Structural Inheritance for the Laramide, Central Montana Uplift: A Wrench-Fault Tectonic Model Related to Proterozoic Orogenesis in the Foreland of the North American Cordillera*

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Abstract

The Central Montana uplift lies in eastern Montana adjacent to the Northern Rocky Mountains on the western edge of the Northern Great Plains Physiographic Province, and just north of the Laramide belt of the Central Rockies. The origins of this deformed region have received little attention relative to Laramide tectonism and Precambrian basement interrelations, particularly within the overall context of plate tectonic evolution of the North American Cordillera.

The Central Montana uplift is characterized at the surface by six well-defined fault zones with general trends to the WNW and NE. These include the Cat Creek, Lake Basin, and Nye-Bowler fault zones (WNW), and the Fromberg, Weldon, and Brockton-Froid fault zones (NE). Previous work attributes development of these fault zones to transcurrent motion on basement-rooted faults that deformed the sedimentary cover during Laramide orogenesis.

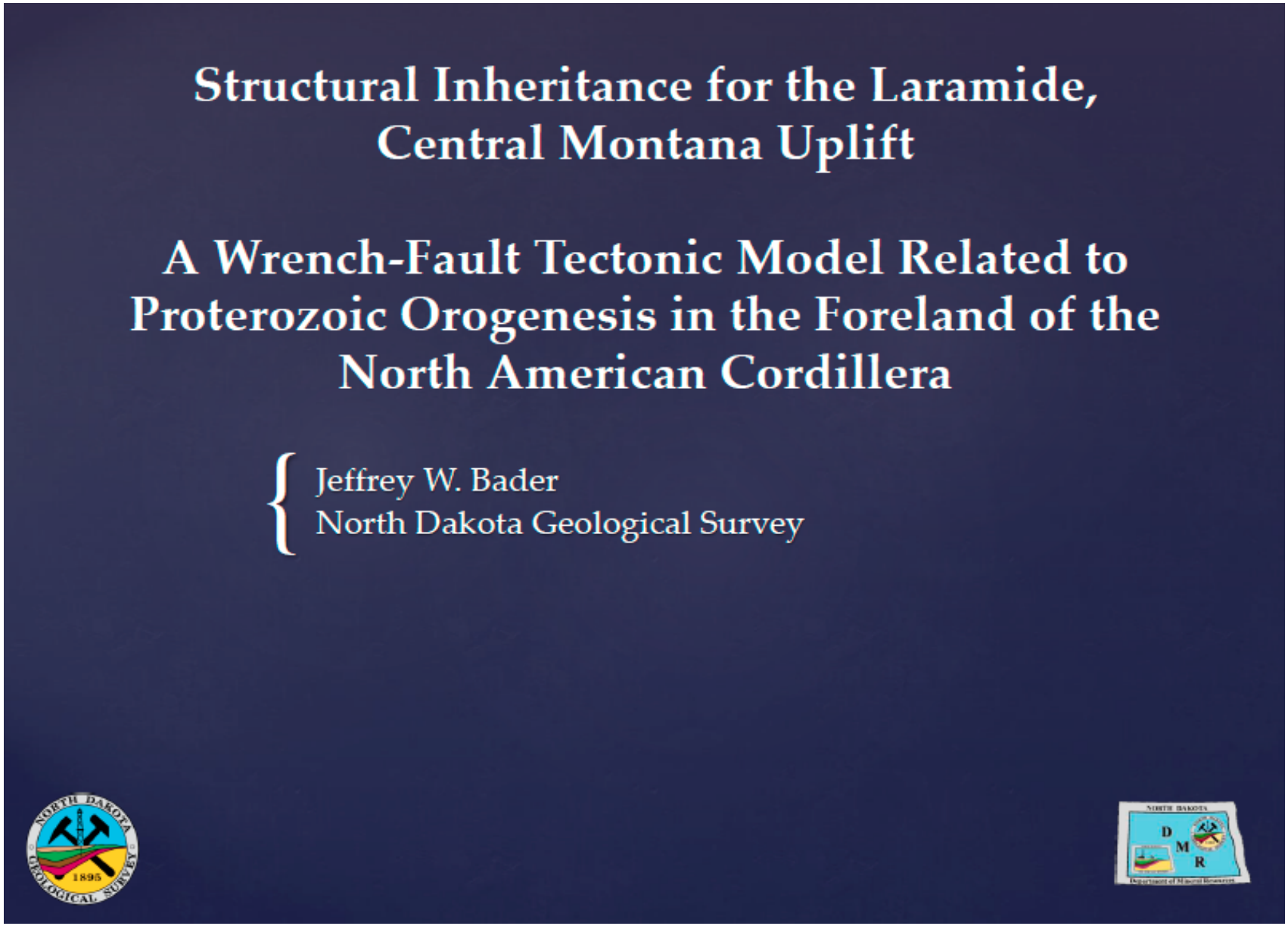
A Paleoproterozoic origin for these fault zones is presented herein, with the faults initially forming as conjugate shears during pure-shear convergence at the northeastern margin of the Wyoming Province. It is further proposed that the conjugate shears were re-activated as simple shears during the Laramide under similar SW-NE stress conditions seen in the Precambrian.

Structural analysis of basement fabrics of the western Beartooth Mountains and Laramide surface structures performed for this study indicate that basement anisotropies (conjugate shears) may have guided Laramide deformation across eastern Montana. Isostatic gravity data support these interpretations. Precambrian development of conjugate shears was likely related to Trans-Hudson (1.78-1.74 Ga) orogenesis along the

eastern Wyoming Province boundary. Data also indicate that these structures were re-activated as wrench faults during the Laramide, forming the Central Montana uplift.

