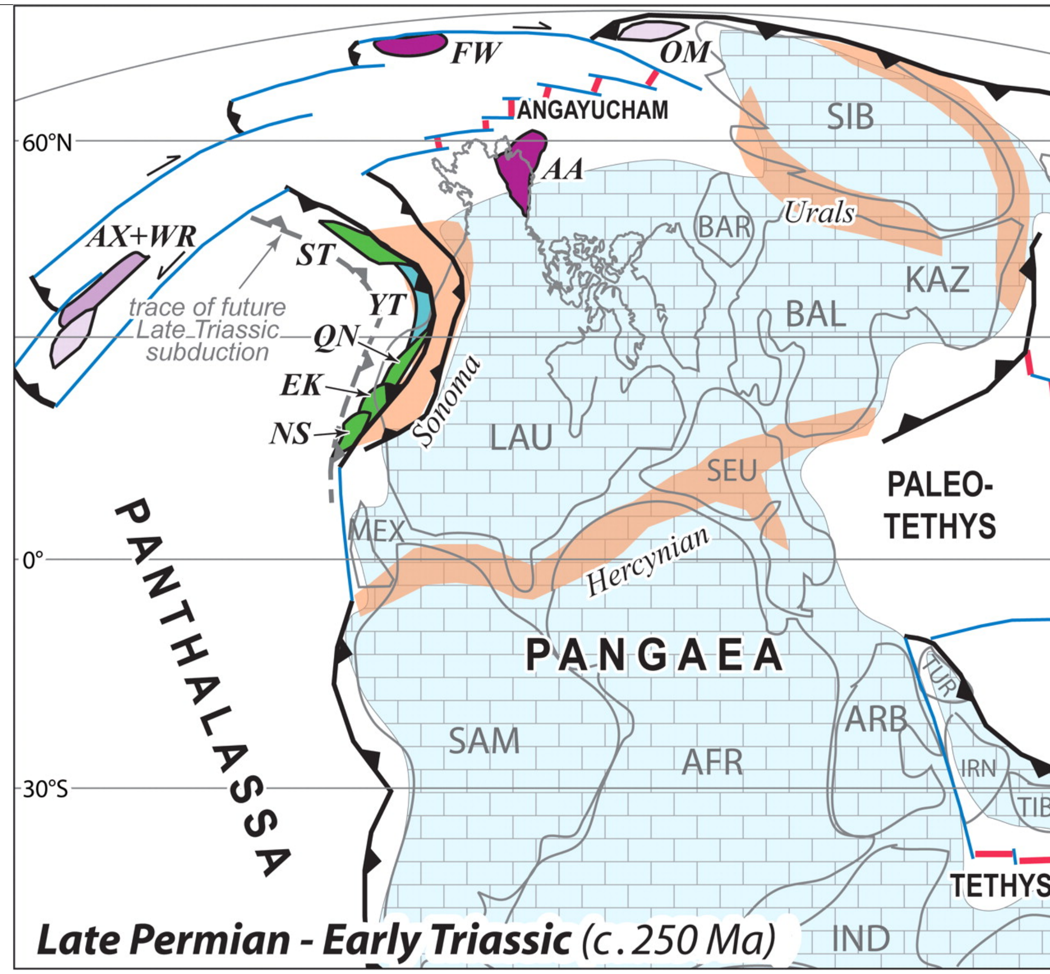
Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009



Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009

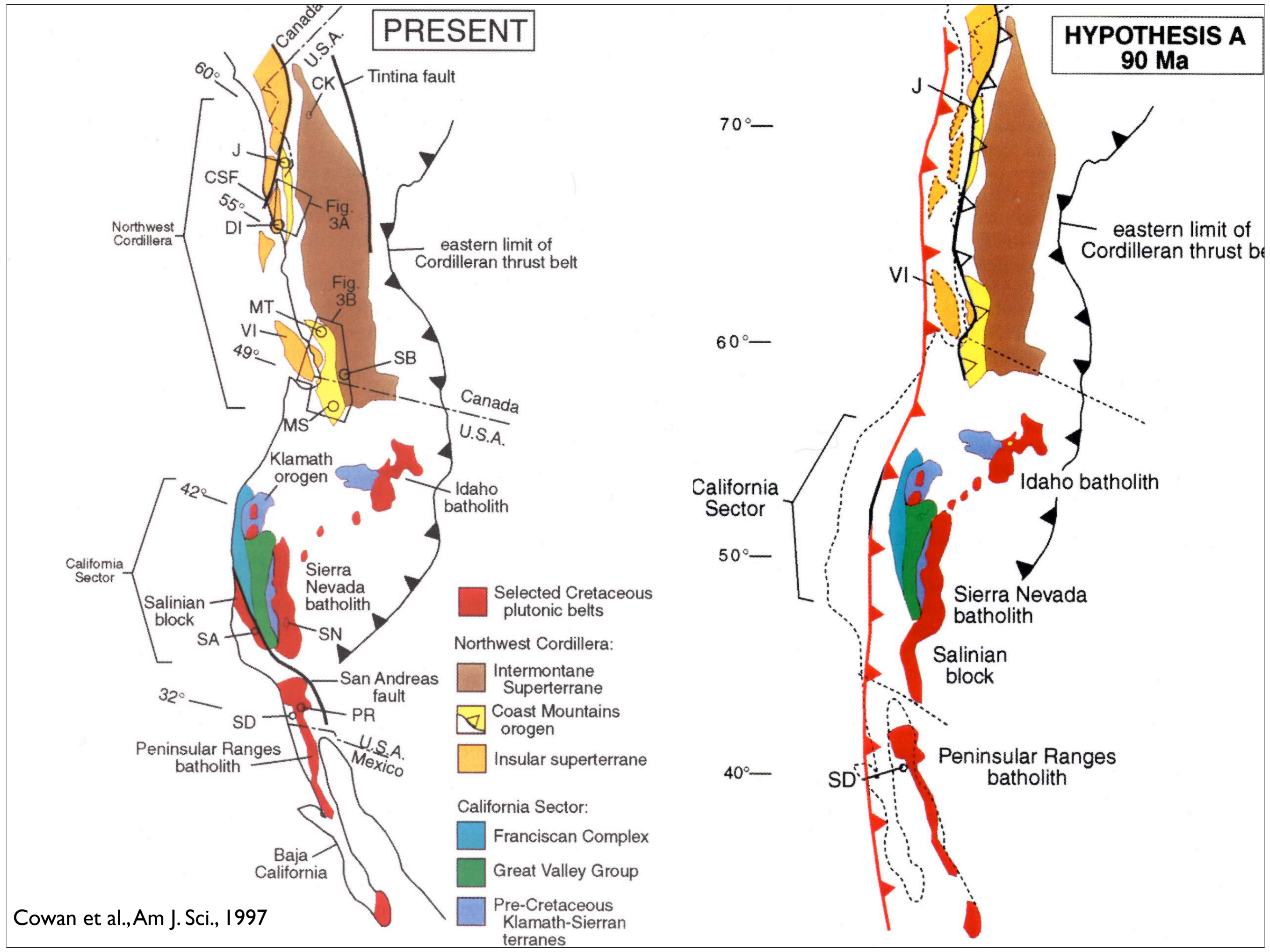


Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009

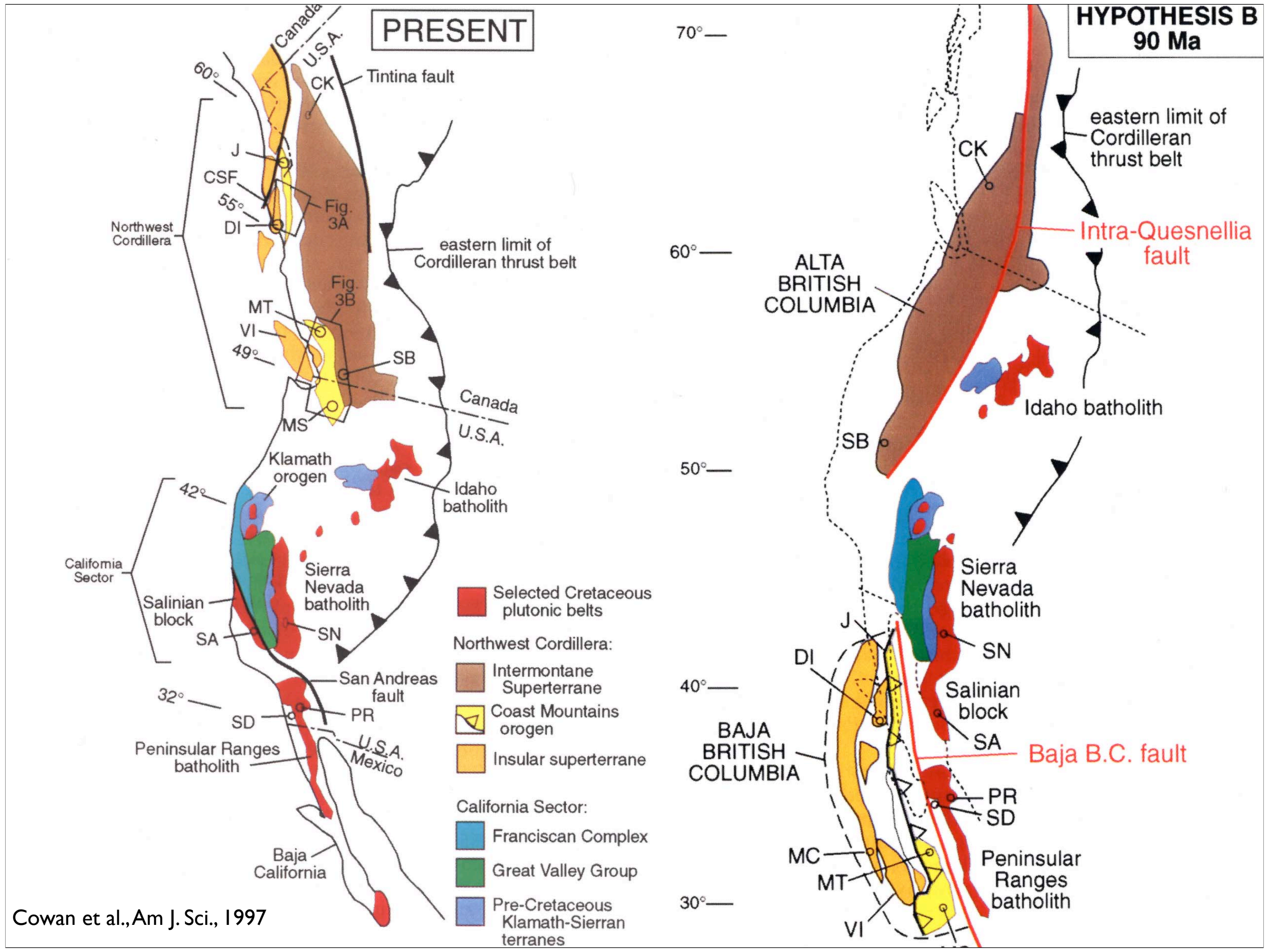


Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009

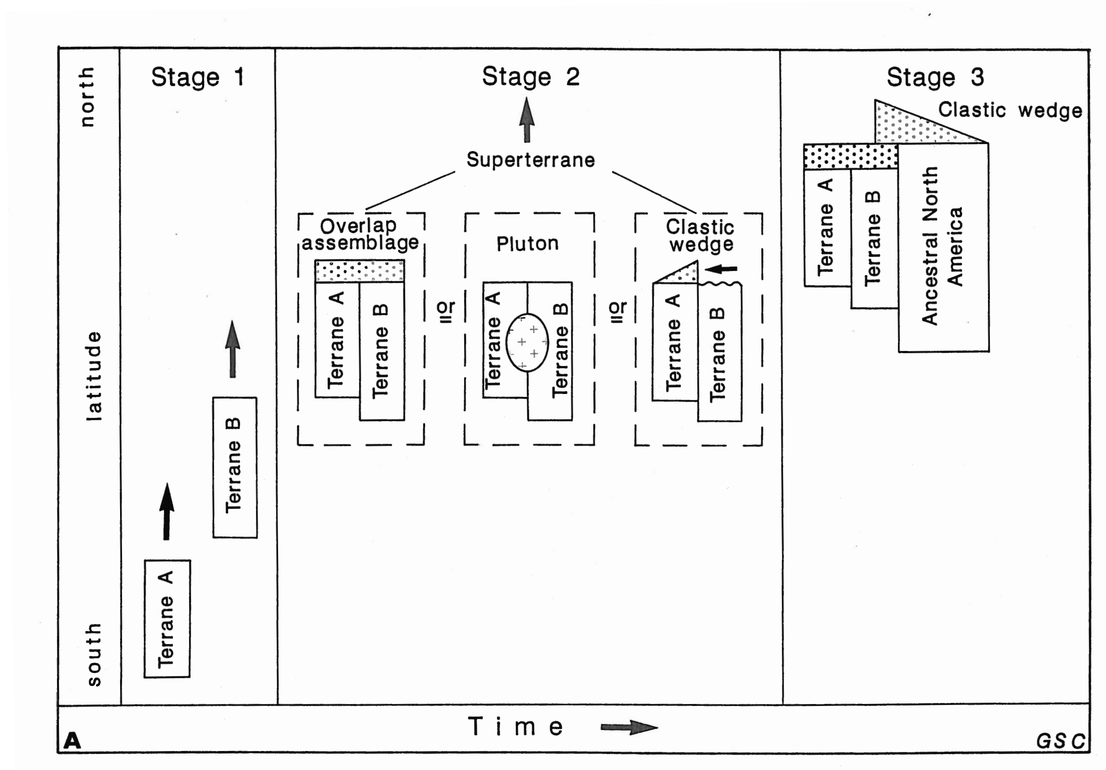
While that covers where a terrane might have come from, the next question is, when did it arrive?



