Structural Inheritance and the Role of Basement Anisotropies in the Laramide Structural and Tectonic Evolution of the North American Cordilleran Foreland, Wyoming - Towards a Unified Hypothesis *

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Abstract

The Laramide belt of the North American Cordillera is a thick-skinned orogen that continues to garner attention due to many unresolved ambiguities, particularly in the subsurface. Recent seismic studies provide a better understanding of Laramide tectonism at deep crustal levels. However, mechanisms for deformation accommodation in the upper crust remain unclear. A structural/tectonic analysis of Precambrian fabrics and structural grain of basement-cored Laramide arches and uplifts in Wyoming using only previously collected data, along with a hypothesis on the potential role of these features in Laramide orogenesis, is presented. This work provides evidence for the presence of Neoarchean convergence zones dominantly directed from SW-NE towards the Wyoming province forming NNW anisotropies. In addition, regional compressional forces from convergence formed WNW- and NE-striking conjugate shears. Precambrian basement fabrics characterize all three directions of major anisotropy and they likely have a complex history of deformation since the Precambrian, most recently during the Laramide orogeny.

This Precambrian deformation system was likely a fundamental tectonic control in Laramide arch/uplift formation in Wyoming. During the Laramide orogeny, reactivation of anisotropies occurred throughout Laramide contraction, forming somewhat symmetrical, but discrete zones of transpression, displaced along a SW-NE-directed Laramide deformational front. Reverse-left oblique-slip faults developed from reactivation of WNW fabrics and, where connected, acted as relay zones facilitating major arch development along NNW-striking faults. Internal controls for Laramide orogenesis in the upper crust are likely related to these basement anisotropies, which may link the evolution of foreland arches at deeper crustal levels to surface structures.

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Towards a Unified Hypothesis

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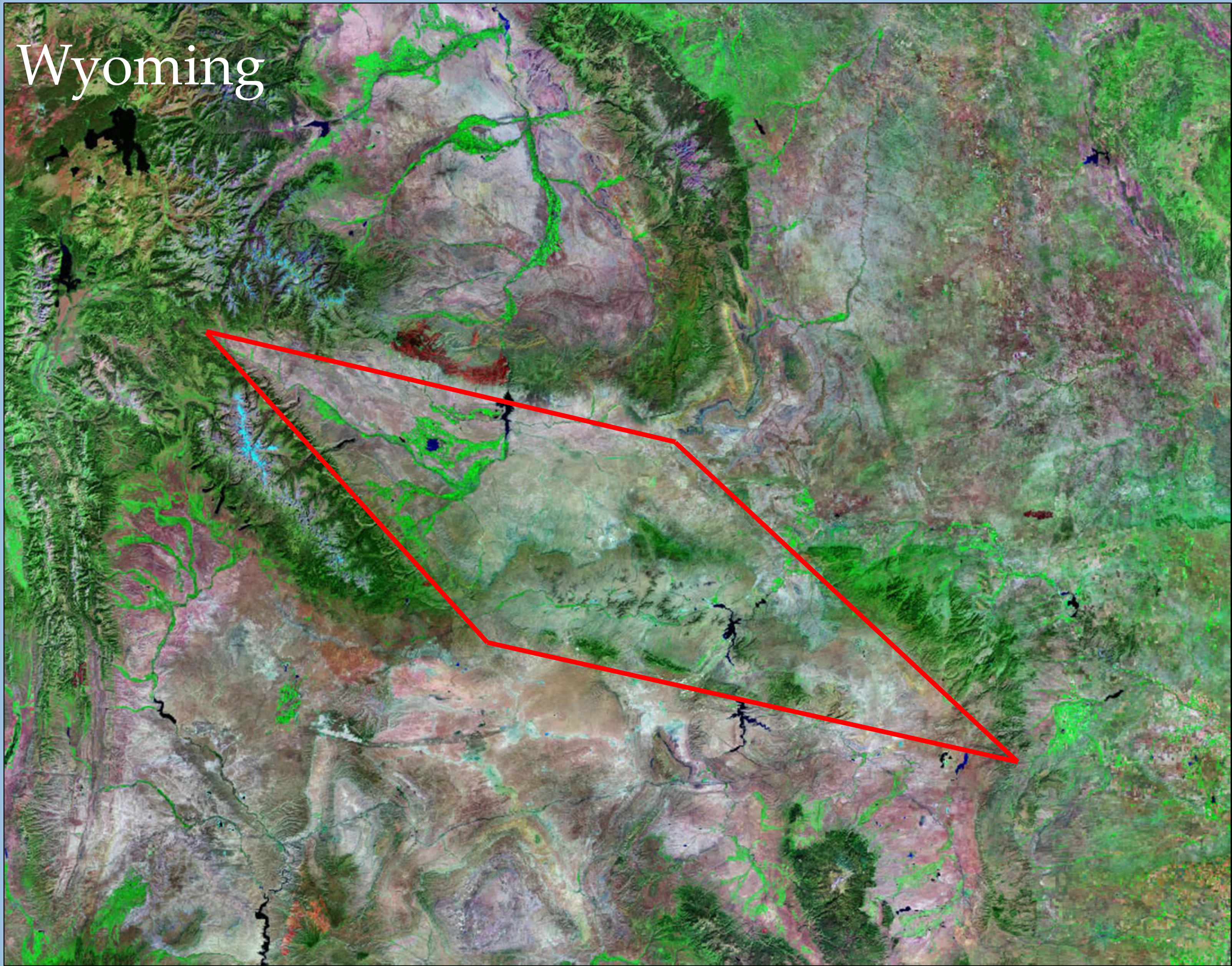
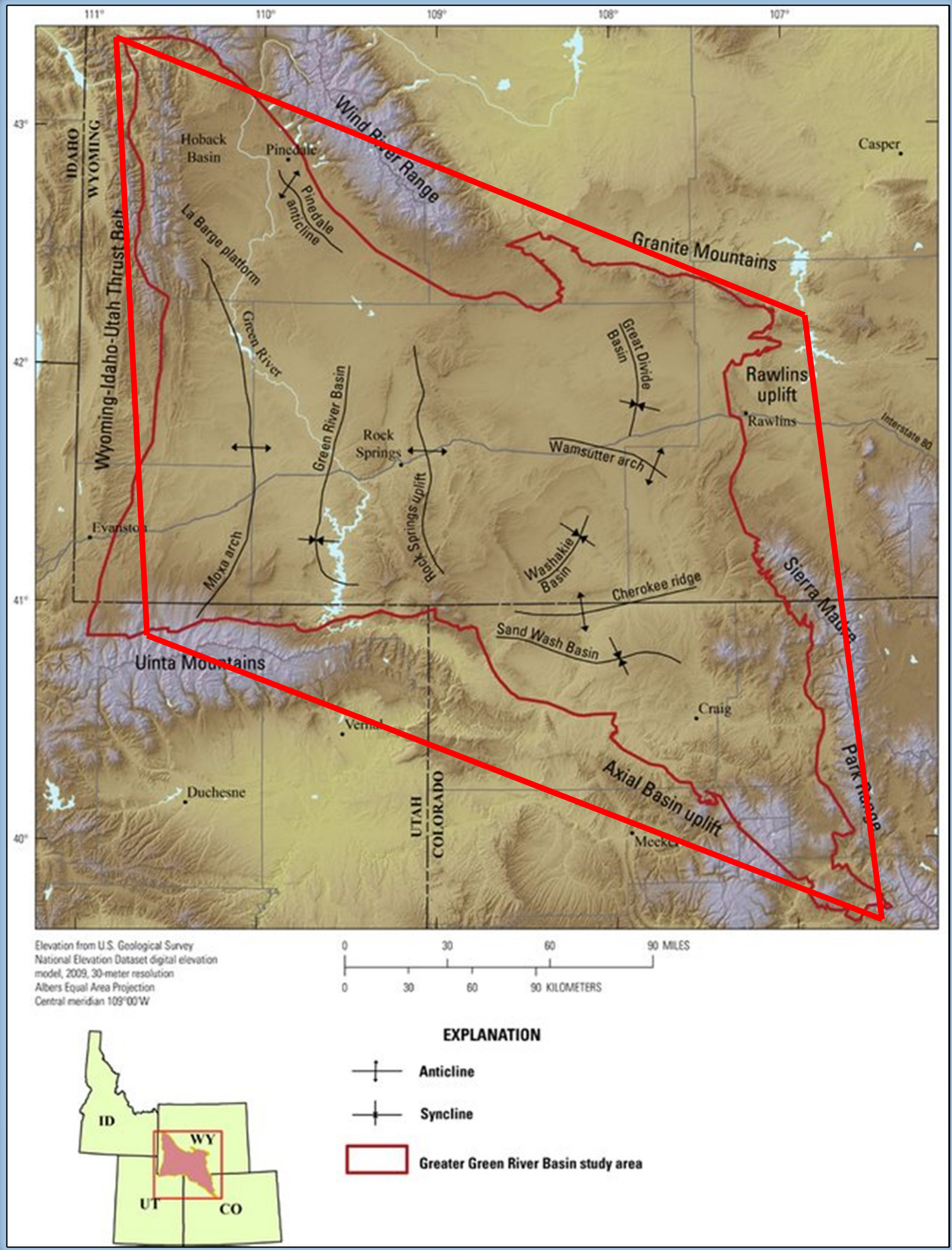
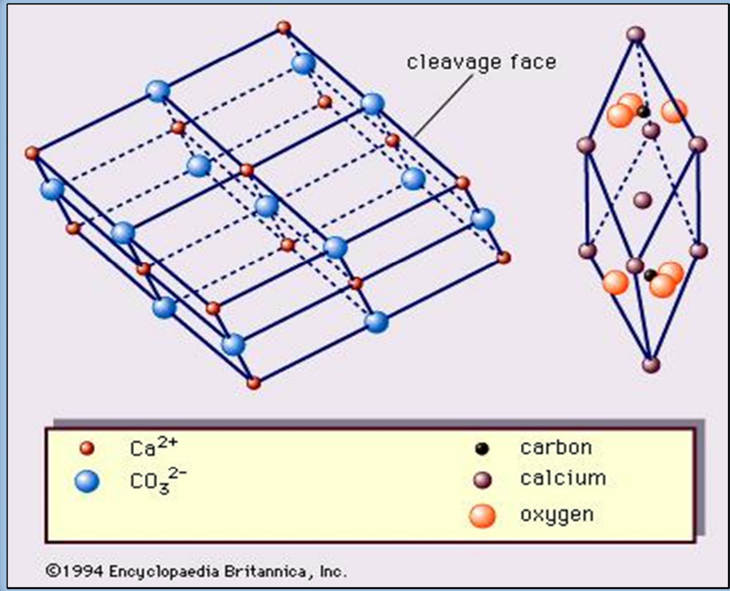
Rocky Mountain Section Meeting
Cheyenne, Wyoming
September 17, 2019



Presenter's notes: Landsat view of Wyoming. The Wind River and Shirley basins, along with the Sweetwater uplift, form a nearly perfect rhomb in the center of Wyoming.