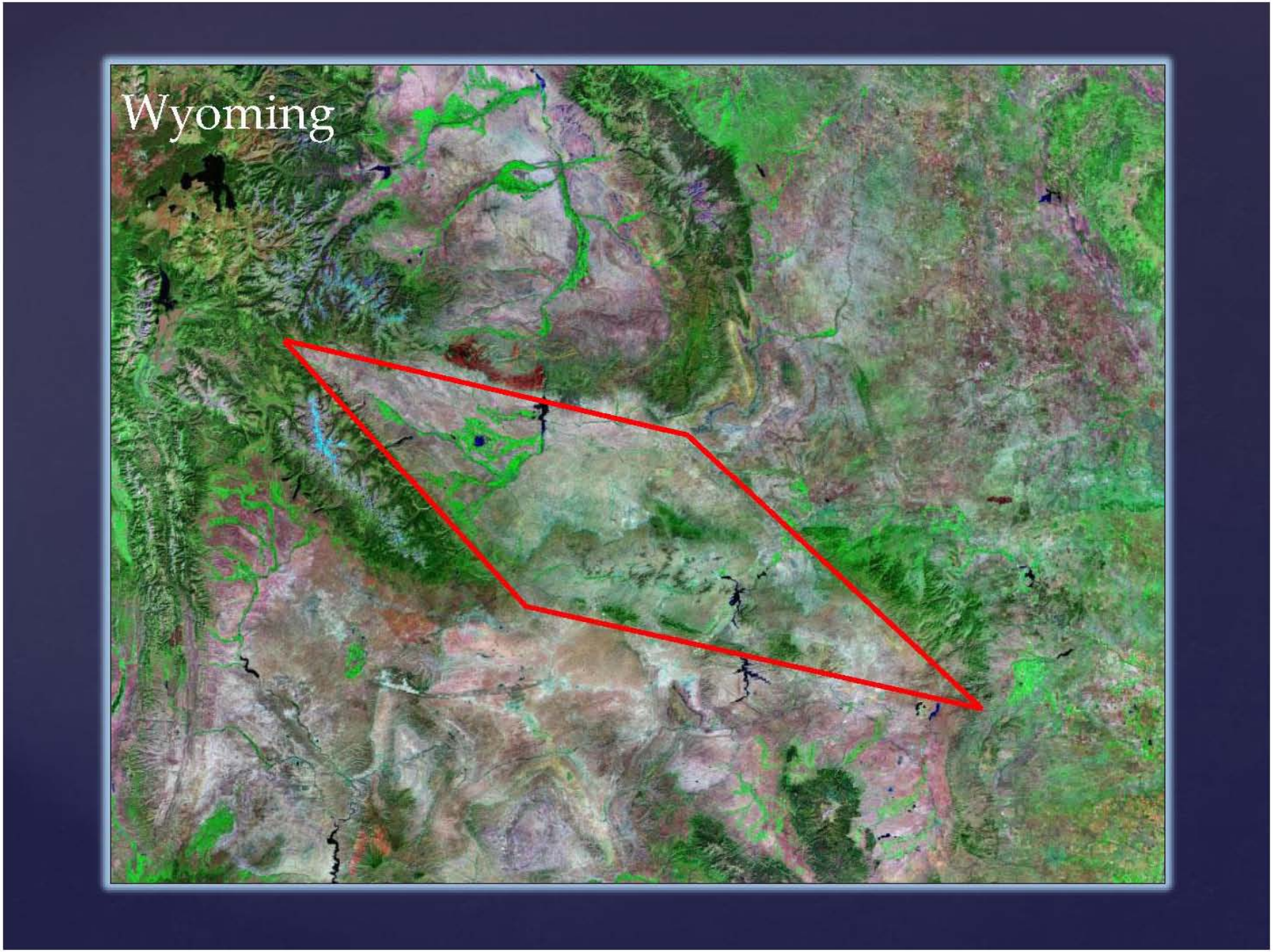
This structural style observed in eastern Montana is also ubiquitous across Wyoming. Therefore, this style is present across the entire Wyoming Province. However, deformation in the core of the craton is likely Archean (Owl Creek and Tensleep fault zones). Basement-rooted deformation zones in northern Wyoming and Montana, and similar zones south of the Owl Creek zone are likely related to Proterozoic pure shear, also directed from SW-NE. Thus, major deformation in basement of the entire province is related first to pure-shear triaxial stress transmitted SW-NE across the craton during Archean convergence (2.6-3.0 Ga), when the craton was much smaller, and then secondly, similar SW-NE-directed pure shear affected the craton in the Proterozoic (1.7-1.9 Ga), after the entire Archean Wyoming Province had been assembled. This second event corresponds to Trans-Hudson orogenesis, and final docking of the Superior and Wyoming cratons to the NE, and Grouse Creek block to the SW.

These Precambrian convergent deformation systems were likely a fundamental tectonic control for Laramide arch/uplift formation in Wyoming and Montana. Western North Dakota and southern Saskatchewan may have developed similar basement anisotropies as a result of docking of the Superior/Wyoming cratons towards the latter stages of the Trans-Hudson orogen. This has implications, not only for the structural and tectonic evolution of the Williston Basin, but also for the formation and development of numerous oil-producing units within the basin.