Cowan et al., Am J. Sci., 1997

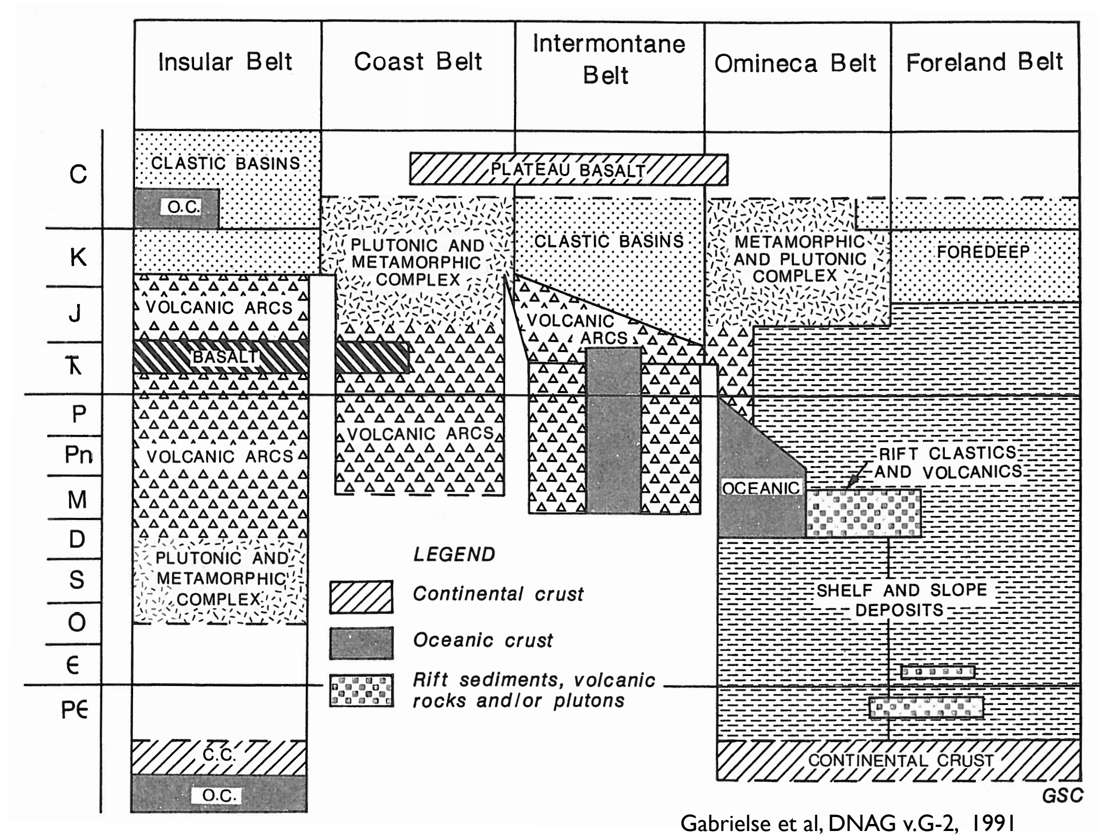


Cowan et al., Am J. Sci., 1997

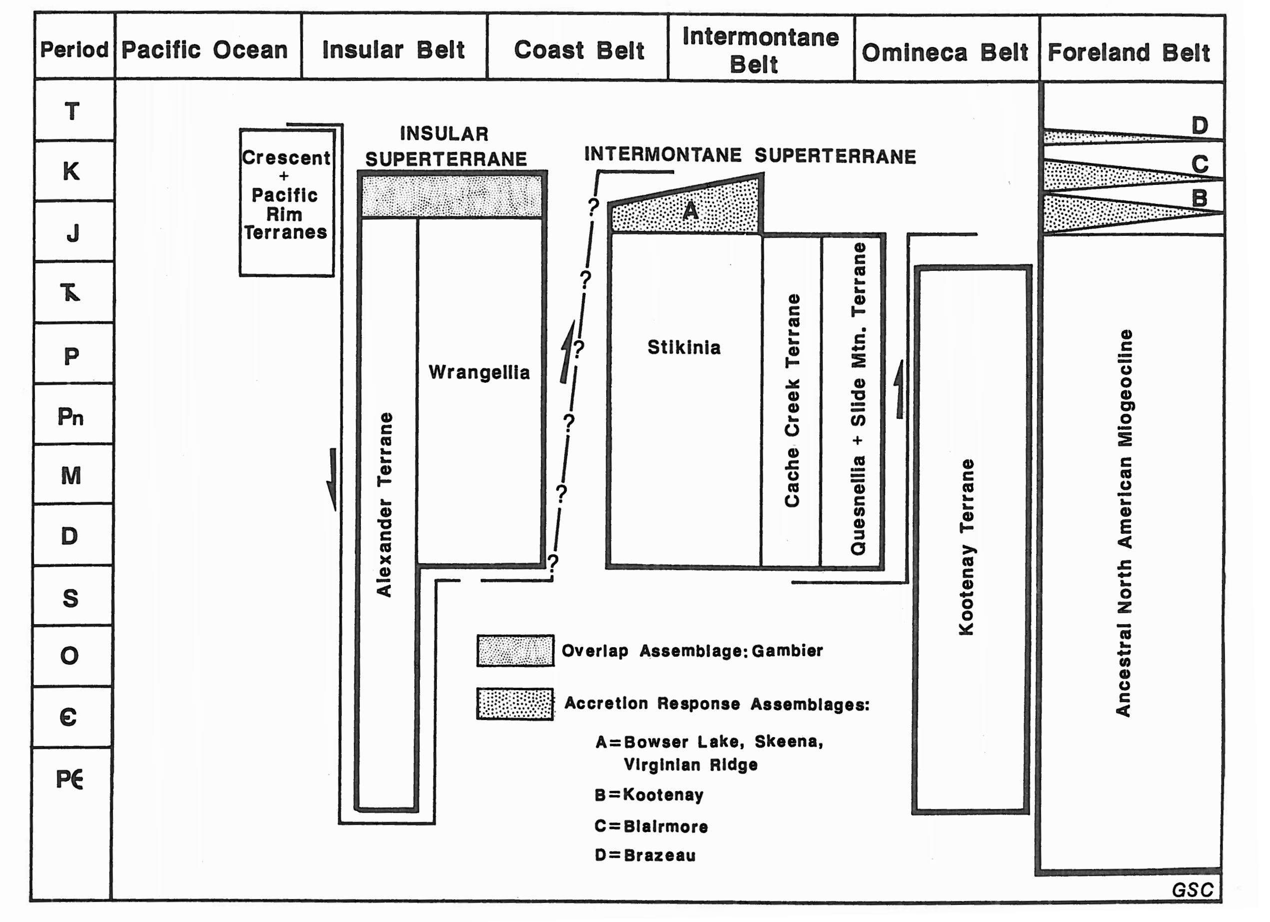


Gabrielse et al, DNAG v.G-2, 1991

OK, when did stuff arrive? Here is where controversy arises. Overlap or stitching plutons usually what is used...

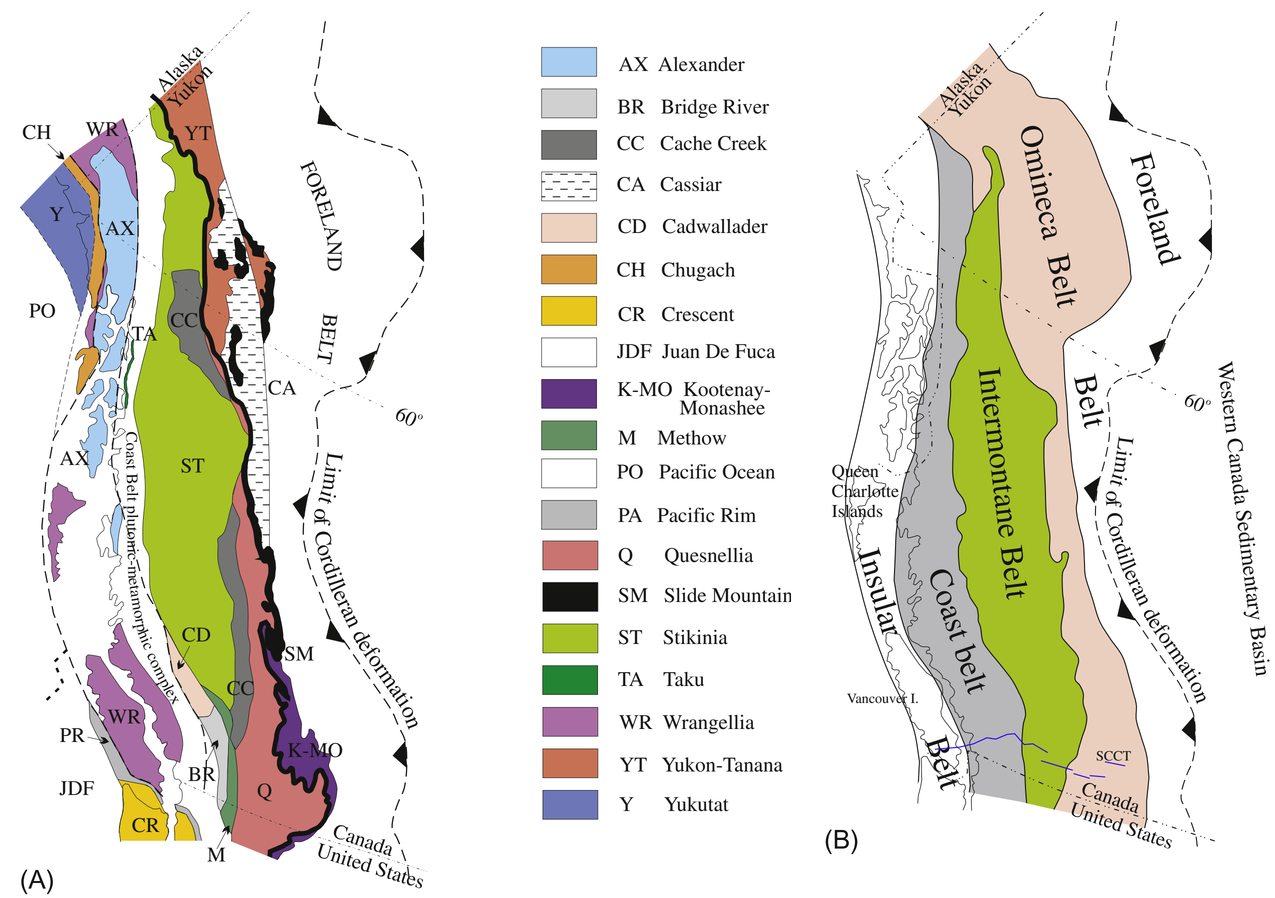


By geologic measures, might think Intermontane terrane docked in J and Insular (Alex + Wrang) in early K.