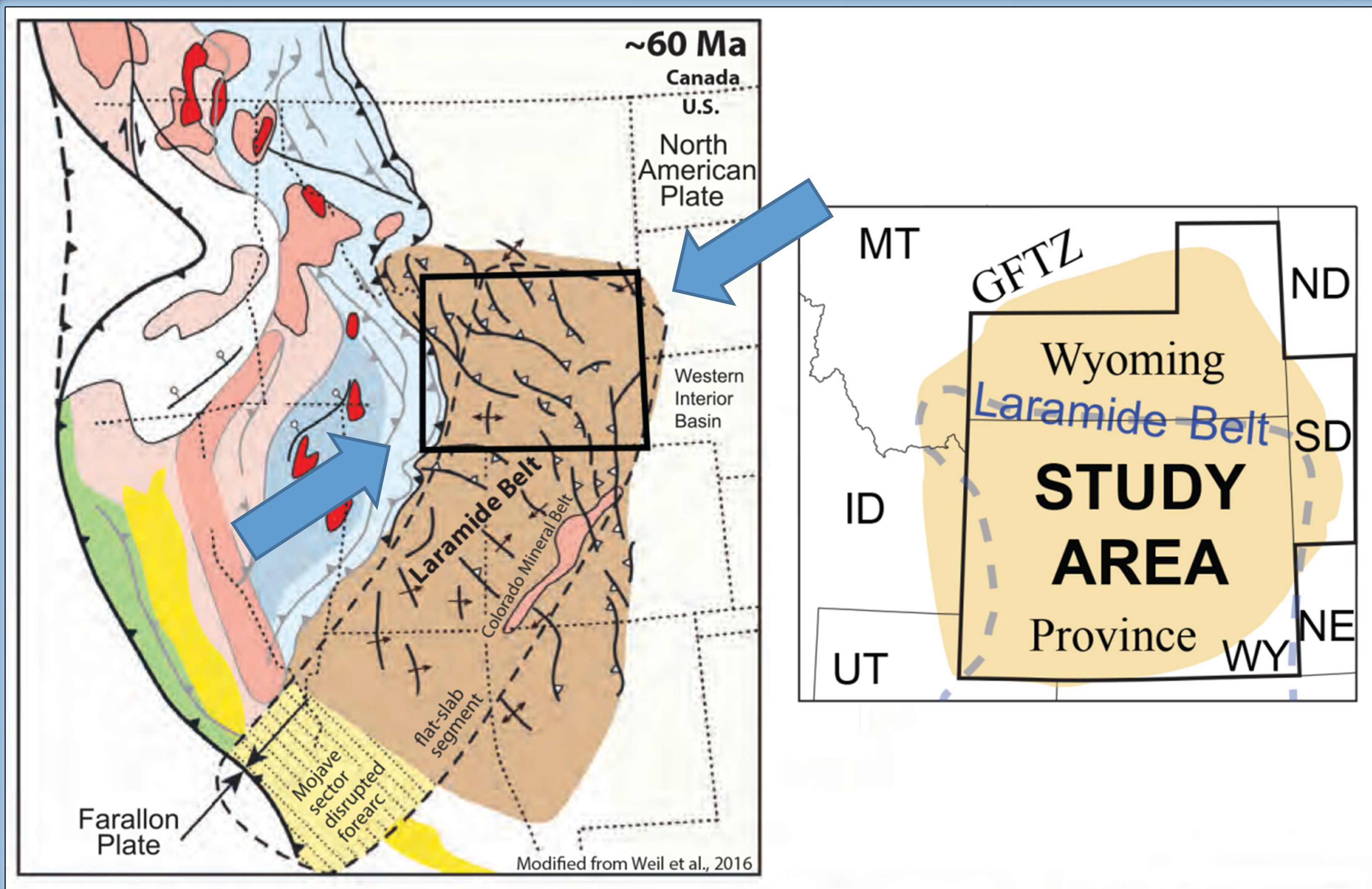
Presenter's notes: The same shape is seen moving to the southwest into the Greater Green River Basin. This "basin symmetry" has not been explained geologically.



Orderly and systematic

- Fundamental origins;
- Scales may be imperceptible to the naked eye; and
- Can be broken up, disguising original symmetry.

Presenter's notes: Like a calcite crystal, we know, just by the shape alone, that these features are not random, they must have a fundamental origin that just needs to be explained.



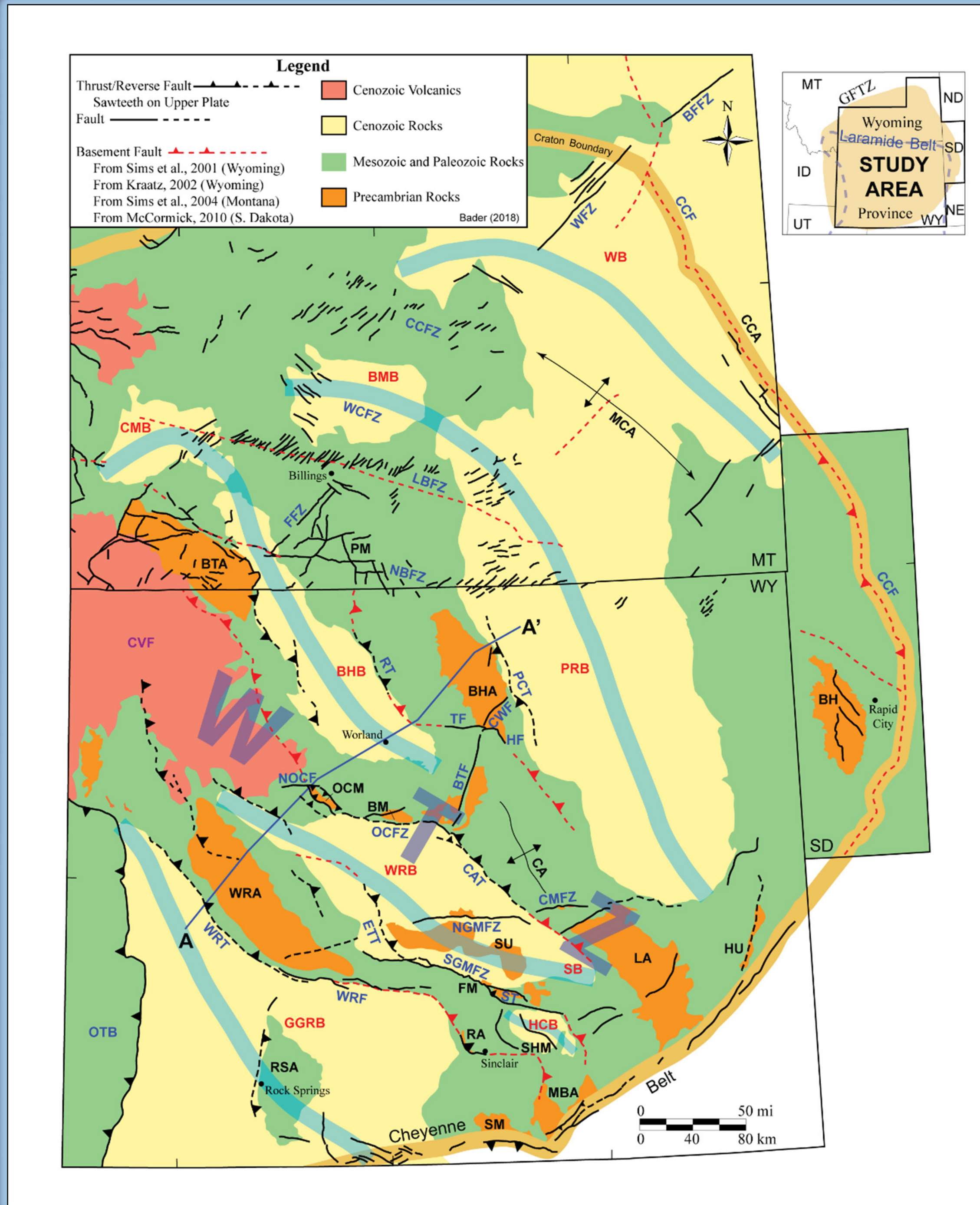
The Laramide Belt

Presenter’s notes: The study area is shown on the right with the Wyoming Province and the northern-end of the Laramide belt shown for reference.

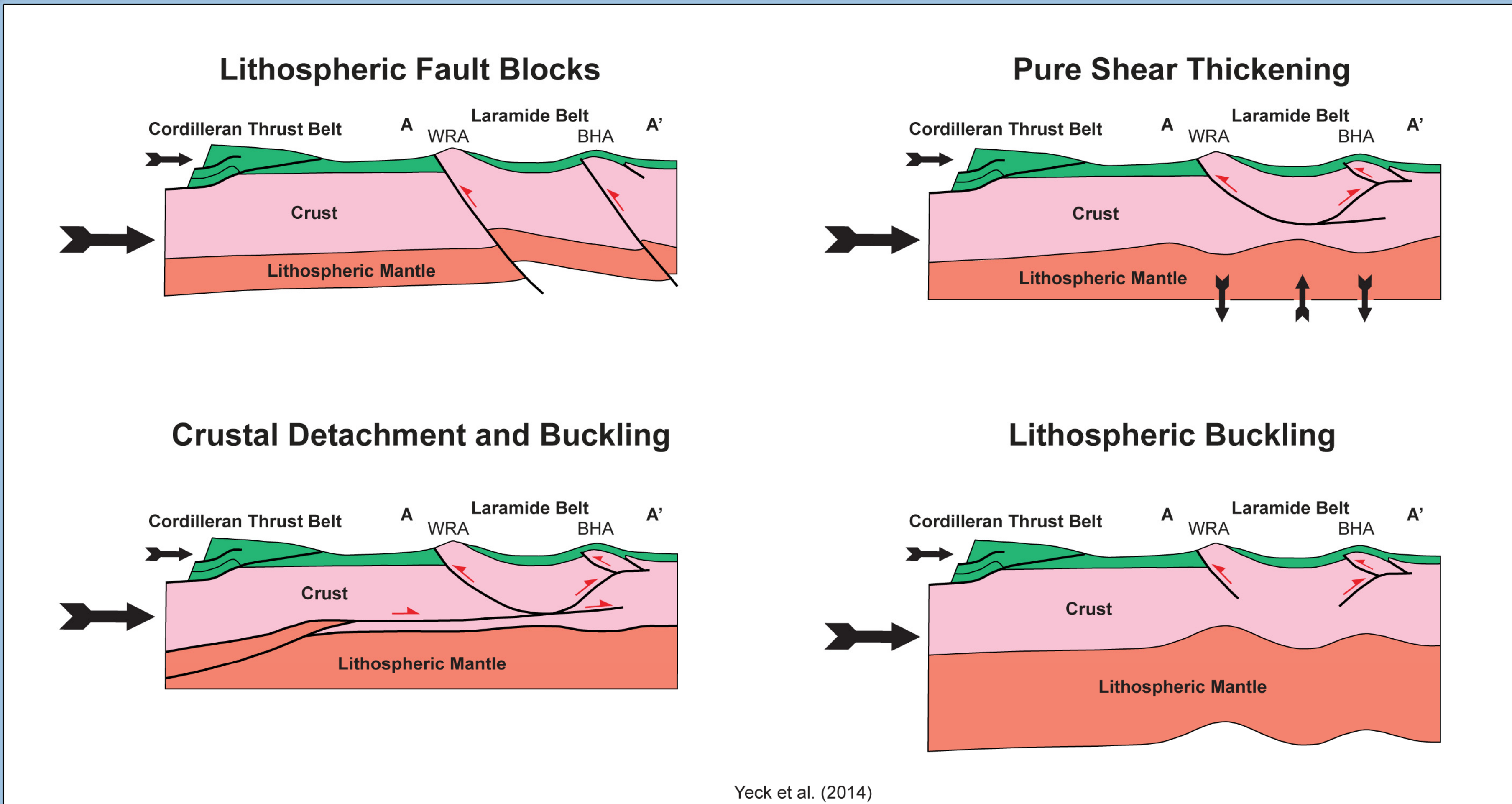
The Laramide belt is characterized by basement-cored thick-skinned arches and uplifts extending from Arizona/New Mexico to southern Montana, as seen for this Paleocene reconstruction of the North American Cordillera (Weil and Yonkee, 2012; Weil et al., 2016). The formation of the belt has generally been attributed to shallow-angle subduction of the Farallon Plate beneath the North American Plate at about 60 Ma. The deformation is up to approximately 1500 km from the Paleocene active continental margin, with nearly 14 km of structural relief on top of the Precambrian in central Wyoming (Snoke, 1993). Also, a major topic of debate is the varied orientations of the Laramide arches and uplifts that appear somewhat random (Gries, 1983; Varga, 1993). Finally, the Laramide shortening direction has been shown to be from the ENE at approximately N60E, sub-parallel to the Farallon Plate orientation (Erslev and Koenig, 2009; Weil and Yonkee, 2012).