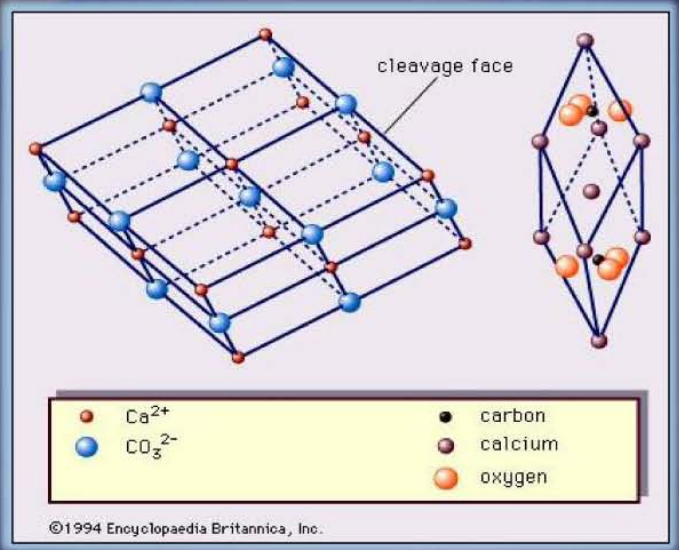
Presenter's notes: This presentation presents the findings of a paper that was recently published in Northwest Geology (Bader, 2019a). It is similar to a paper that was published in Lithosphere in 2018 for the Laramide of north-central Wyoming (Bader, 2018). This work is consistent with that 2018 paper not only mechanically, but temporally as well.

First realize that this work is unlike most, in that the data set for the study consists of assimilation and synthesis of previous work done by others over the last century for the Laramide. So with this presentation, I will continue to try to piece together many of these previous studies, and thus my push for a unified hypothesis for Laramide orogenesis.



Presenter's notes: This is a view from space; a Landsat image of the state of Wyoming. What compelled me was this shape right in the center of Wyoming. The Wind River and Shirley basins, along with the Sweetwater uplift, form a nearly perfect rhomb.

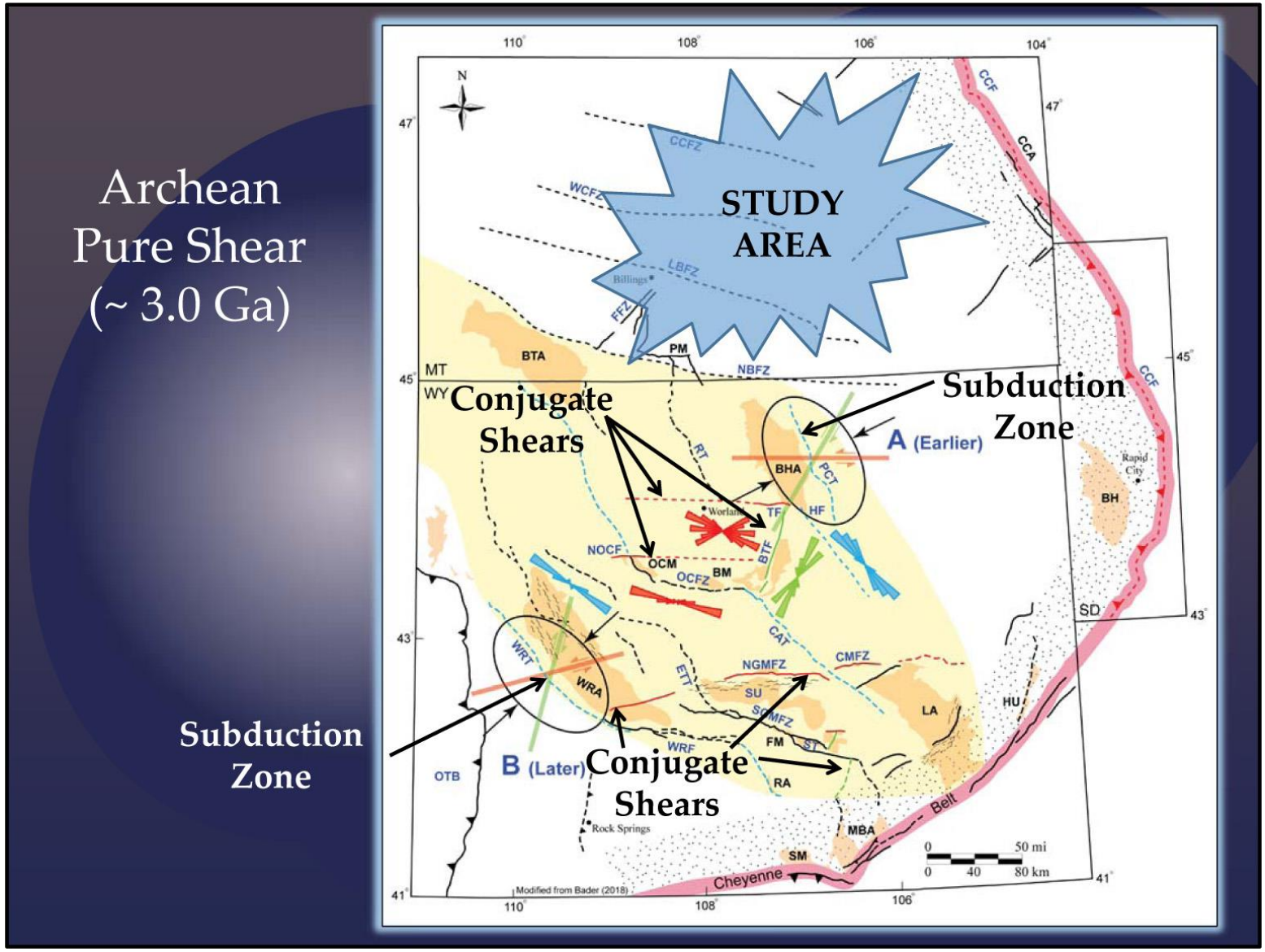
Presenter's notes: The same shape is seen moving to the southwest into the Greater Green River Basin. This "basin symmetry" has not been explained geologically.