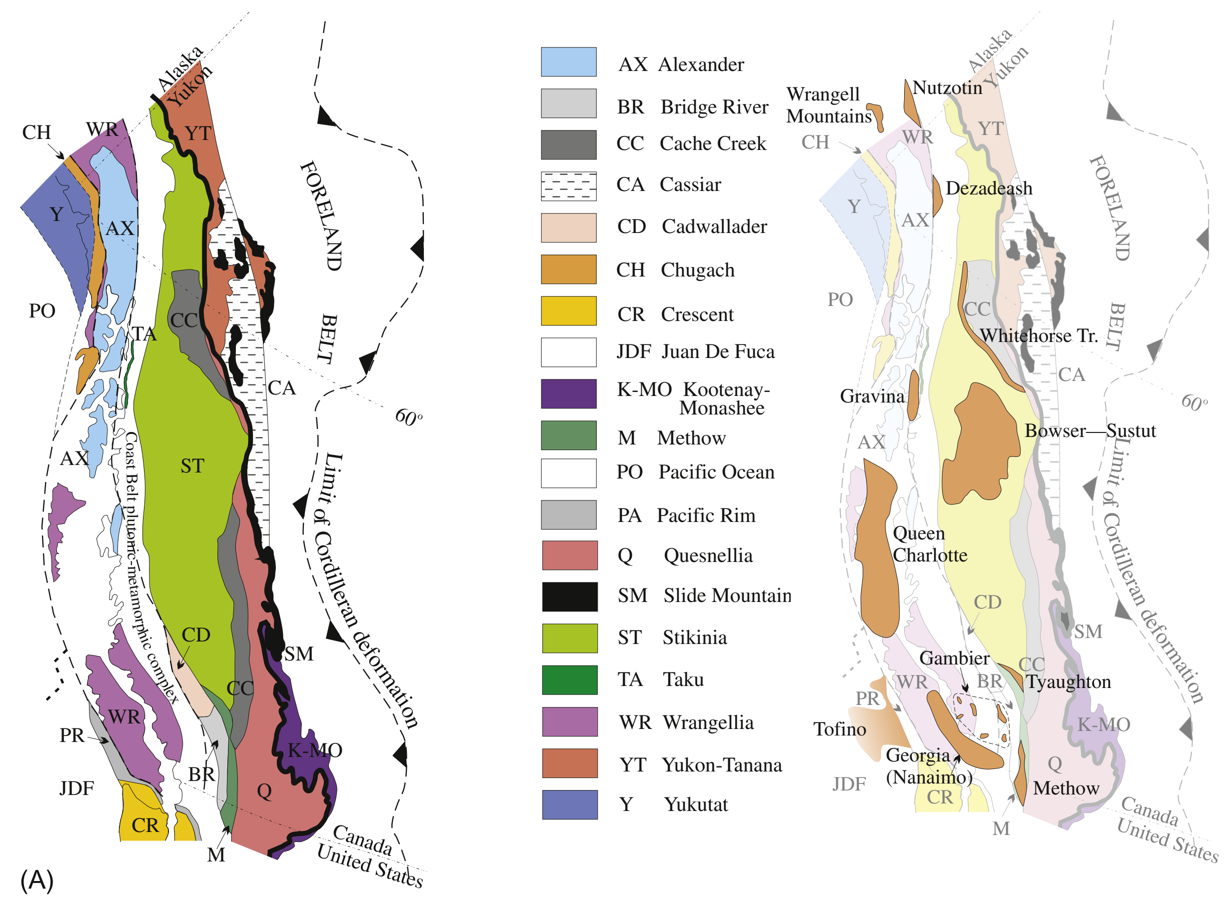


Gabrielse et al, DNAG v.G-2, 1991

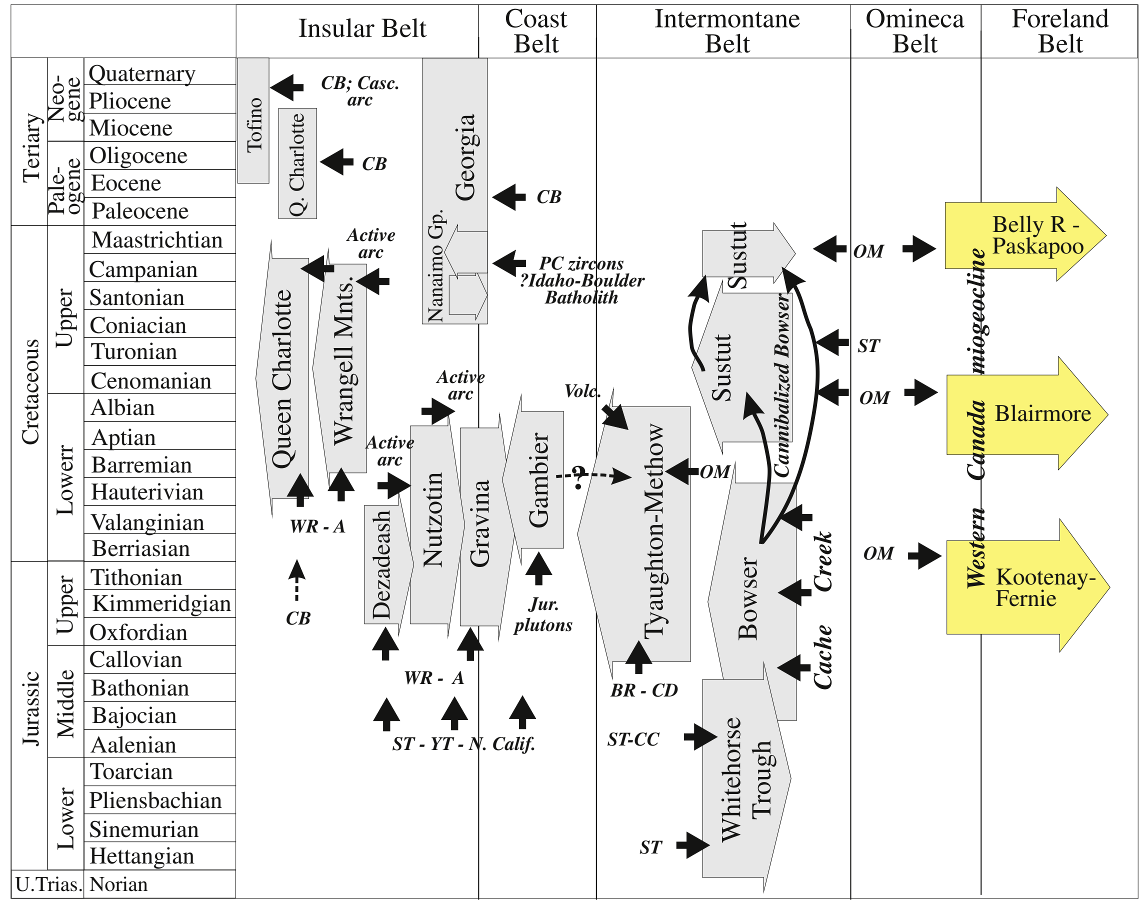
...and this is the cartoon interpretation.