Study Area

- Basins
  - Reverse-S shape
- Basement
  - Along 3 potential directions of anisotropy
    - NNW = Arches
    - WNW & NE = Uplifts
- Models (A-A')

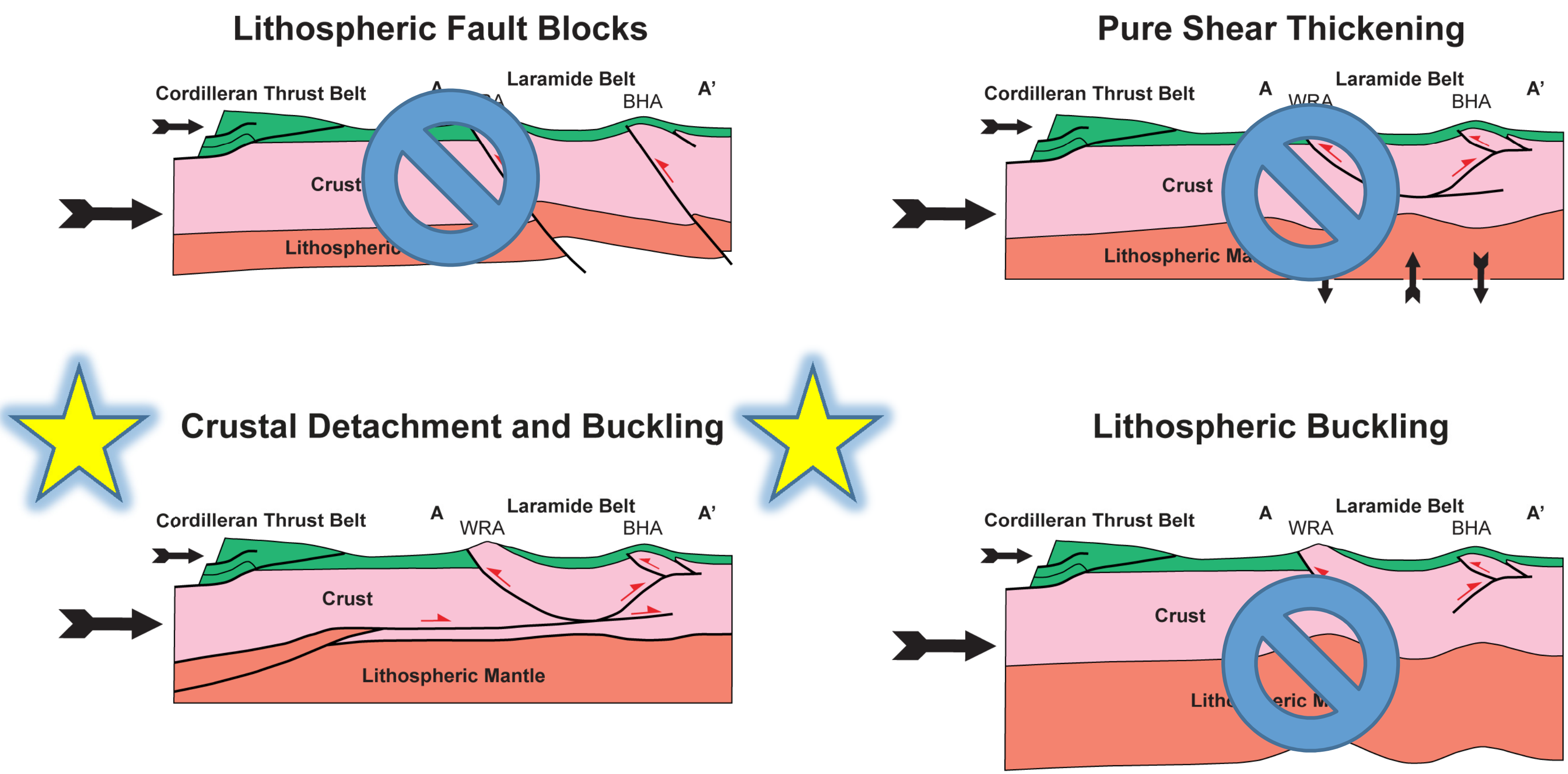


Presenter's notes: Composite geologic map of the study area in Wyoming, with Montana and South Dakota added to show the boundary of the Wyoming craton. The main area of study is the region encompassed by A-A'. Basins are shown in yellow including the Powder River, Bighorn, Wind River/Shirley, and Greater Green River basins. Note that these basins all have a reverse-S shape to some degree, even up into Montana. Major Precambrian exposures include: 1) the Bighorn, Beartooth, Wind River, and Laramie arches, trending NNW; 2) uplifts, trending WNW including the Owl Creek/Bridger Mountains, and the Sweetwater uplifts; and 3) the Big Trails fault zone that defines the main NE-trending uplift in the study area. Note that the WNW and NE fault-zone trends are present into Montana as well. Basement exposures define three (3) potential directions of anisotropy at the surface, NNE, WNW, and NE. Recently presented models along Section A-A' trend across two arches and two uplifts.



Models

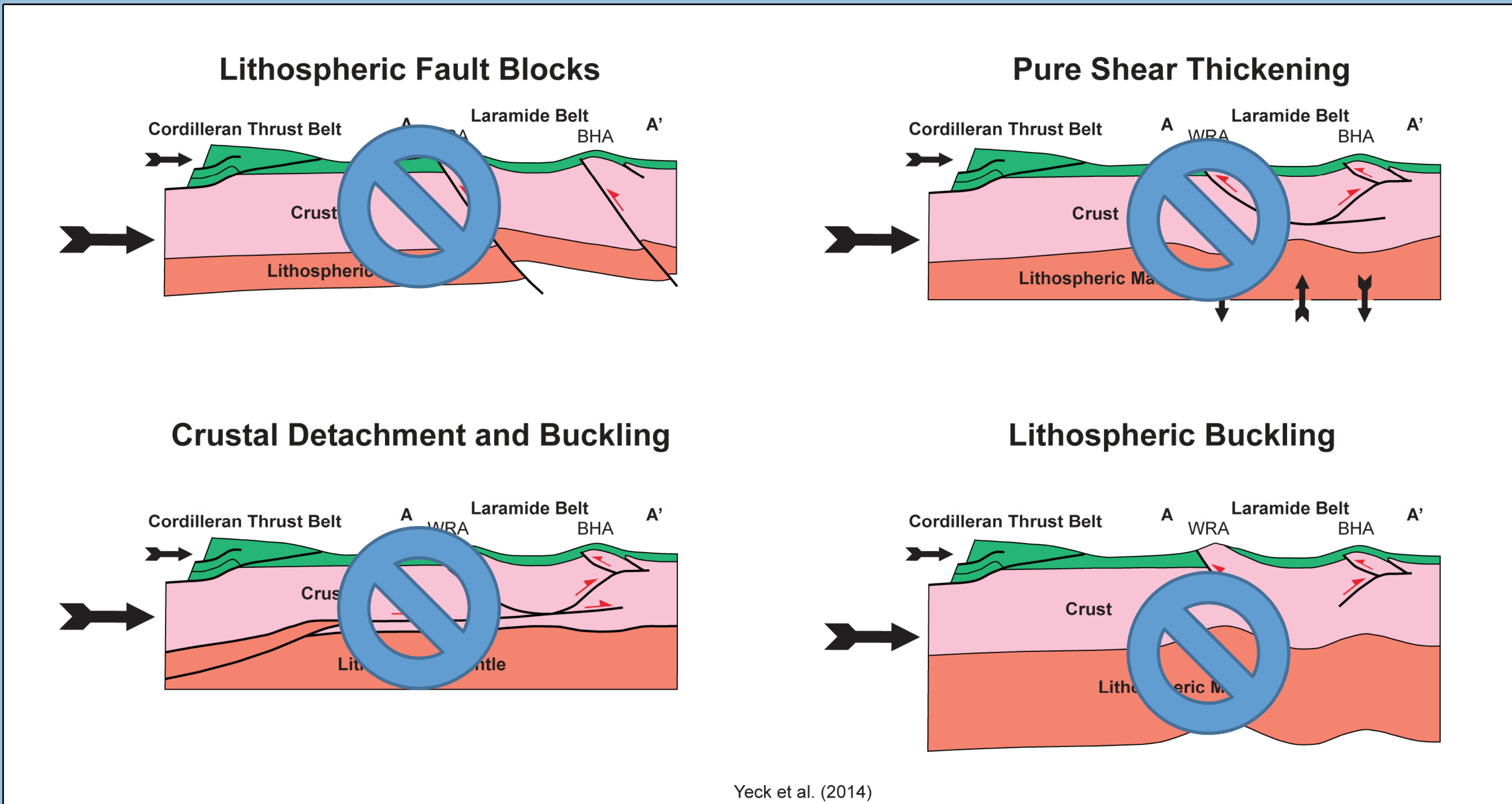
Presenter's notes: Four previously presented models were evaluated during the Bighorn arch seismic experiment, or BASE, conducted in 2010 (Erslev, 2005; Yeck et al., 2014; Worthington et al., 2016). For each of these, the surface and near surface are the same, but mid- to lower-crust and mantle lithosphere geometries differ.



Yeck et al. (2014)

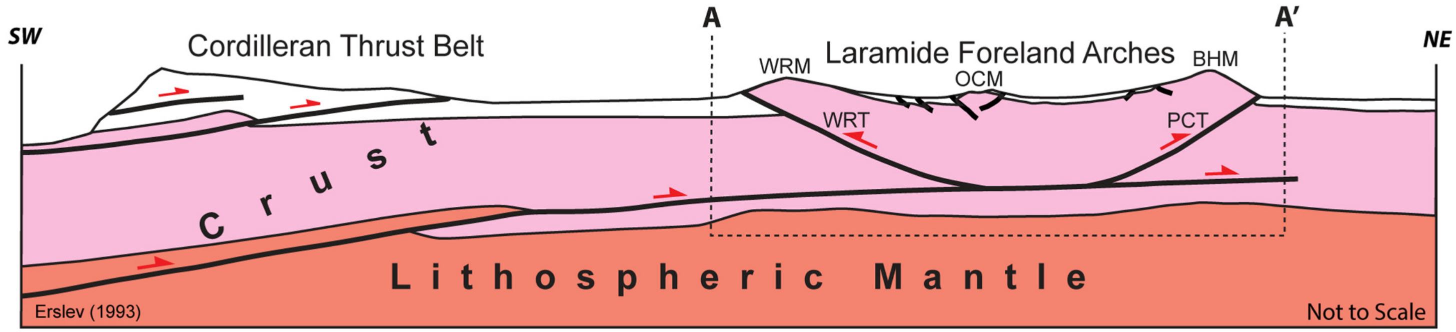
Models

Presenter's notes: BASE (Yeck et al., 2014) showed that the generally preferred model through the last few decades, crustal detachment with some buckling, seems the best possibility, because the Moho appears to be relatively unaffected due to the detachment, unlike other models which require deformation of the Moho during Laramide orogenesis.