Orderly and systematic

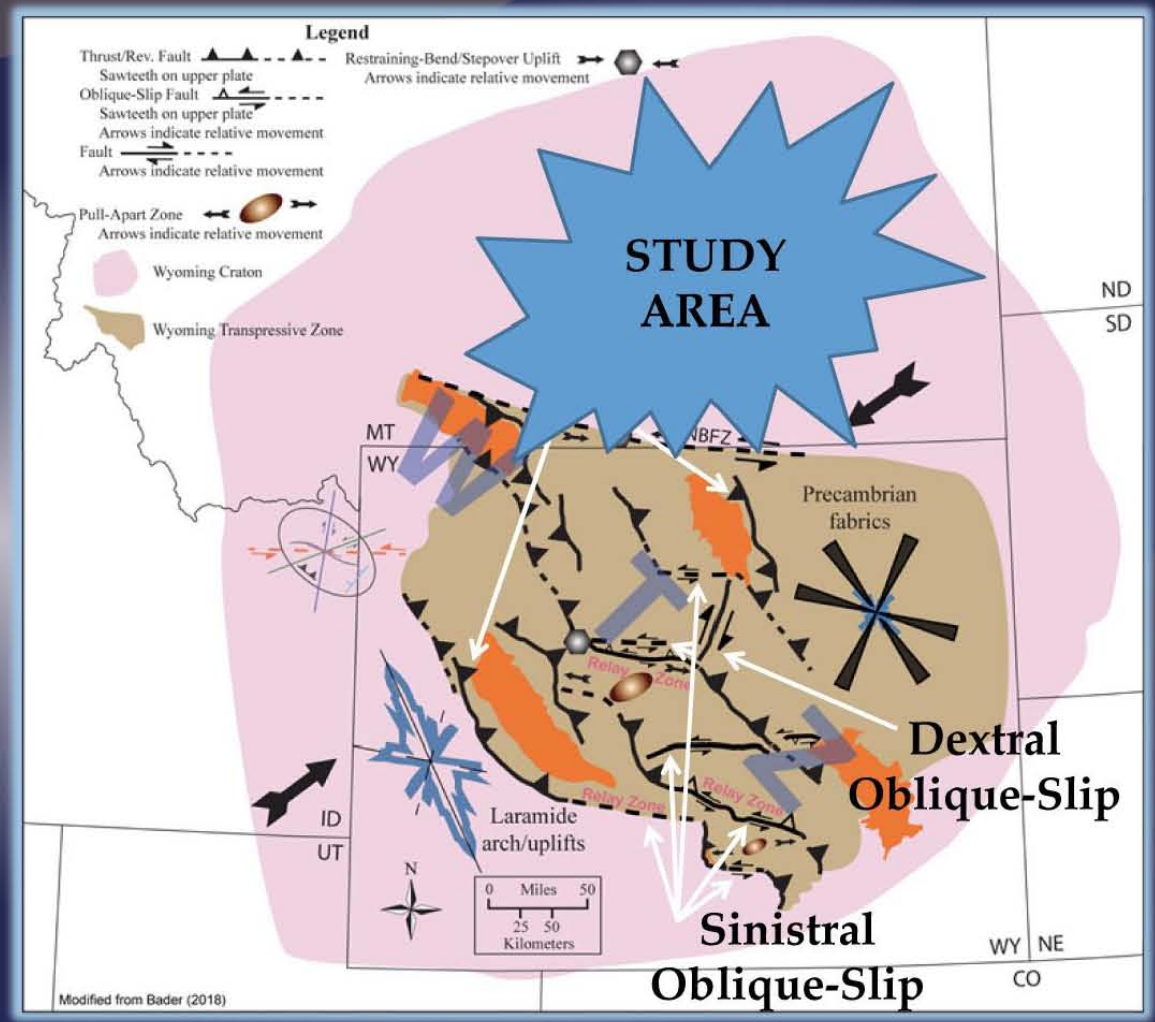
- Fundamental origins;
- Scales may be imperceptible to the naked eye; and
- Can be broken up, disguising original symmetry

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.