Ricketts, in *Sed Basins US & Canada*, 2019

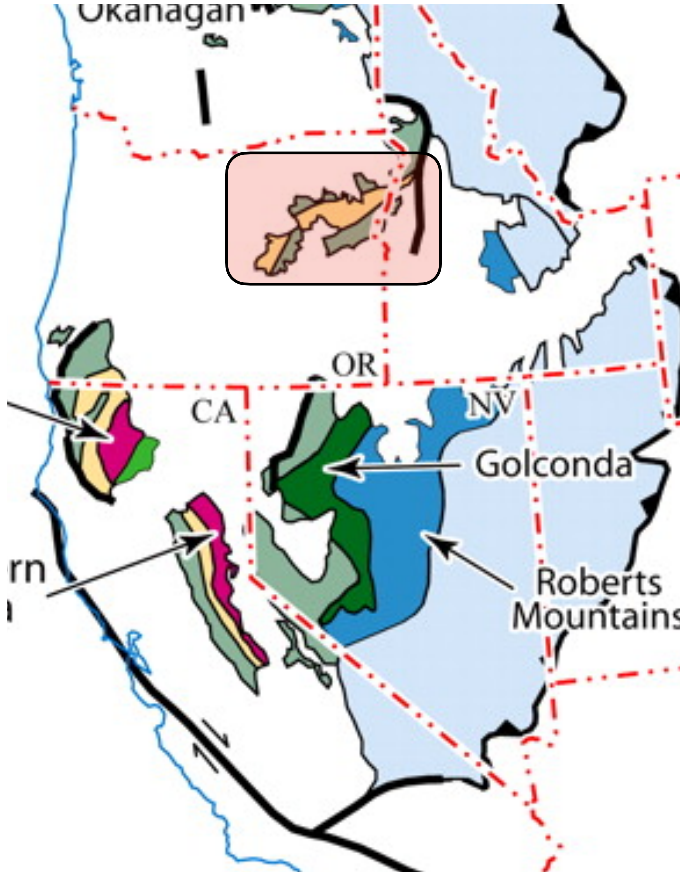


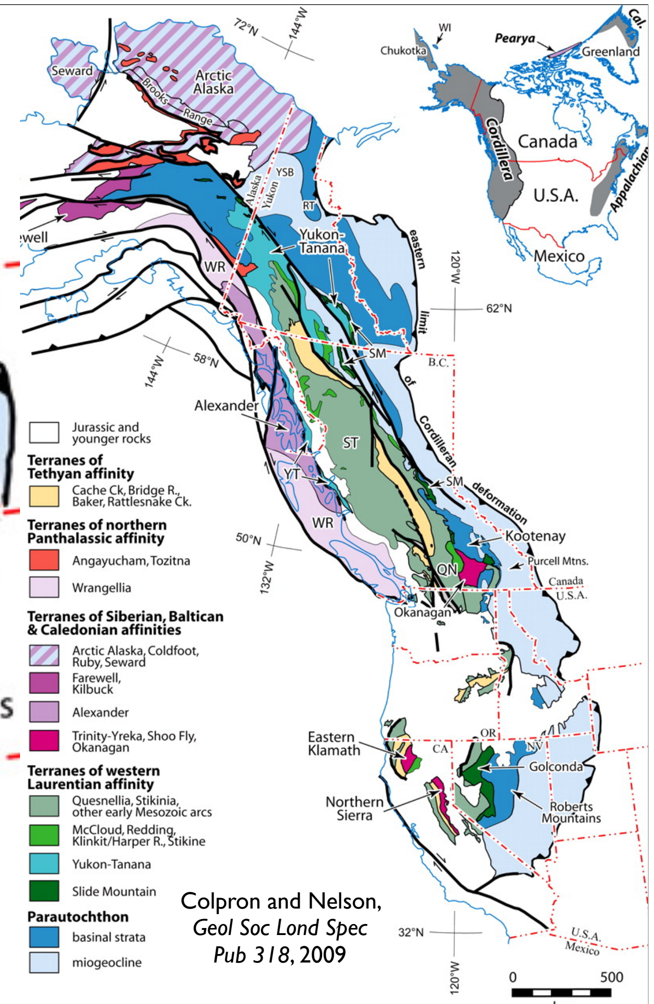
Ricketts, in *Sed Basins US & Canada*, 2019



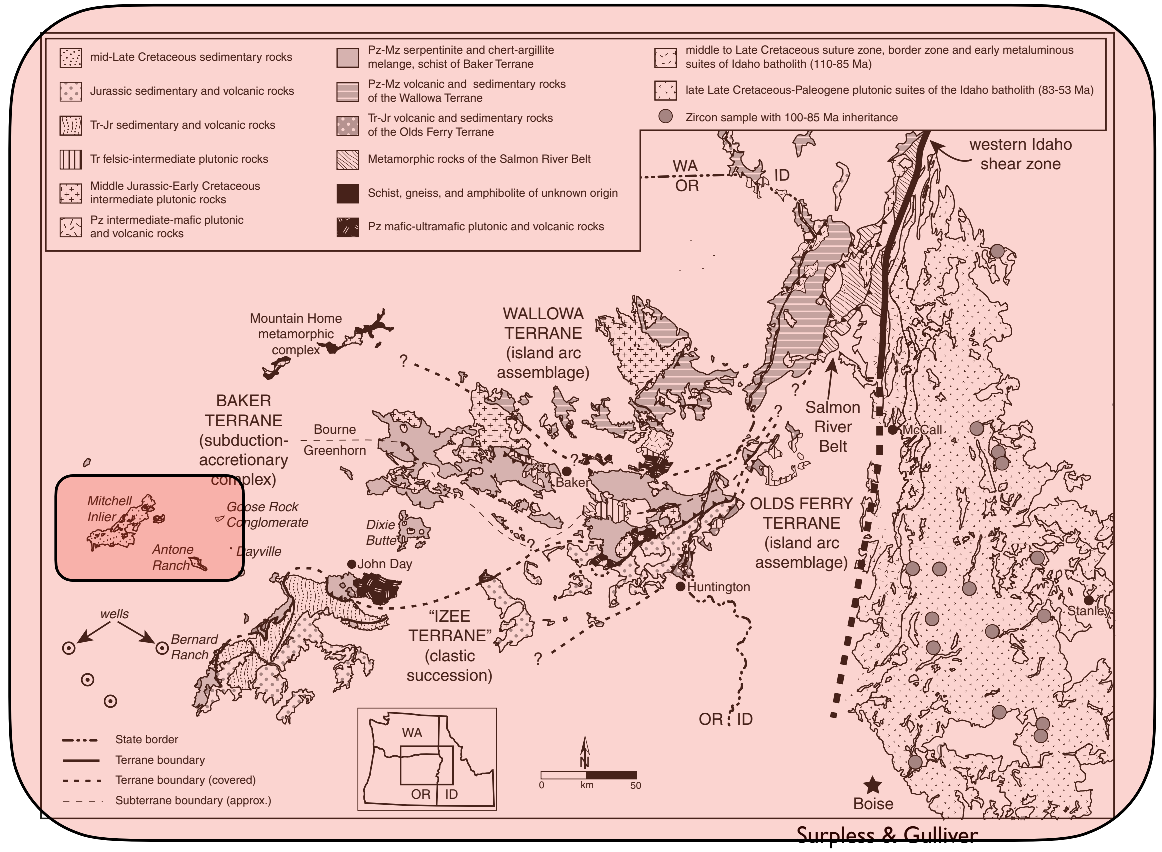
Ricketts, in *Sed Basins US & Canada*, 2019

A summary of the main provenance characteristics for each sedimentary basin (see text of relevant basins for sources of information). Black arrows indicate the generalized polarity of sediment supply into the basins. Additional abbreviations are CB, Coast belt; Casc. Arc, Cascade arc; Volc., volcanic source; N. Calif., northern California; OM, Omineca belt. Yellow arrows differentiate (generalized) Foreland Basin sediment flux. Large arrows indicate the generalized polarity of sediment flux into the basins.