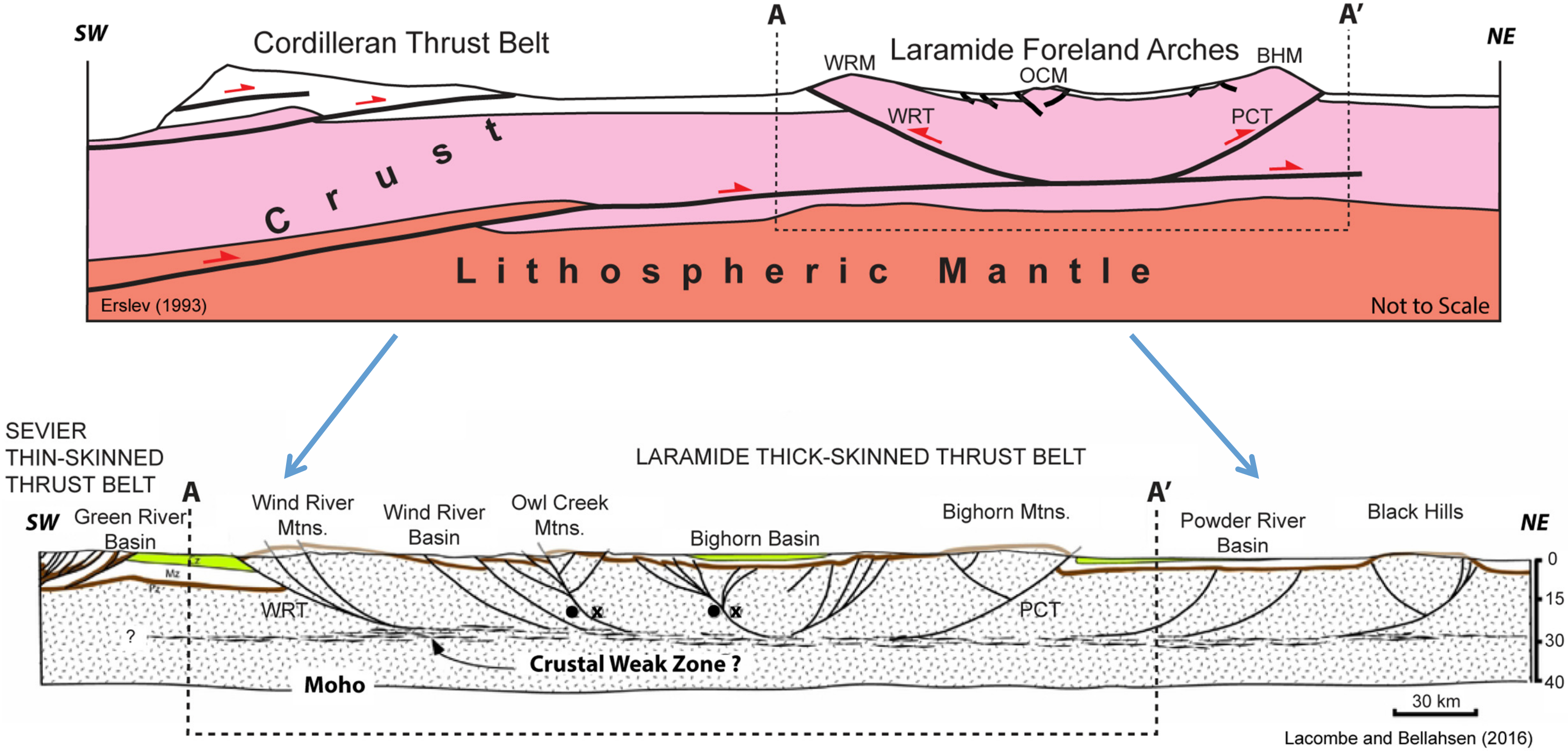
Models

Presenter's notes: However, the crustal detachment model has at least three (3) fatal flaws, among others, that also eliminate it from the debate. A fifth, and partially discussed (historically) model related to structural inheritance has been recently introduced (Bader, 2018). However, a review of the crustal detachment model and flaws is first warranted.



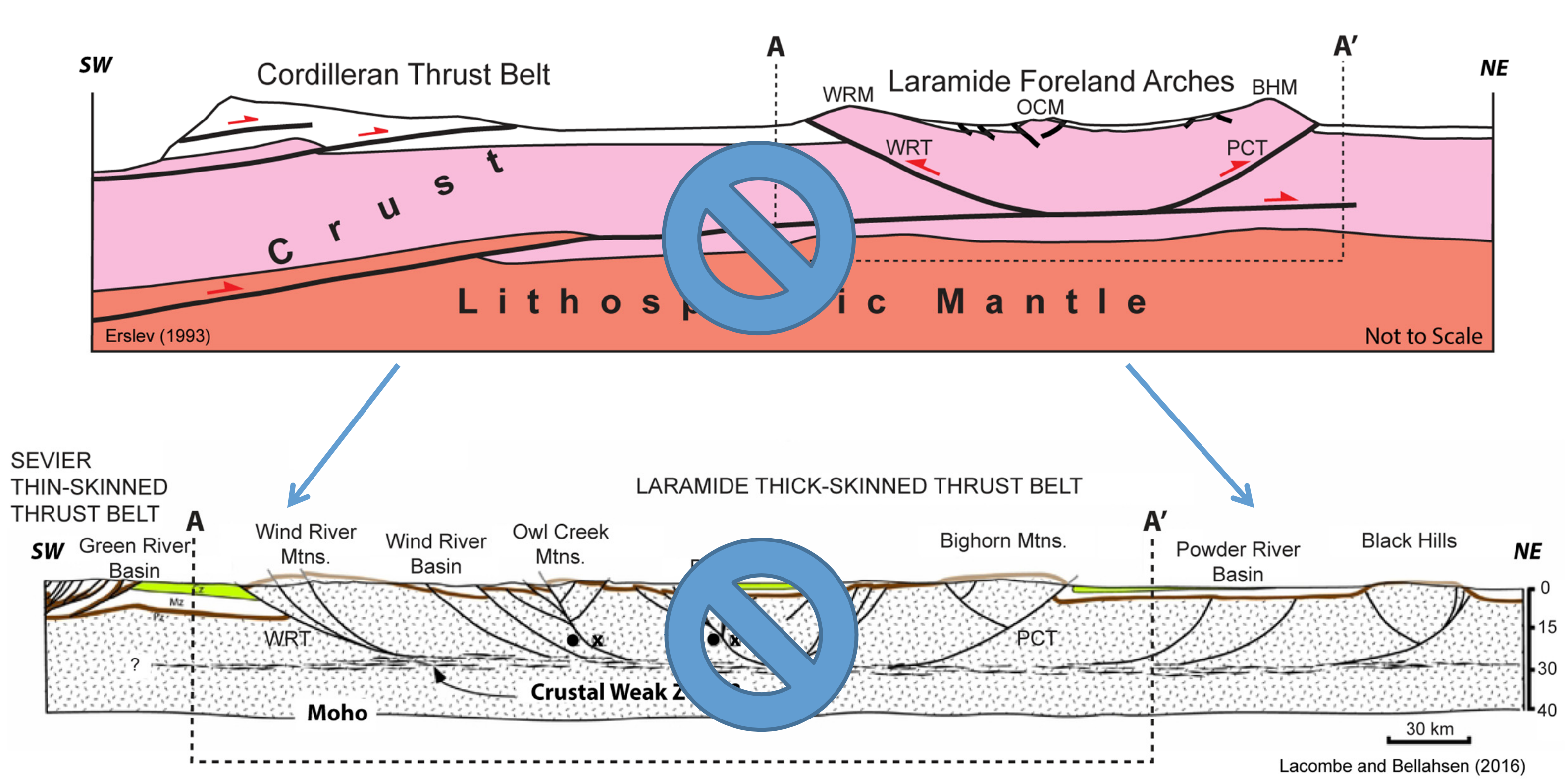
Crustal Detachment

Presenter's notes: This model, first envisioned by Blackstone (1990), and then enhanced by Erslev (1993), depicts foreland arches forming in the Laramide related to mid-crustal detachment developing in the hinterland of the North American Cordillera. This model shows the main Laramide thrusts as listric faults that sole out into a mid-crustal detachment, and the smaller faults, such as in the Owl Creek area, are relatively shallow thrusts and back thrusts.



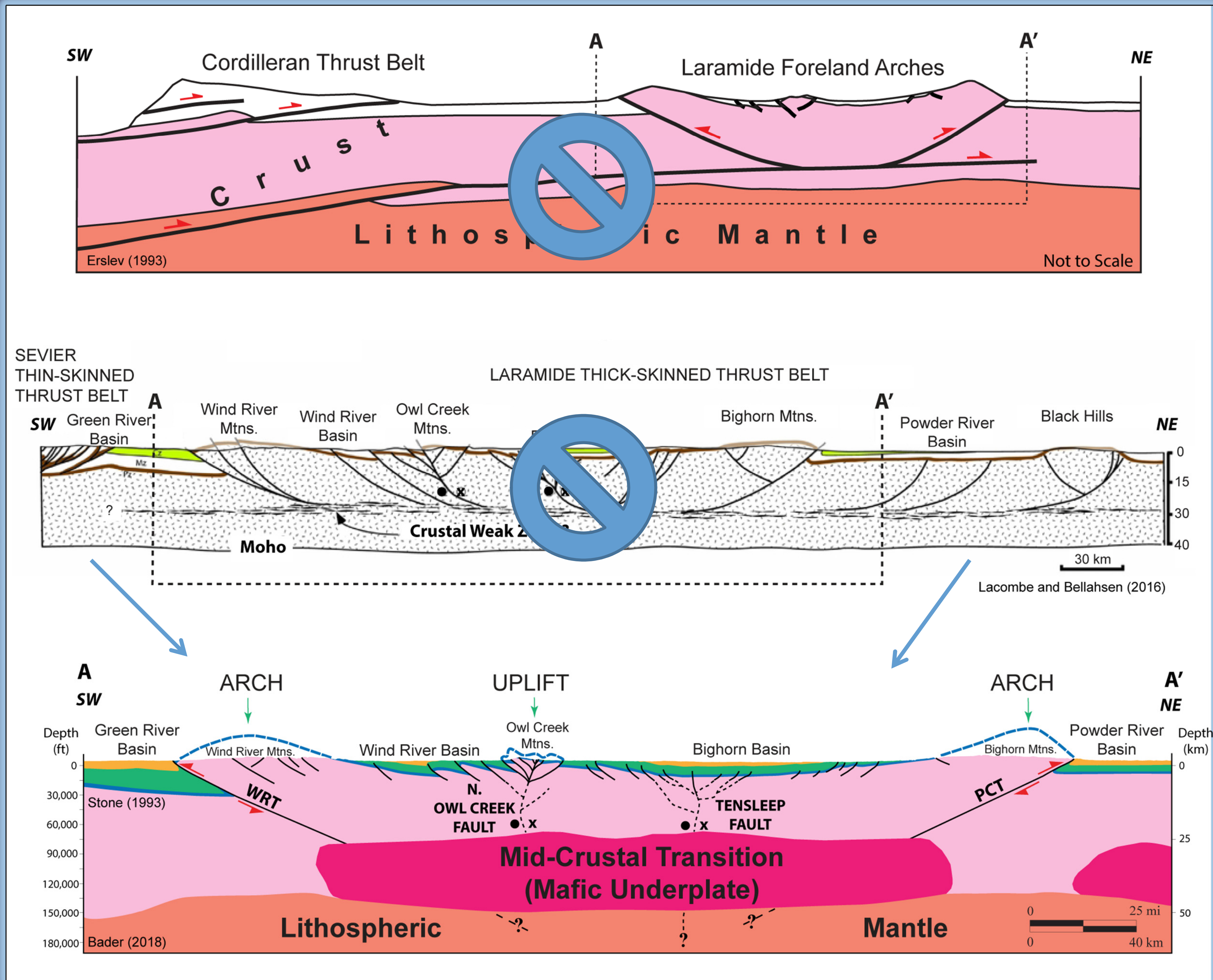
Crustal Detachment II

Presenter's notes: Lacombe and Bellahsen (2016) carried things a step further, incorporating the oblique-slip nature of faults in the Owl Creek and Tensleep fault zones, initially proposed by Molzer and Erslev (1995) and later confirmed by Stone (2002). They show the faults as being severely listric in nature to accommodate steeper fault dip at the surface and soling out into a mid-crustal weakness zone.



Crustal Detachment II

Presenter's notes: Although plausible, with the given data, the crustal detachment model has fatal flaws including: 1) major thrusts are not listric, but planar to 25 km where the reflector is truncated, as if it was severed/cut by something (Smithson et al., 1979; Stone, 2003). The reflector disappears and doesn't merge with some sort of decollement; 2) the N. Owl Creek fault and Tensleep fault are nearly vertical, basement-rooted faults, not consistent with development in a foreland fold and thrust belt (Hoppin et al., 1965; Paylor and Yin, 1993); and 3) the mid-crustal detachment zone has not been observed in seismic studies (Yeck et al., 2014; Worthington et al., 2016), among several other less significant discrepancies.