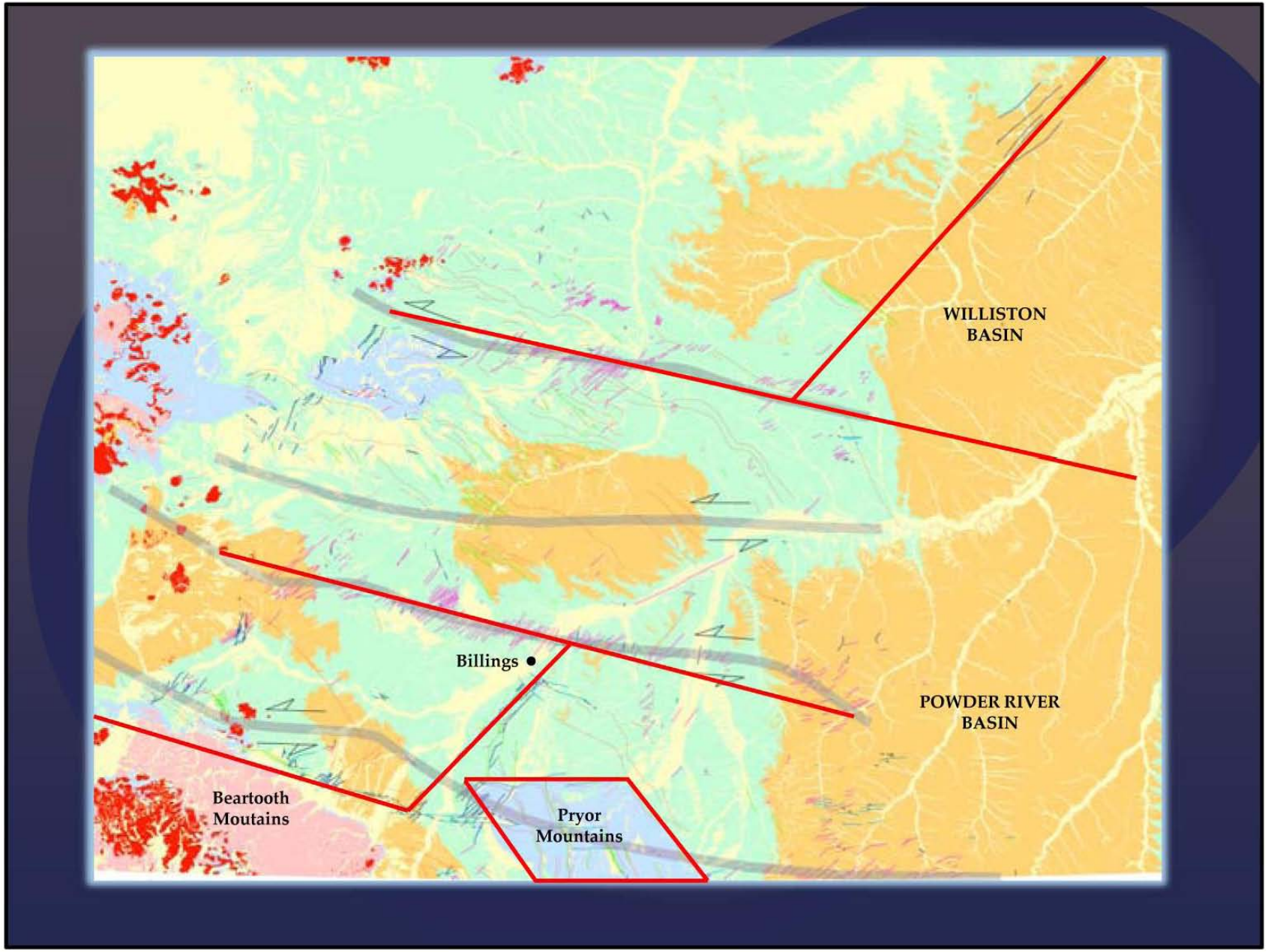
Presenter's notes: So the Montana work is related to a study on structural inheritance in Archean rocks at the northern end of the Laramide belt in north-central Wyoming, just south of this study. The general conclusion from that work, published in Lithosphere (Bader, 2018), was that zones of basement weakness formed in the central core of the Wyoming Province during Archean convergence events, and were then reactivated during the Laramide orogeny under similar stress/strain conditions as seen in the Precambrian. Simply put, pure shear deformation in the Archean forms fundamental and major zones of weakness across the Wyoming craton shown in yellow, and these basement anisotropies were then reactivated as simple shears and major thrusts during the Laramide, as seen on the next slide.