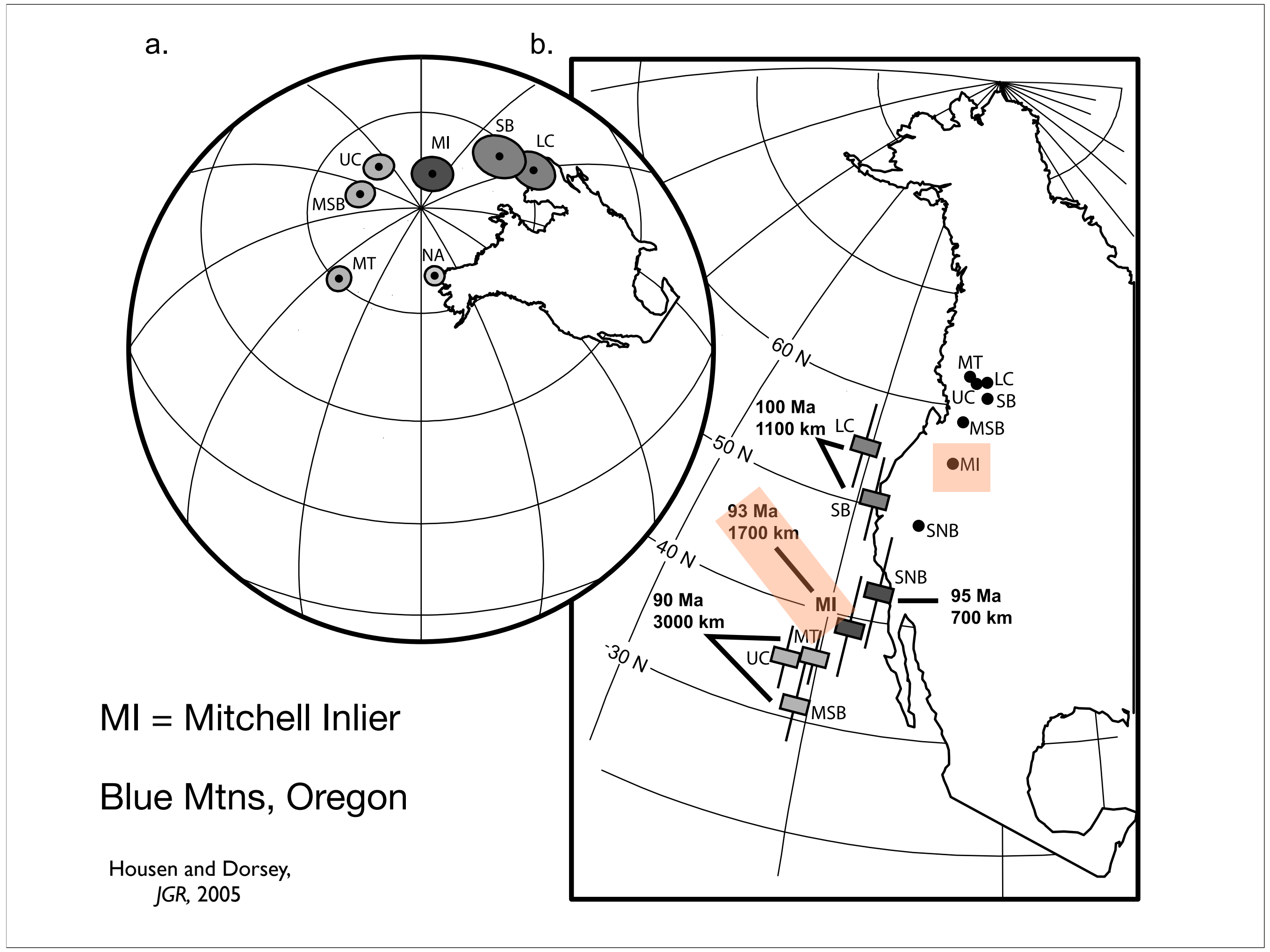




Colpron and Nelson, *Geol Soc Lond Spec Pub 318*, 2009

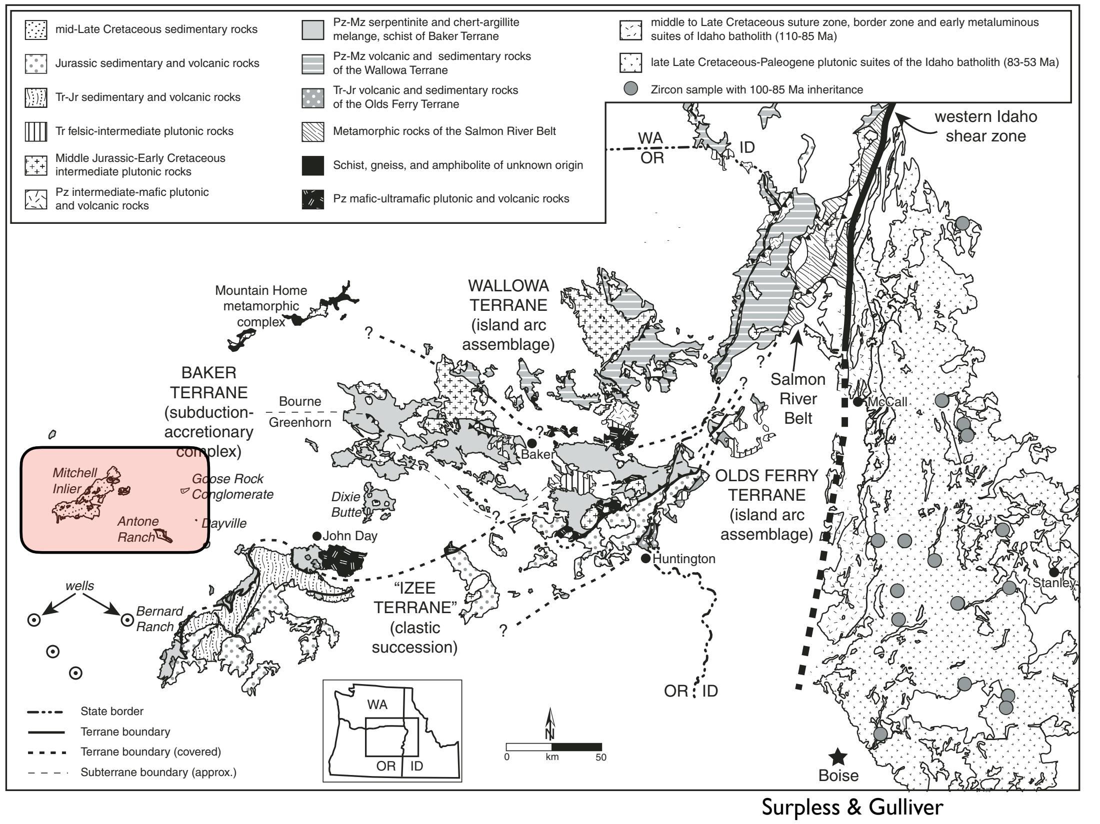


Surpless & Gulliver
GSA SP 540, 2018

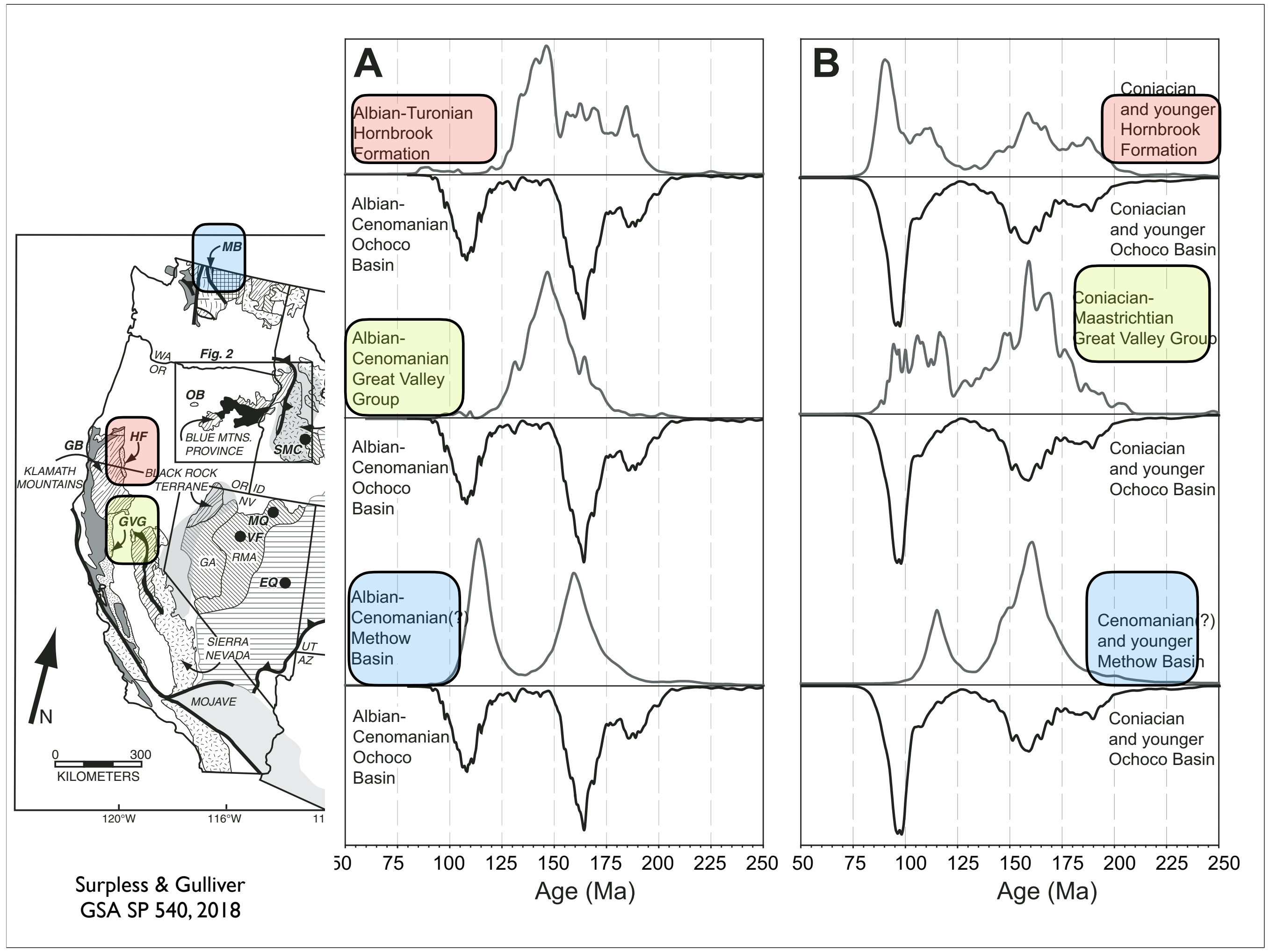


Based on some pretty ugly paleomag, find that Blue Mtns probably was south of Sierra Nevada and 1700 km south of present location. Infer this was part of Intermontane super terrain.

(a) Paleomagnetic poles calculated for tilt-corrected results from this study (MI pole). Also plotted are the mid-Cretaceous NA reference pole [Housen et al., 2003], poles for units in the Insular superterrane with high-quality results (MT, Mount Tatlow [Wynne et al., 1995]; UC, upper Churn Creek [Enkin et al., 2003]; MSB, Mount Stuart batholith [Housen et al., 2003]) and poles from units in the Intermontane superterrane with high-quality results (SB, Spences Bridge [Irving et al., 1995]; LC, lower Churn Creek [Haskin et al., 2003]). (b) Paleogeographic map showing position of North America, reconstructed using the Housen et al. [2003] NA pole. Paleolatitudes, with 95% confidence bars, for the paleomagnetic results in Figure 18a and the paleolatitude of the Sierra Nevada (SNB) [Frei et al., 1984; Frei, 1986] are shown. The ages of magnetization for each set of results and the post-Cretaceous amounts of northward translation are also given. The labeled dots denote the study locality for each paleomagnetic result.