Crustal Detachment vs. Convergent Deformation

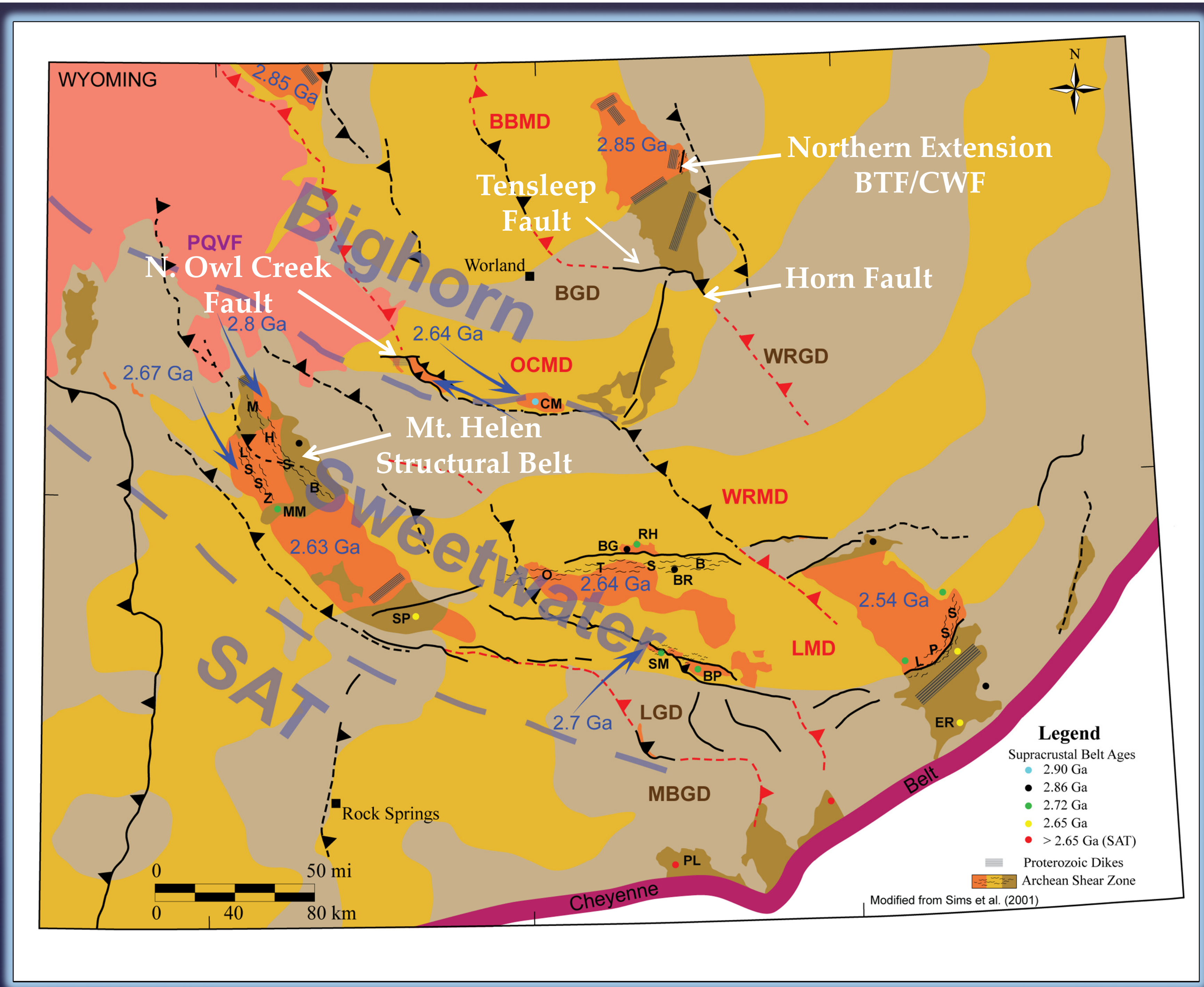
Presenter's notes: The bottom model is the Convergent Deformation Model of Bader (2018). This model proposes that initial deformation of the basement occurred in the Precambrian during ENE convergence/subduction when the Wyoming craton boundaries were approximately at the present day Bighorn and Wind River mountains.

The Piney Creek and Wind River thrusts are proposed to represent relict subduction zones, and the N. Owl Creek and Tensleep faults are relict conjugate shears formed in-board of the subduction zones in the Neoarchean (Sylvester, 1988). The mid-crustal transition zone, in the form of a mafic underplate, would have developed either in the late Archean and/or into the Proterozoic, thus severing and truncating the earlier formed Neoarchean subduction zones, as seen from the Deep Probe work in the western portion of the study area (Snelson et al., 1998; Gorman et al., 2002). This convergence deformation zone was then just reactivated during the Laramide when tectonic stress due to convergence was again from the ENE.

This model explains the fatal flaws of the crustal detachment model, discussed above, and is supported by data from numerous sources (Smithson et al., 1979; Frost et al., 2000; Chamberlain et al., 2003; Gorman et al., 2012; Heron, et al., 2019).

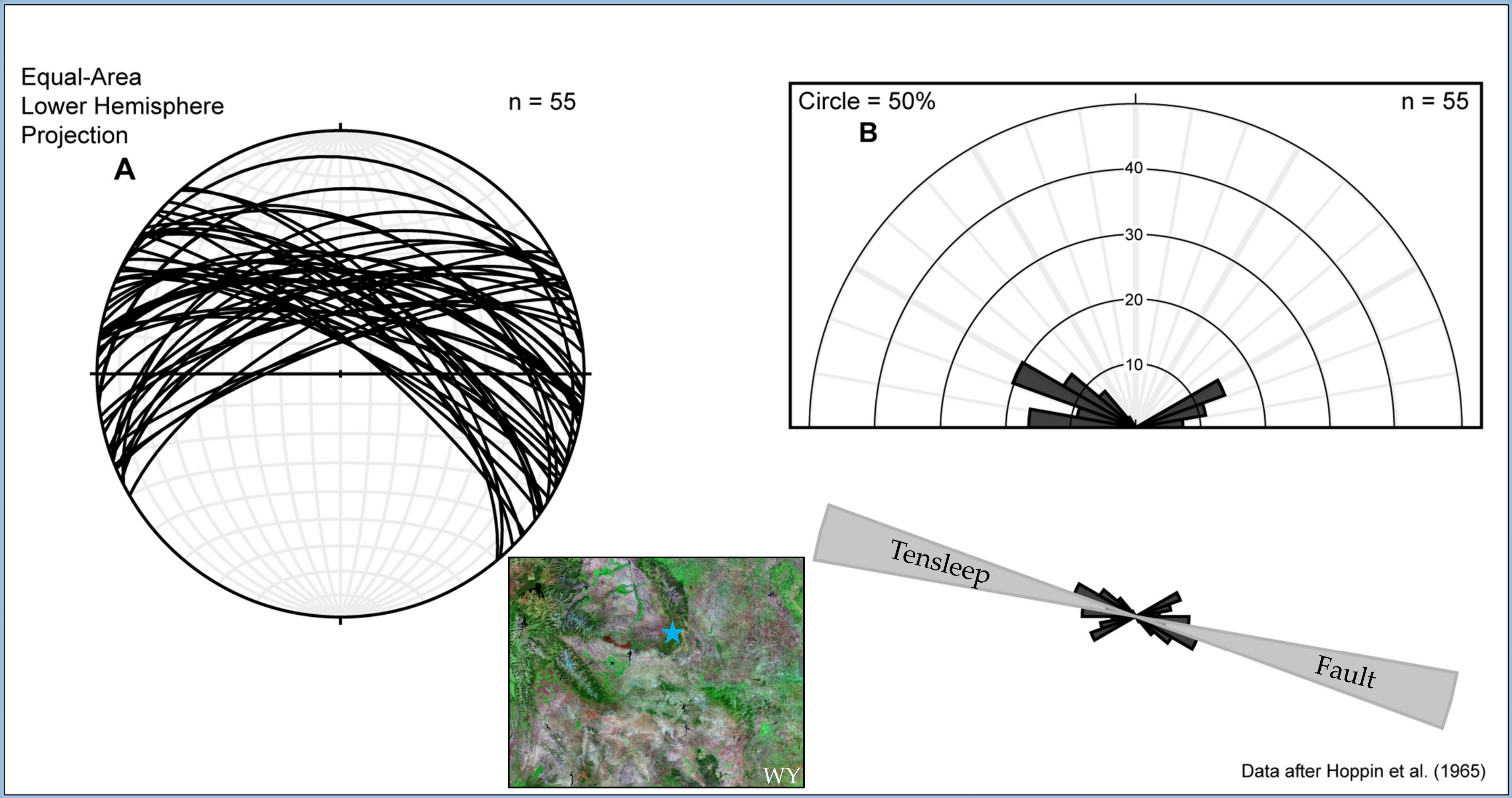
Methodology

- Structural Analysis-Precambrian
  - Types (shear zones, dike swarms, supracrustal belts)
  - Ages
  - Spatial Distributions
  - Orientations
  - Kinematics
  - **Fabrics**
- Structural Analysis-Laramide
  - Types (faults, folds)
  - Ages
  - Spatial Distributions
  - Orientations
  - Kinematics
  - **Determine Relationship to Precambrian Basement**
- Identify Potential for Structural Inheritance
  - Precambrian Pure Shear
    - Plate Tectonics
  - Laramide Simple Shear
    - Plate Tectonics



Presenter's notes: Precambrian basement map of Wyoming. Magmatic and gneissic domains defined from aeromagnetics and surface exposures, form a crude circular or ring pattern with the oldest rocks in the core and generally younging to the SSW (Bowers and Chamberlain, 2006; Frost et al., 2006a). Major faults are shown in black and red, along with Proterozoic dike swarms, supracrustal belts with ages, shear zones, and subprovince boundaries that trend to the NW (Dvjoracek, 1988; Frost, 1993; Sims et al., 2001; Chamberlain et al., 2003; Resor and Snoke, 2005; Frost et al., 2006b; Grace et al., 2006). Note the three dominant trends of potential basement weakness are present; NNW, WNW, and NE including supracrustal belts, Proterozoic dike swarms, and Archean shear zones, along with major faults.