Laramide Simple Shear

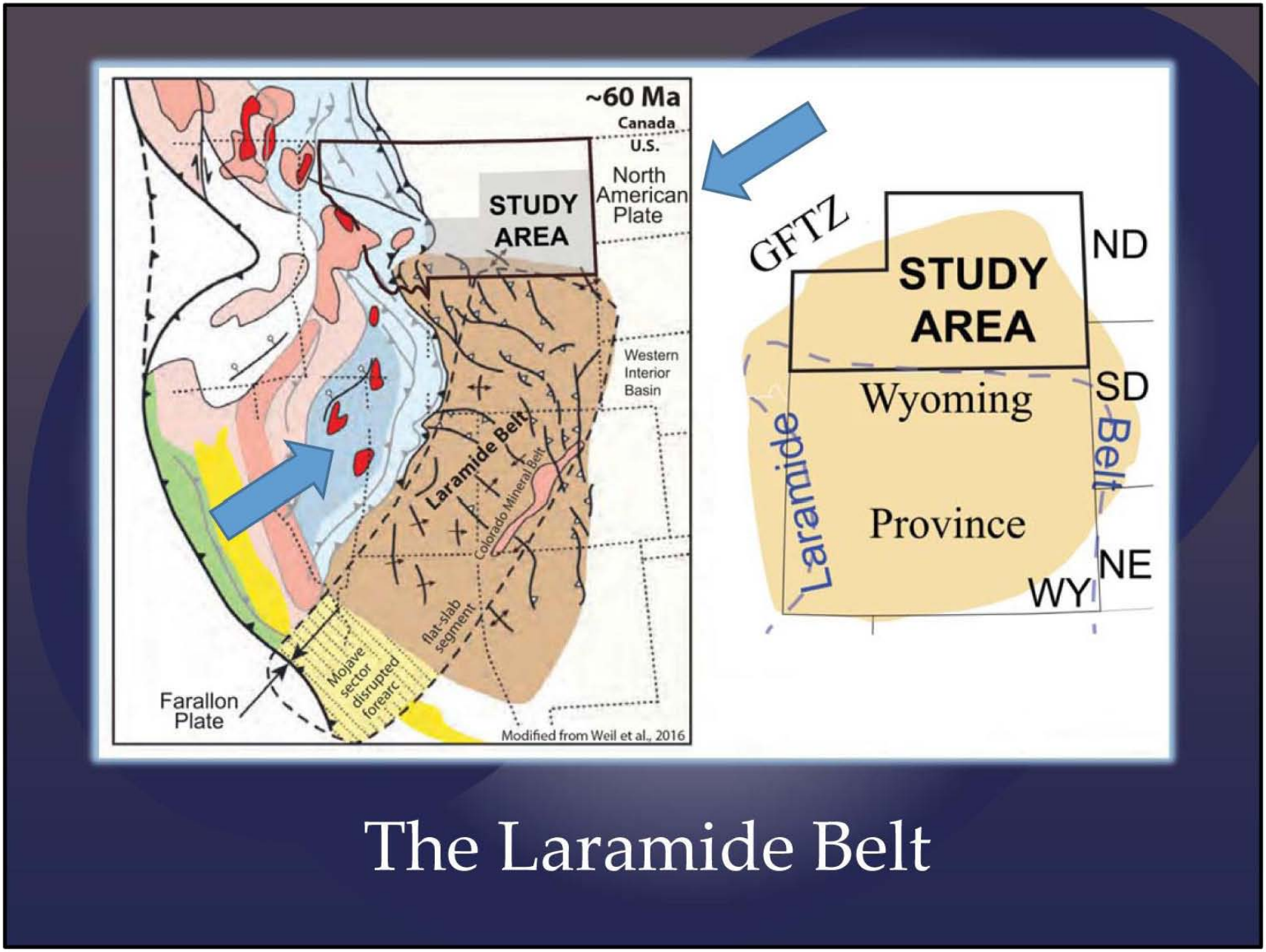


Presenter's notes: In the Laramide, PHS at N60E reactivates the system, major thrusts such as the Wind River and Piney Creek are reactivated and, where connected, lateral shift is facilitated by WNW striking reverse-sinistral oblique-slip faults across the craton. Relay zones (S. Owl Creek fault) between major thrusts developed as a result of this sinistral simple-shear across the WNW-striking structures in the Laramide. Dextral faults (e.g., Big Trails fault) also reactivated, but less extensively. Now let's move north to the study area.

Presenter's notes: This is a preliminary tectonic map of eastern Montana that eventually became a poster that was presented at GSA in 2012, but never published. Once this map was completed, I began working on a paper to present and discuss what I was seeing. At first it was one paper, then it got broke into two, Wyoming and Montana. This presentation includes the Montana part.



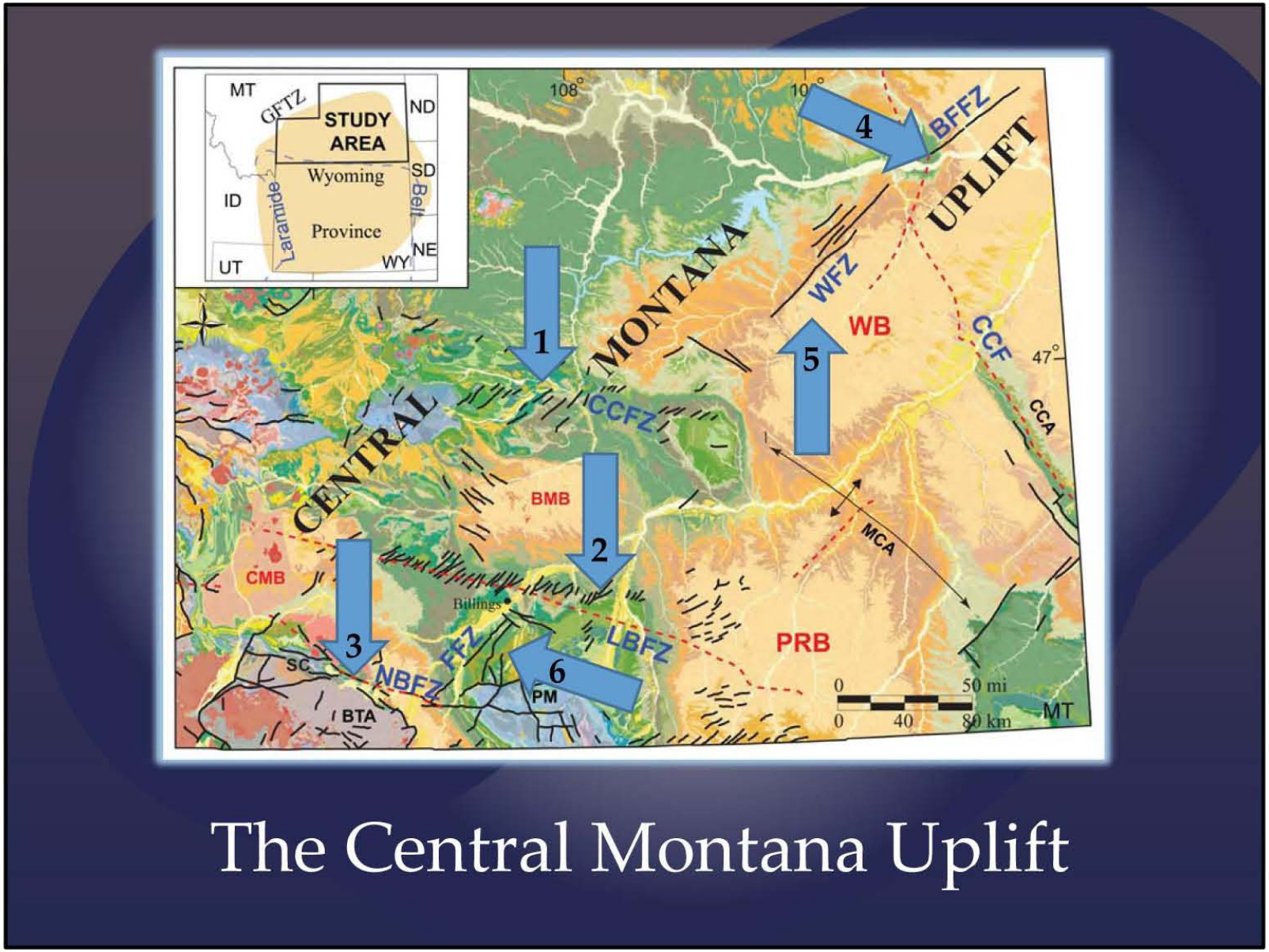
Presenter's notes: So, in conjunction with the Wyoming work, similar patterns were noted in the structural grain of eastern Montana. These patterns suggested that similar convergence events and associated deformation may have occurred in the Paleoproterozoic at the northeastern margin of the Wyoming Province.