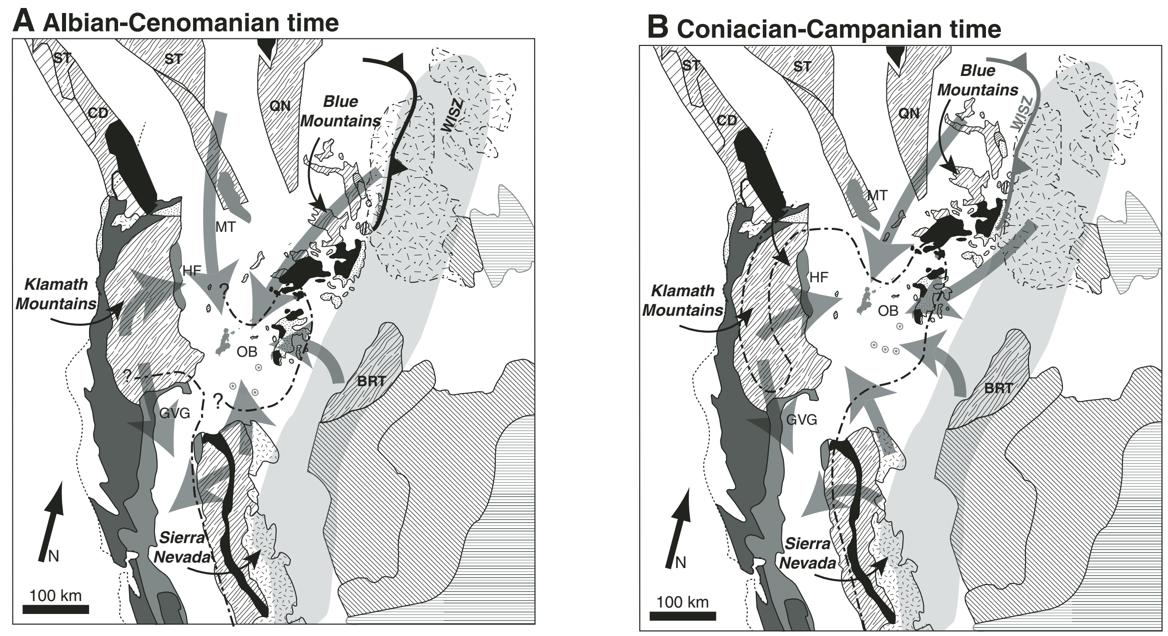


Surpless & Gulliver
GSA SP 540, 2018



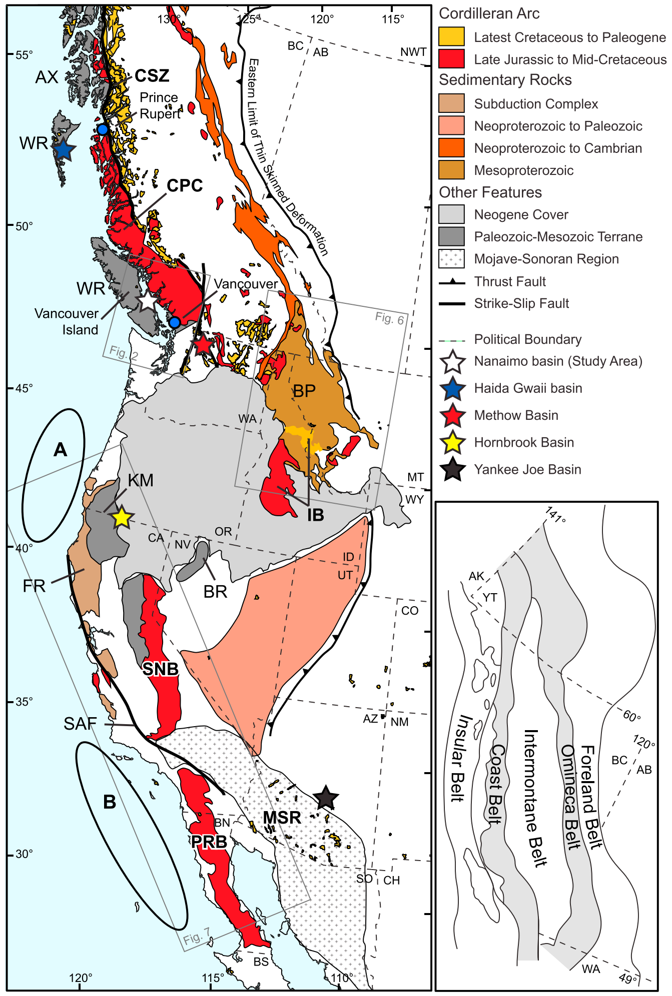
Surpless & Gulliver
GSA SP 540, 2018

Would be nice to have compared with something from Mojave latitude, given some other suggested relationships.



Surpless & Gulliver
GSA SP 540, 2018

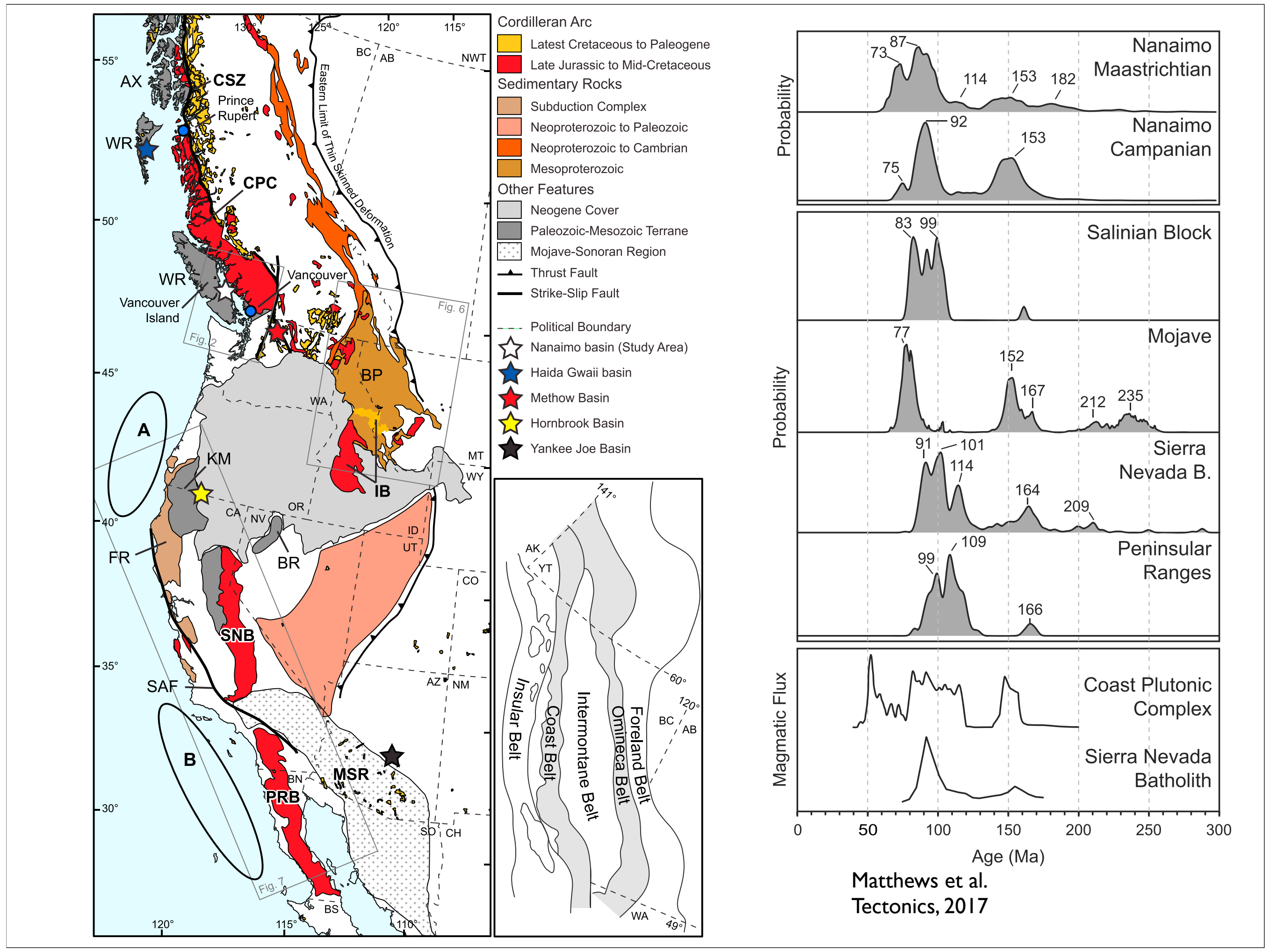
Surpless and Gulliver clearly prefer this basin to link Idaho batholith and Klamath Mtns, limiting N-S translation.