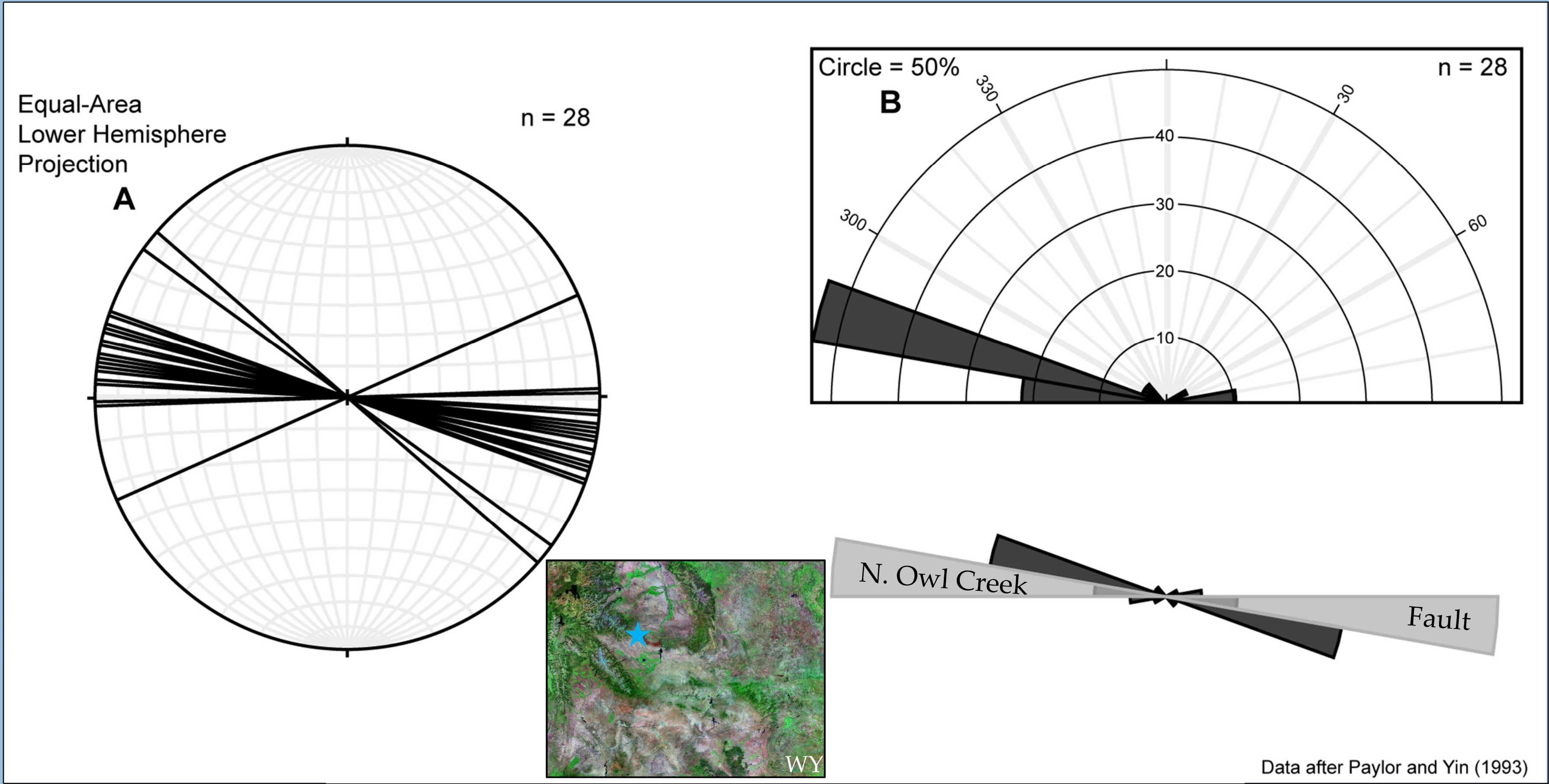
Basement data were analyzed along the potential zones of weakness (WNW, NNW, and NE), including foliation data in gneissic exposures across north-central Wyoming, and Proterozoic dike swarm data along the N. Owl Creek fault.



Tensleep Fault

(Shear Zone Foliations)

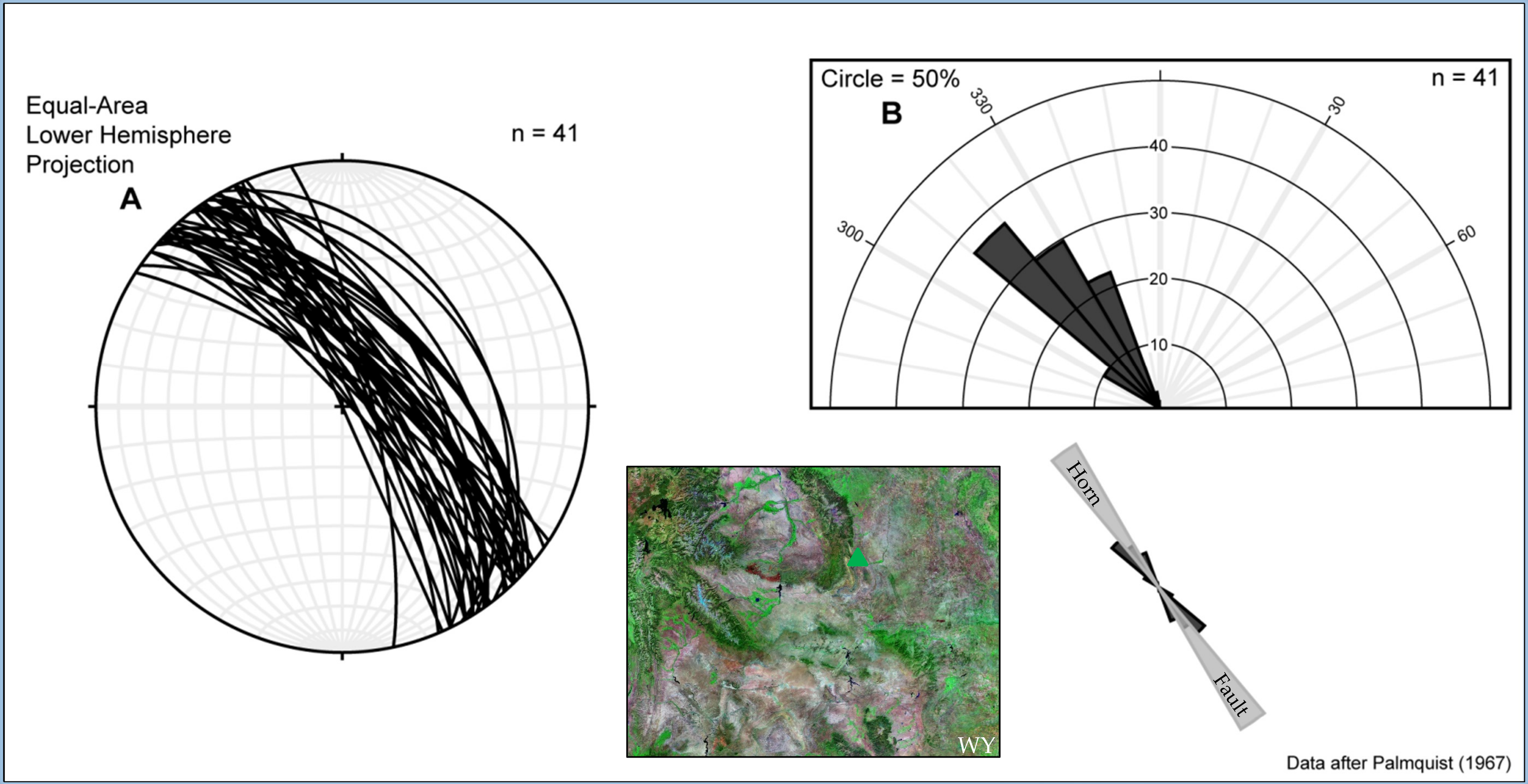
Presenter's notes: Foliation data from gneissic exposures lateral to the Tensleep fault. Fabrics show a general WNW trend that is roughly parallel to the strike of the Tensleep fault, suggesting a Precambrian ancestry for the fault.



N. Owl Creek Fault

(Mafic Dike Swarms)

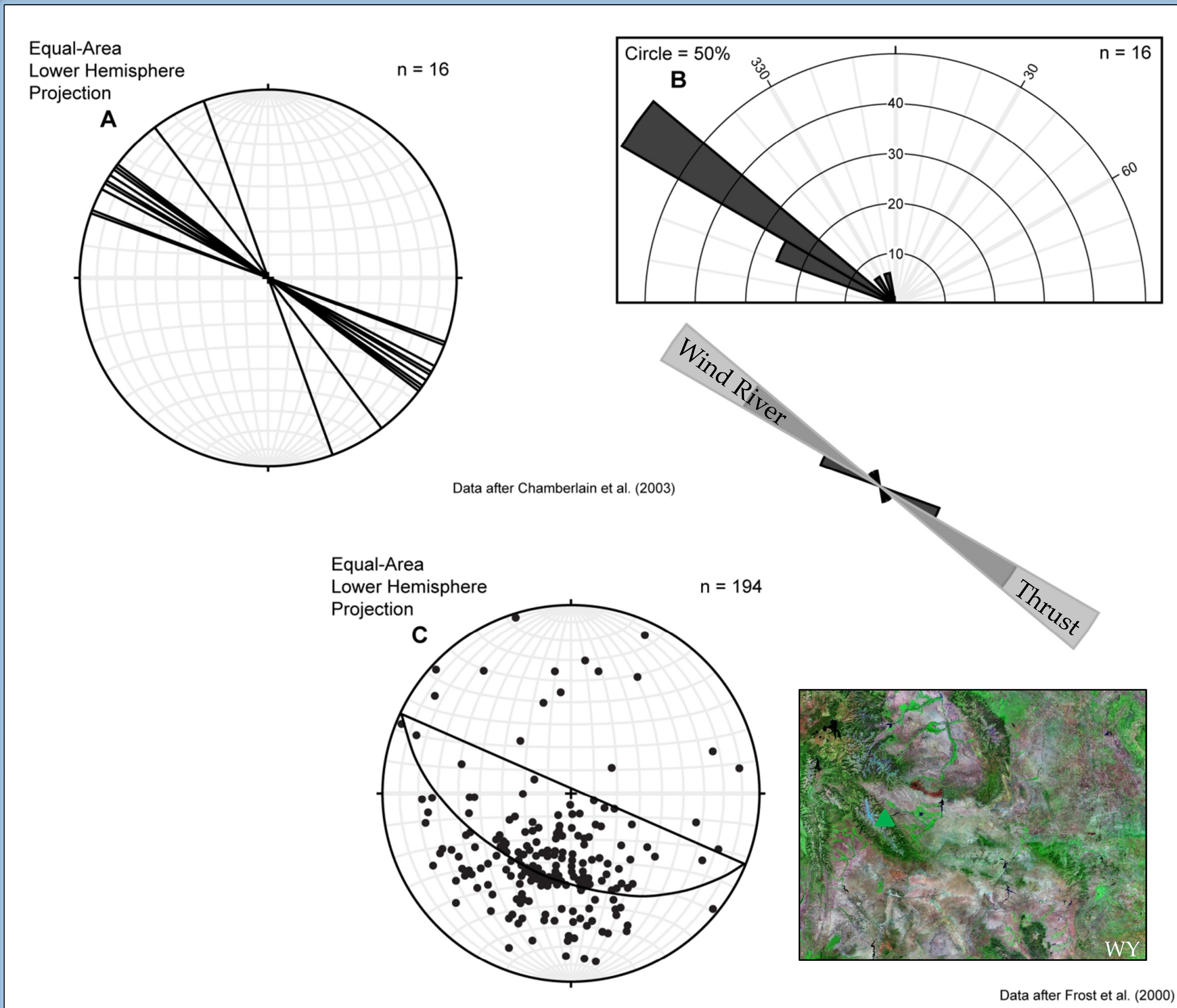
Presenter's notes: Dike swarm data from just south of the N. Owl Creek fault. Note general WNW trend that is sub-parallel to the strike of the N. Owl Creek fault, again, suggesting a possible Precambrian origin.