Presenter's notes: Seen just north of the Laramide belt on this slide. The study area is in central and eastern Montana, a substantial area, covering about half of Montana. The Wyoming study concentrated on north-central Wyoming looking at the core of the Wyoming craton, whereas this study deals with the northernmost portion of the craton. (*Presenter's notes continued on next slide.*)

(*Presenter's notes continued from previous slide*.)

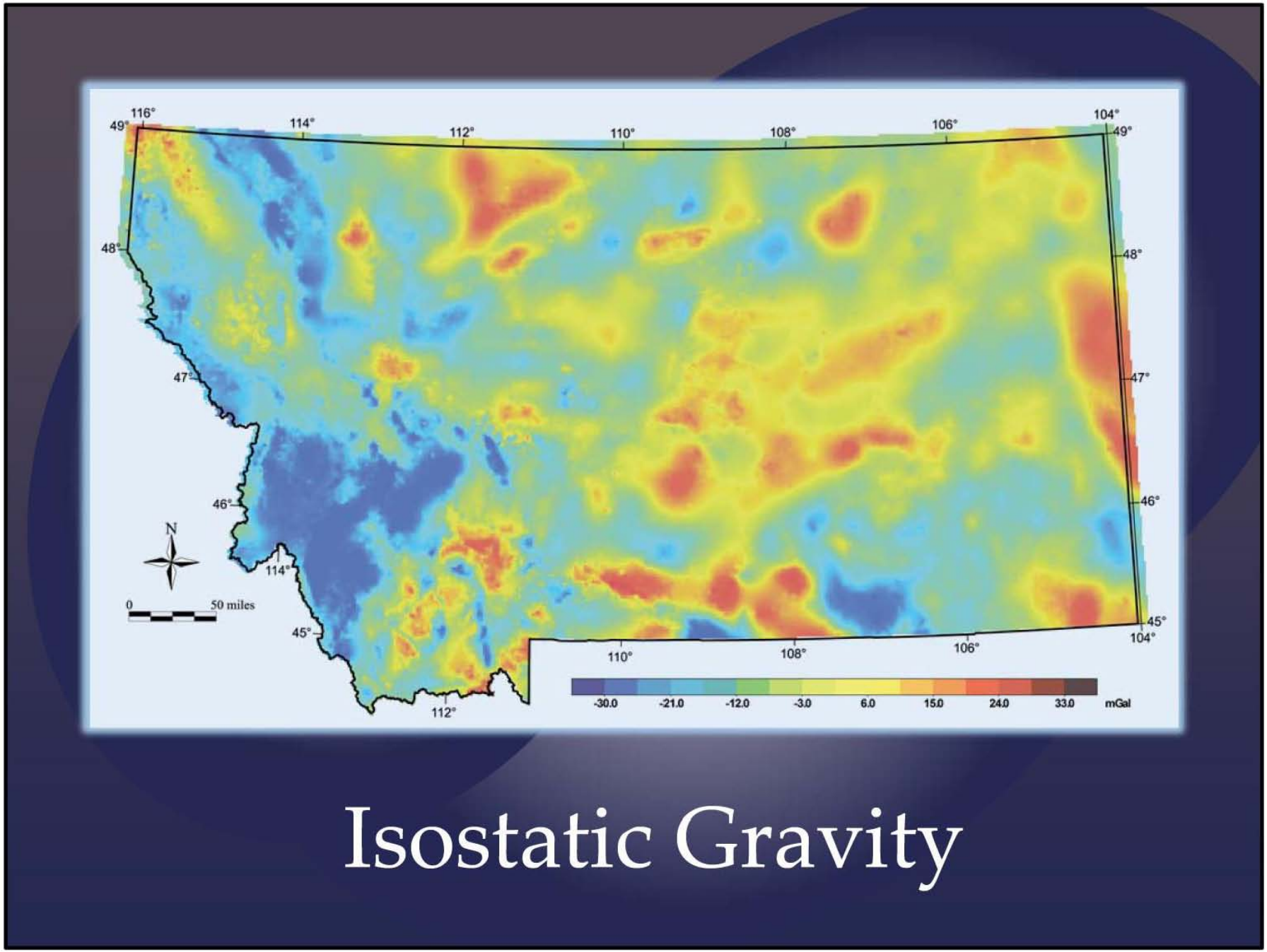
Reviewing the Laramide belt; it is characterized by basement-cored thick-skinned arches/uplifts extending from AZ/NM to southern MT, as seen for this Paleocene reconstruction of the North American Cordillera (Weil and Yonkee, 2012; Weil et al., 2016). The formation of the belt has generally been attributed to shallow-angle subduction of the Farallon Plate beneath the North American Plate at about 60-million years ago.
Deformation is up to approximately 1,500 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 controversary is the varied orientations of the Laramide arches and uplifts that appear somewhat random (Gries, 1983; Varga, 1993). I will continue my Wyoming argument that orientations of Laramide structures seen at the surface are anything but random, and the patterns seen in northern Wyoming continue to nearly Canada/North Dakota, and perhaps beyond. Finally, the Laramide shortening direction has been shown to be from the ENE at about N60E, sub-parallel to the Farallon Plate orientation.