Another example of using detrital zircons…

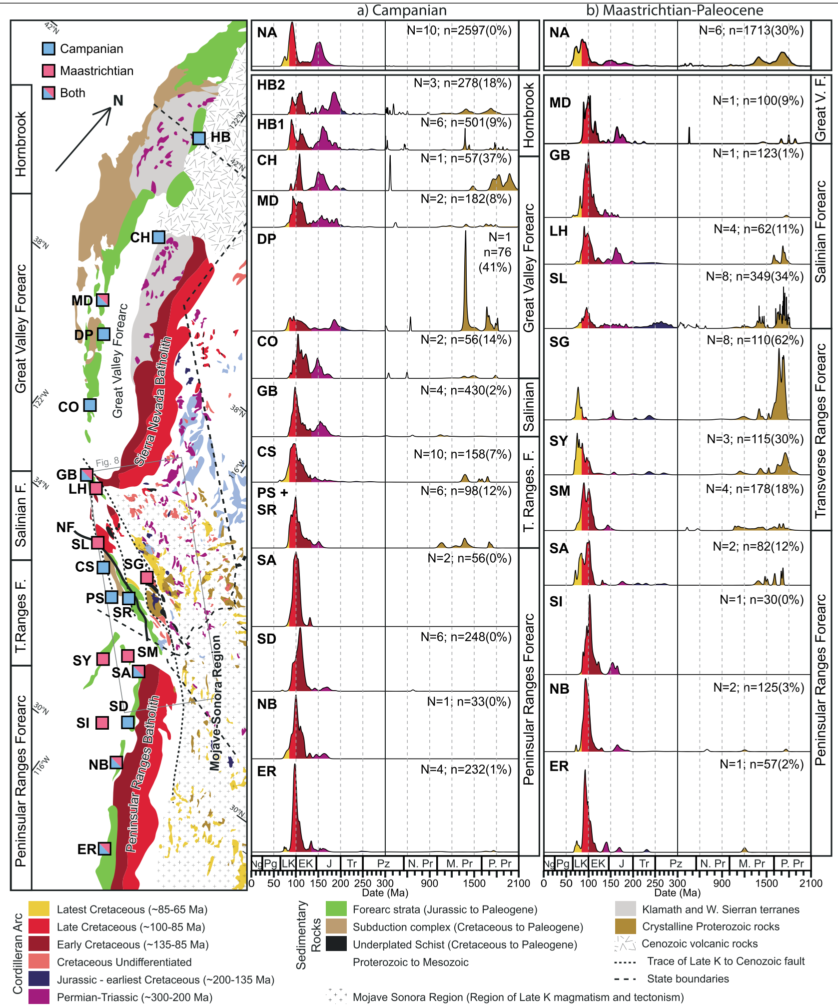
This time Nanaimo basin (Wrangellia proper)

Matthews et al.
Tectonics, 2017



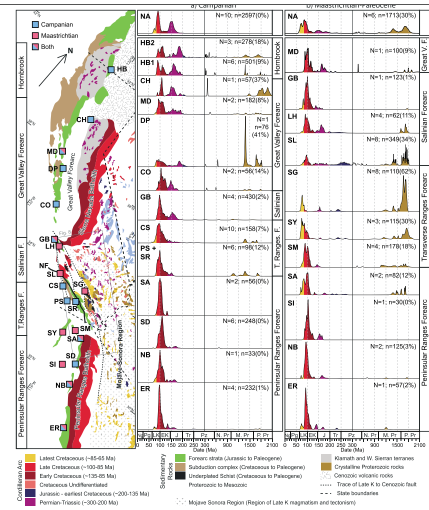
Which matters most—presence of peak or height? And note that heights are of the age distributions of the arcs, not comparing to other sedimentary rocks. Note too lack of comparison to So Canada rocks.

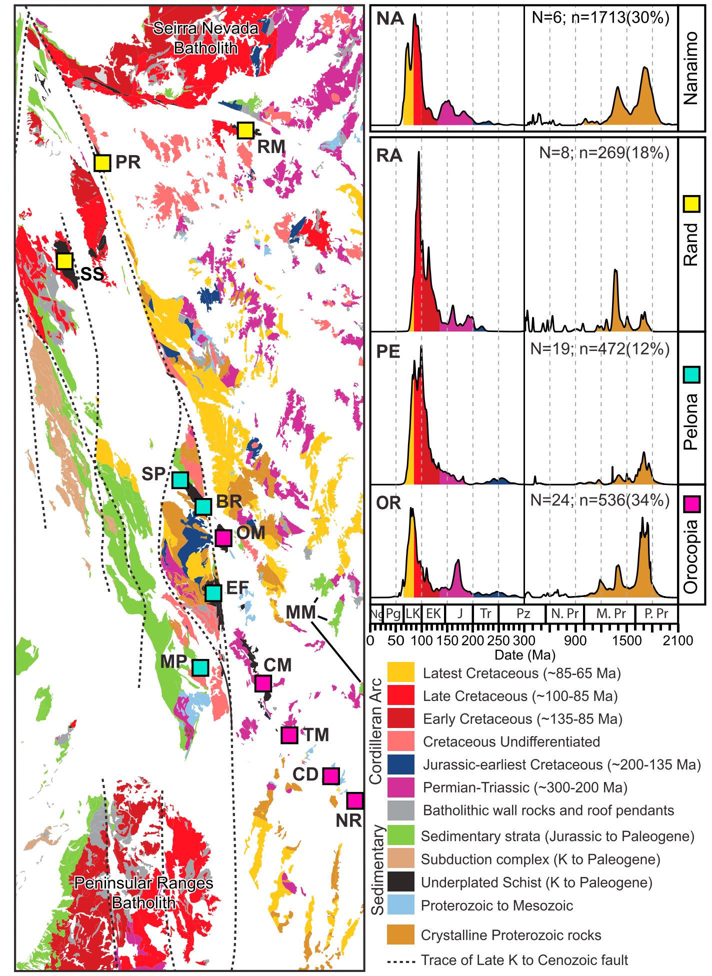
Normalized probability density functions for the Campanian and Maastrichtian formations of the Nanaimo basin and Zircon U-Pb age distributions for the major Mesozoic arcs of western North America (modified after Sharman et al. [2014]); data from Premo et al. [1998], Silver and Chappell [1988], Grove et al. [2008], Chapman et al. [2012], Barth et al. [2013], Kimbrough et al. [2015]; also shown are magmatic flux curves for the CPC west of the CSZ near Prince Rupert [Gehrels et al., 2009] and the Sierra Nevada Batholith [Ducea, 2001].



Here comparison is to other sedimentary deposits

Matthews et al.
Tectonics, 2017





Here comparison is to subducted metasedimentary rocks

Matthews et al.
Tectonics, 2017

FWIW, the text has to go through a lot of arguing to rule out rocks in NW US as source—basically, there are zircons of the right age in there (Lemhi Basin, parts of Idaho batholith) but they argue some other zircons would have shown up as well (esp. Archean).

Normalized PDFs for the Nanaimo basin Maastrichtian formations (NA) are compared to composite PDFs of all sample locations from the Pelona (PE), Orocopia (OR), and Rand (RA) schists, grouped according to Jacobson et al. [2011]; sample locations included in each PDF are indicated by colored square; palinspastically restored map of the Late Cretaceous Mojave region [after Sharman et al., 2014; Jacobson et al., 2011]; N is the number of samples; n is the number of measurements; curves >300 Ma are displayed at 10 times the scale; note the horizontal scale change at 300 Ma; for the Nanaimo basin data 206Pb/238U dates are used <1200 Ma, 207Pb/206Pb dates >1200 Ma; curve fills correspond to colors in legend and highlight major arc magmatic phases; see appendix F in the supporting information for details of sample groupings and data sources; MM denotes outcrops of the McCoy Mountains Formation; abbreviations for sample locations as follows; RM—Rand Mountains; PR—Portal Ridge; SS—Sierra de Salinas; SP—Sierra Pelona; BR—Blue Ridge; OM— Orocopia Mountains; EF—East Fork; MP—Mount Pinos; CM—Chocolate Mountains; TM—Trigo Mountains; CD—Castle Dome; NR—Neversweat Ridge.