Horn Fault

(Foliations)

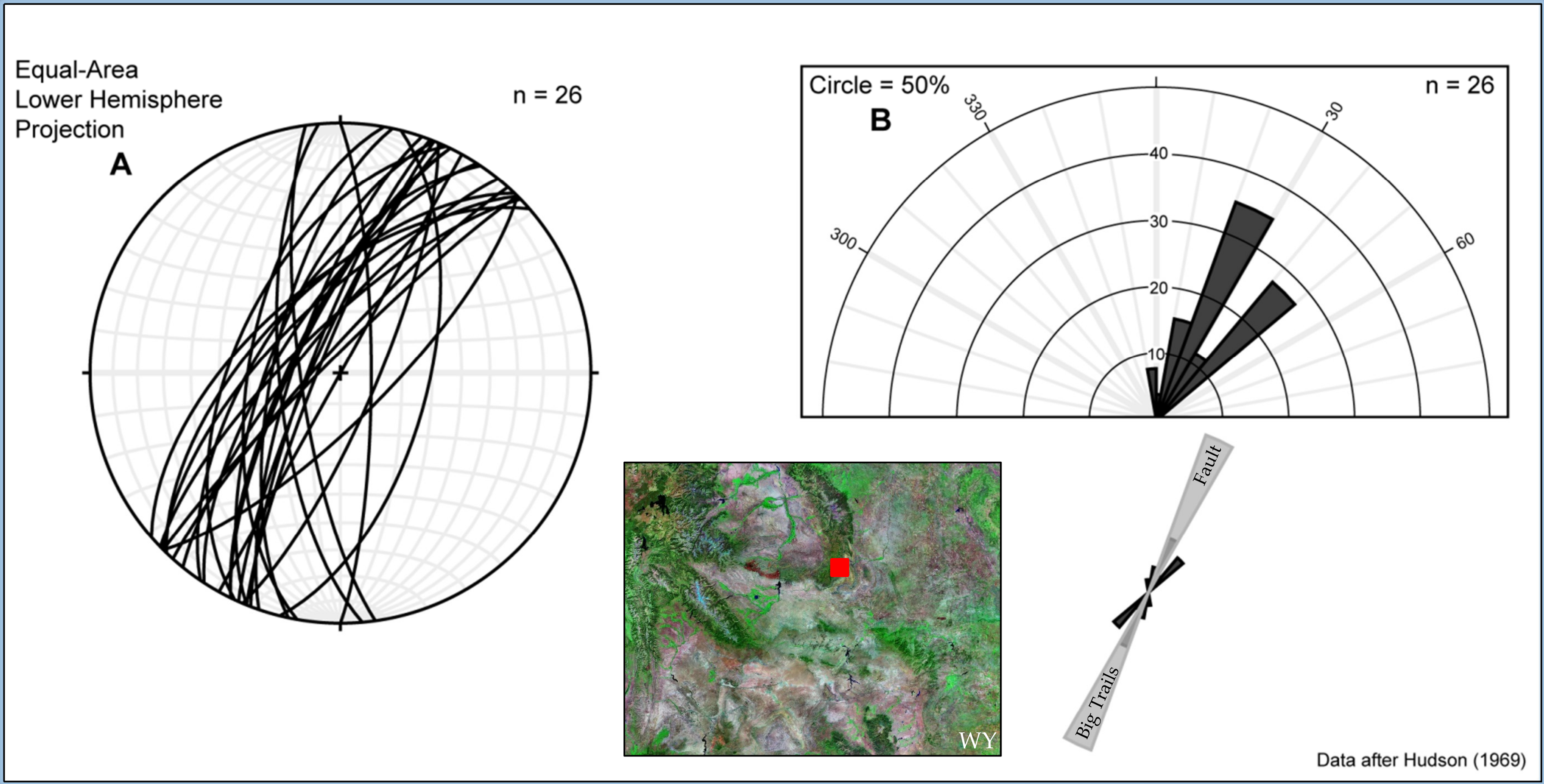
Presenter's notes: The Horn fault on the eastern side of the Bighorn Mountains. Foliations here in gneissic rocks show a unimodal trend to the NNE, very consistent with the strike of the Horn fault. Again, potential evidence of Precambrian age.



Mt. Helen Structural Zone

(Shear Zone Foliations)

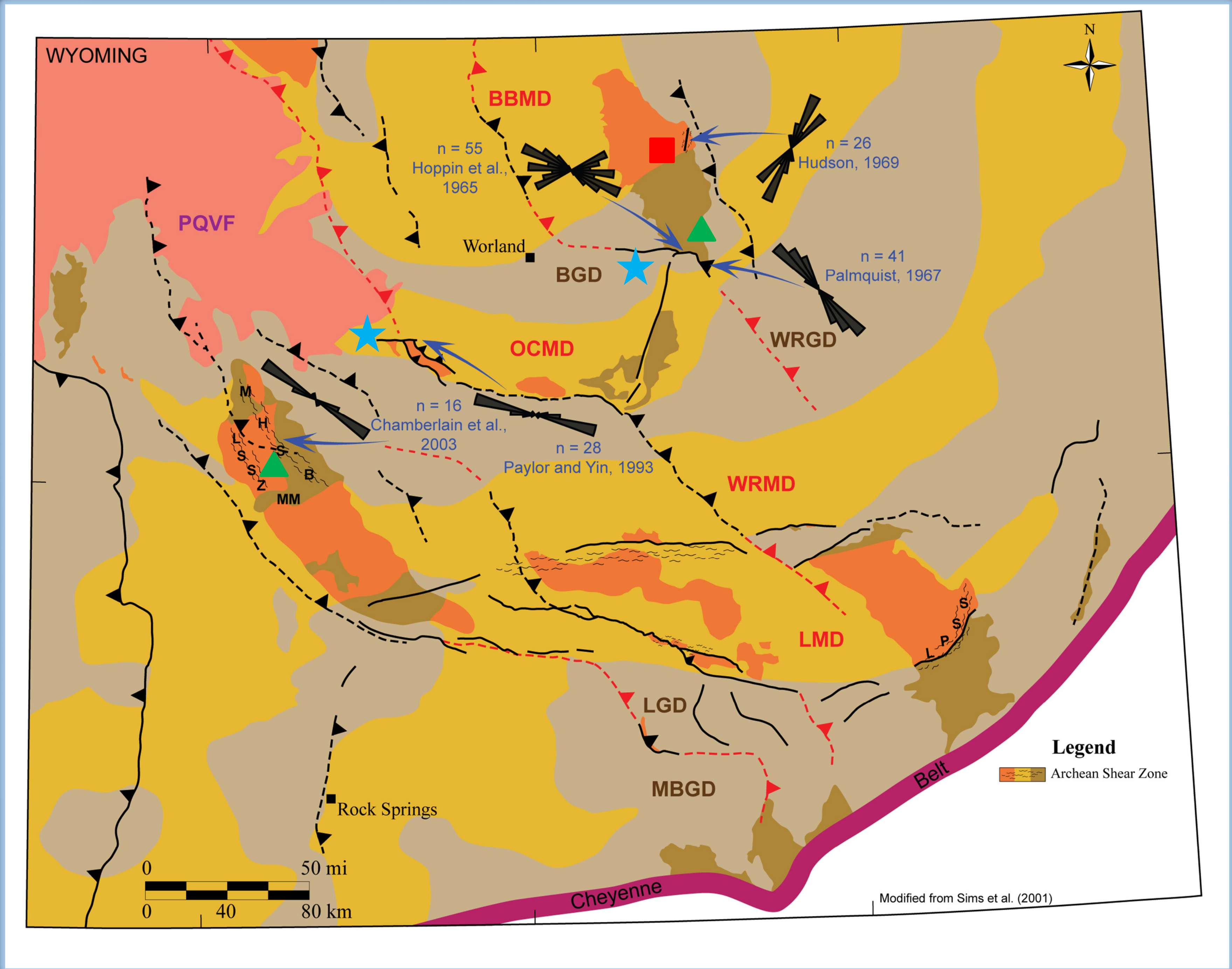
Presenter's notes: Mt. Helen structural zone. Data show somewhat bimodal trends, but generally sub-parallel to the trend of the Wind River thrust. The Lake Surprise shear zone just to the west of the Mt. Helen zone, also has numerous mylonites with similar orientation. In addition, work by Frost et al. (2000) and Chamberlain et al. (2003) have identified the Mt. Helen structural belt as a deep, high-temperature shear zone related to a long-lived Late Archean magmatic arc oriented NNW. Strong evidence for Precambrian influence on Wind River thrust development in the Laramide.



Big Trails Fault

(Foliations)

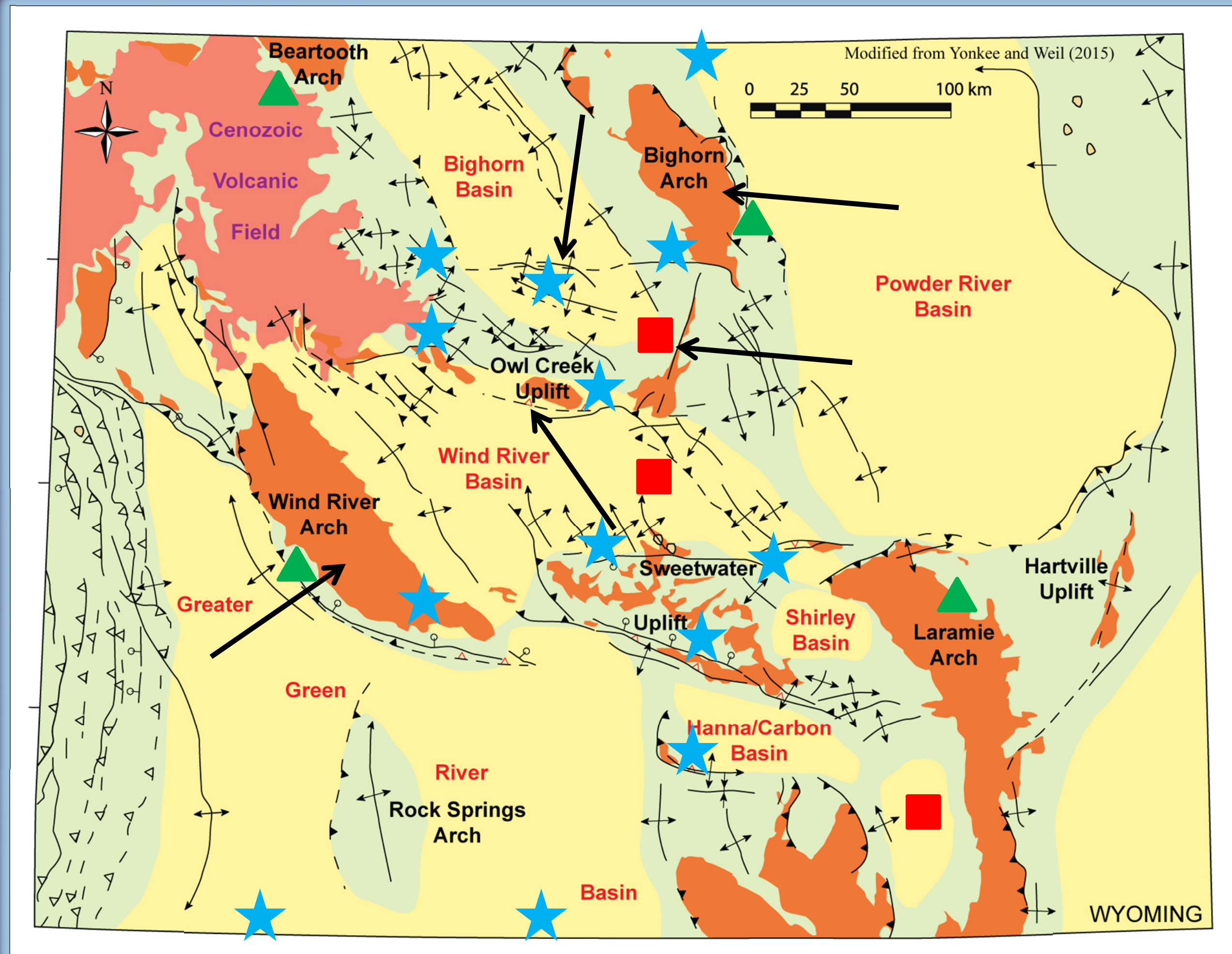
Presenter's notes: NE-striking Big Trails fault zone also shows evidence of Precambrian influence based on fabric data.

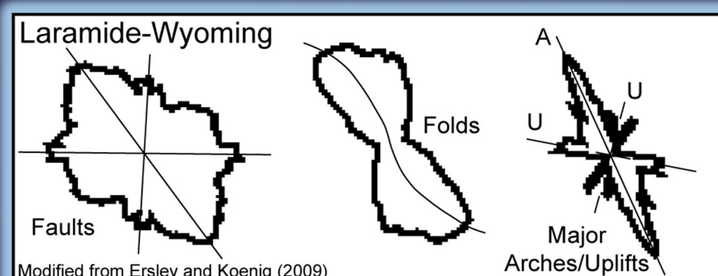


Presenter's notes: Wyoming Precambrian basement map showing rose diagrams for basement fabrics from this study for comparison to Laramide structures. Blue stars, WNW trends; green triangles, NNW trends; and red square, NE trend.

Laramide Deformations

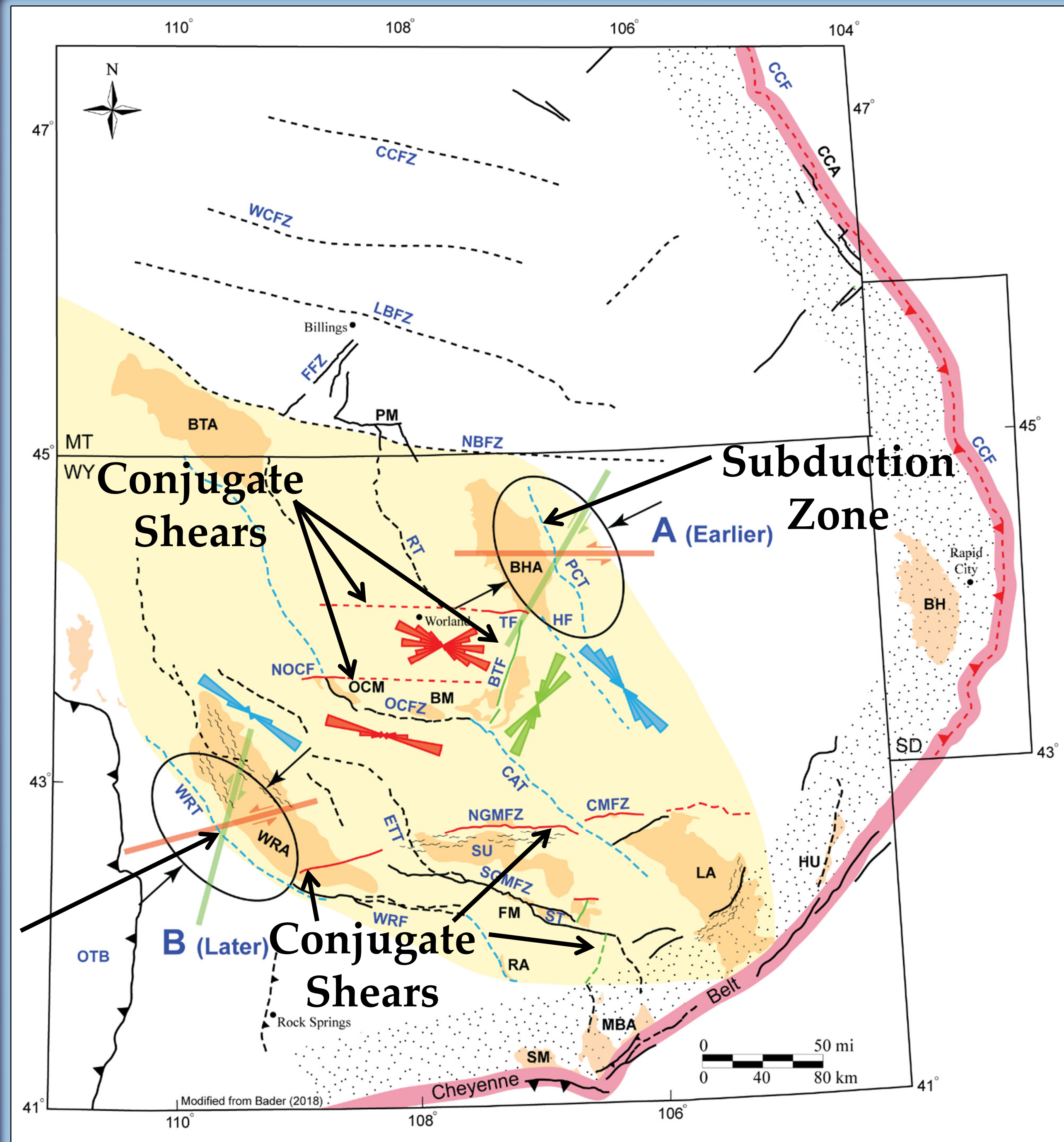
- NNW
  - Arcuate shape
  - Major thrusts
- WNW
  - Rectilinear shape
  - Reverse sinistral
- NE
  - Rectilinear shape
  - Reverse dextral





Presenter's notes: NNW structures, green triangles with a distinct arcuate shape; these are the prototypical Laramide arches brought up along medium angle thrust/reverse faults (Smithson et al., 1979; Erslev, 1993). WNW structures, blue stars with distinct rectilinear deformation zones; these are reverse left-oblique-slip fault zones (Hoppin et al., 1965; Stone, 1985; Ver Ploeg, 1985; Molzer and Erslev, 1995; Stone, 2002; Weil et al., 2016). NE structure, red square and also rectilinear deformation zone, reverse right-oblique-slip fault zone (Hoppin, 1961; Ver Ploeg and Greer, 1997; Weil et al., 2014). Note that these features are present across the state and are consistent with the work of Erslev and Koenig (2009), who measured 1,000's of structures in Wyoming. Faults with the three directions, curvilinear folds trending NW-SE (Stone, 1985; Ver Ploeg, 1985; Weil et al., 2016), and arches/uplifts with similar trends to fault strike.

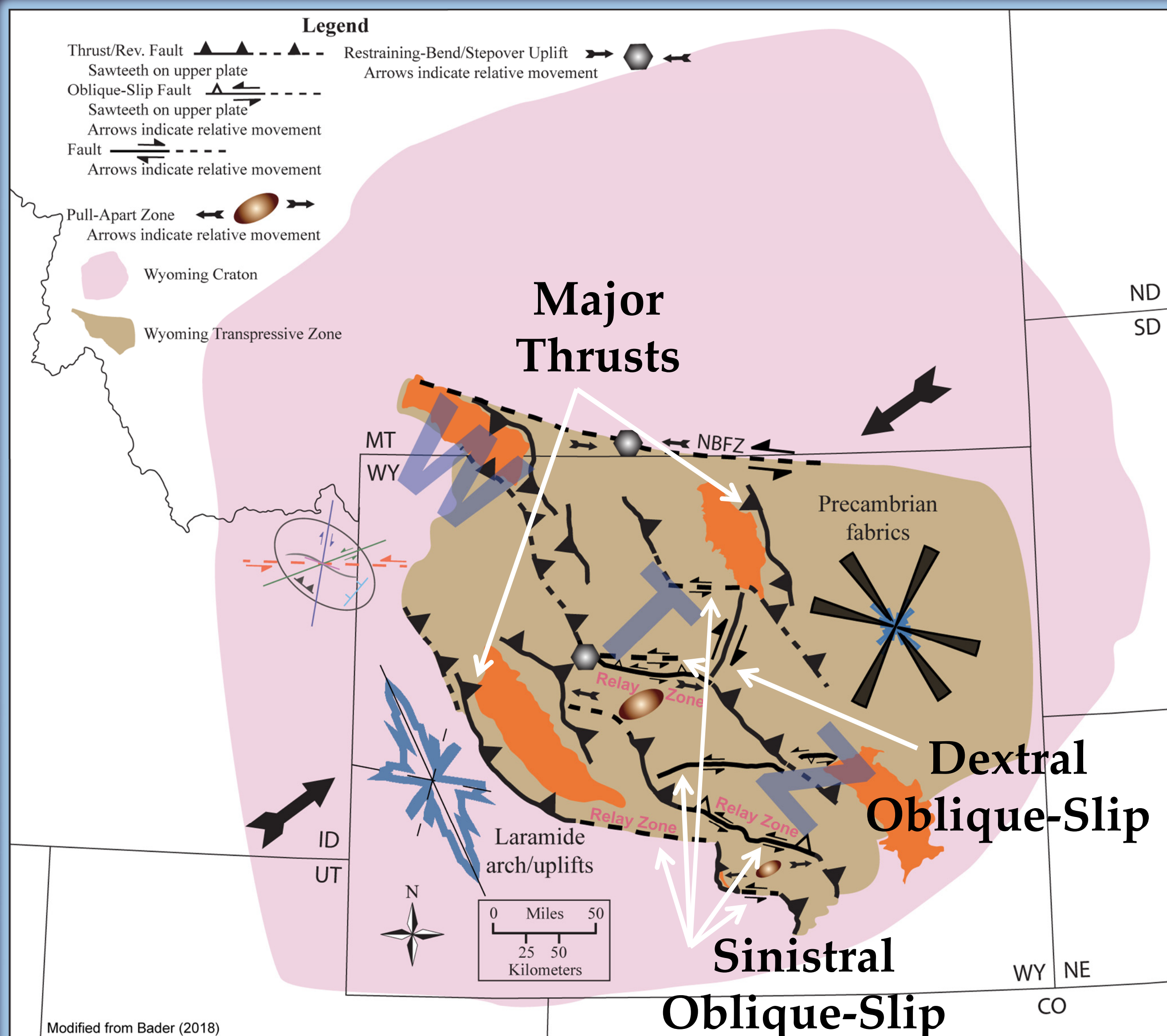
Archean Pure Shear (~ 3.0 Ga)



Subduction Zone

Presenter's notes: Strong evidence for structural inheritance across the craton. Basement fabrics developed initially through pure-shear deformation likely at subduction zones after 3.0 Ga, as shown by the outline of the craton (yellow) at that time (Chamberlain et al., 2003). Subduction/convergence and development of conjugate shears probably was earlier to the NE, followed by subduction to the SW, as substantiated by several workers (Frost et al., 2000; Chamberlain et al., 2003; Frost et al., 2006a). These zones were then just reactivated in the Laramide as the PHS was in a similar orientation as during the Precambrian, from the ENE/WSW (Erslev and Koenig, 2009; Weil and Yonkee, 2012; Bader, 2018).

Laramide Simple Shear



Presenter's notes: In the Laramide, PHS at N60E reactivates the system, major thrusts such as the Wind River and Piney Creek are reactivated and, where connected, lateral shift is facilitated by WNW striking reverse-sinistral oblique-slip faults across the craton (Bader, 2018). Relay zones (e.g., S. Owl Creek fault) between major thrusts developed as a result of this sinistral simple-shear across the WNW-striking structures (e.g., N. Owl Creek fault) in the Laramide. Dextral faults also reactivated, but less extensively. Area defines the Wyoming Transpressive Zone (WTZ) of Bader (2018).

Conclusions

- Convergent deformation system (CDS) developed in the Precambrian
  - Convergence/subduction at NE and SW Archean continental margins
  - Developed NNE fabrics (shear zones) transverse to ENE PHS
  - Pure shear = conjugate shears in cratonic rocks = WNW and NE fabrics (conjugate shears)
  - Supracrustal belts and rifting events concurrent/post-date along CDS trends

- Reactivation of the system during the Laramide under ENE PHS
  - Contraction due to shallow-angle subduction of Farallon Plate
  - Simple shear = reactivation of WNW and NE fabrics across the Wyoming Transpressive Zone (WTZ)
  - Where connected, WNW fabrics = relay zones, facilitating major arch development along NNW-striking faults
  - Explains "SYMMETRY" seen across the entire Wyoming Province
  - Helps resolve several discrepancies of previous models
    - Shifting shortening directions
    - Presence of high-angle fault zones where crustal shortening is dominant
    - Presence of compressional and extensional structures
    - Better explains deformation so far inboard from the active continental margin
    - Explains planar attitude of the Wind River and Piney Creek thrusts at depth
      - Loss of seismic signal at depth
      - Presence of a mid-crustal transition zone = mafic underplate = Deep Probe and EarthScope BASE
        - Alleviates need for zone of mid-crustal detachment

- Insights
  - Nature of Neoarchean and Paleoproterozoic anisotropies along active Precambrian continental margins
    - Preexisting and primary basement heterogeneities controlled subsequent deformational events in the Laramide belt of Wyoming, and probably Montana
    - Insight into Neoarchean terrane amalgamation and later Paleoproterozoic convergent episodes related to the development and possible final assembly of Laurentia

Presenter's notes: As per Heron et al. (2018), we need to look deeper to try and identify signs of lower crustal underplating and mantle lithosphere scars that may give us further insight into basement control in complicated orogenic belts such as the Laramide.

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