The Central Montana Uplift

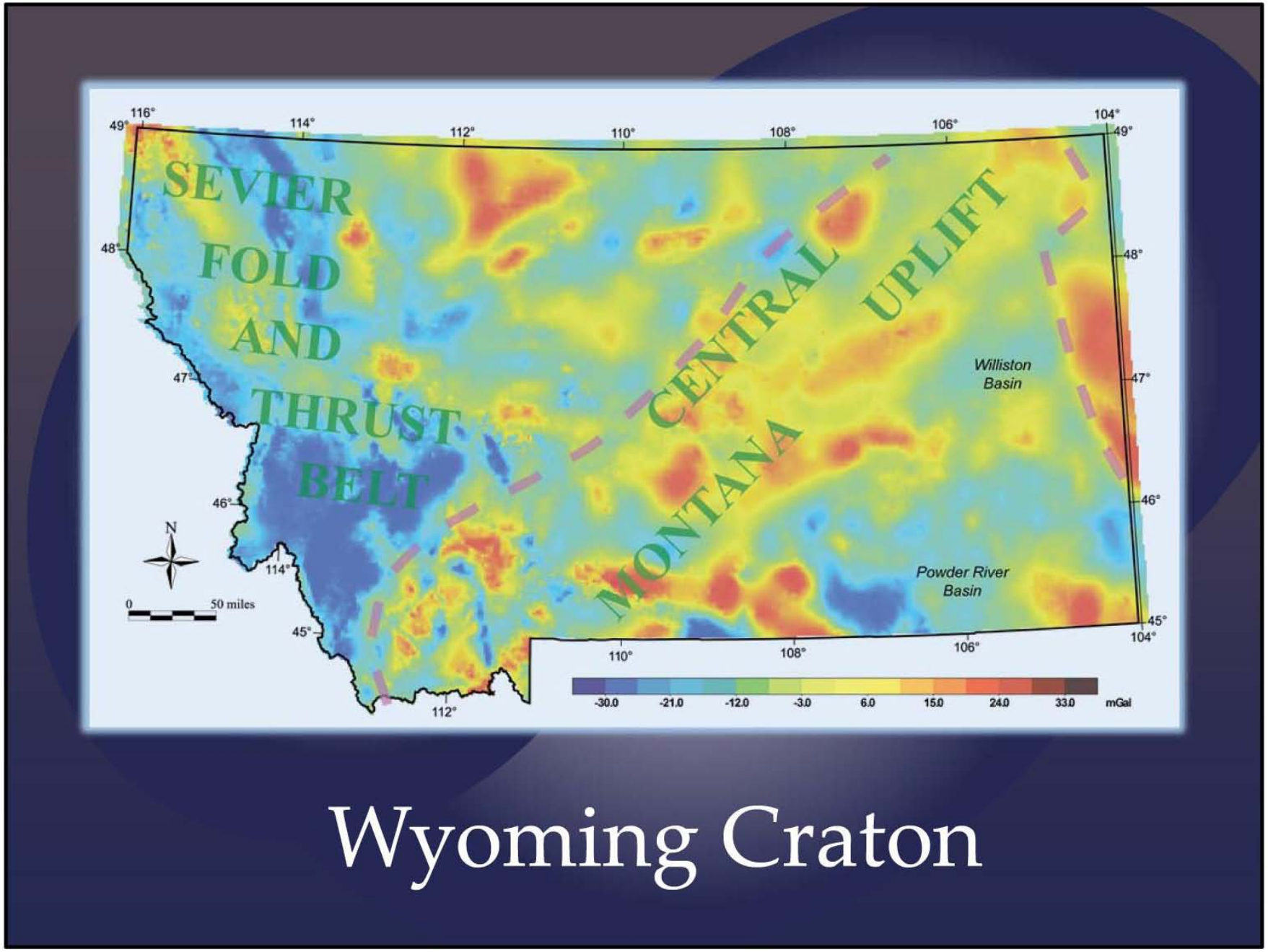
Presenter's notes: This is a geologic map of the Central Montana uplift. It is characterized by six rectilinear faults zones, three WNW, and three NE, that give the uplift a general NNE structural grain. These zones have generally been attributed to basement-rooted wrenching during the Laramide. The Laramide Williston and Powder River basins dominate the eastern part of the study area, along with the Cedar Creek anticline. Smaller basins include the Bull Mountains and Crazy Mountains basins present in the core of the uplift. The Pryor Mountains and Laramide Beartooth arch are present at the southern margin of the study area.

Presenter's notes: The objectives of this study were relatively straightforward, and the preliminary results are as well. Firstly, I wanted to confirm the nature of the surface fault zones. This was done using isostatic gravity data along with structural analysis. Secondly, I wanted to partly test my hypothesis that the WNW-and NE-fault zones were reflections of Precambrian basement weakness that were reactivated during Laramide orogenesis. Isostatic gravity data along with fabric data from the Beartooth Mountains was used for this part of the study. Finally, I used the data to see if there was evidence for structural inheritance, focusing on what we unequivocally know about plate tectonic relations in both the Precambrian and during the Laramide.



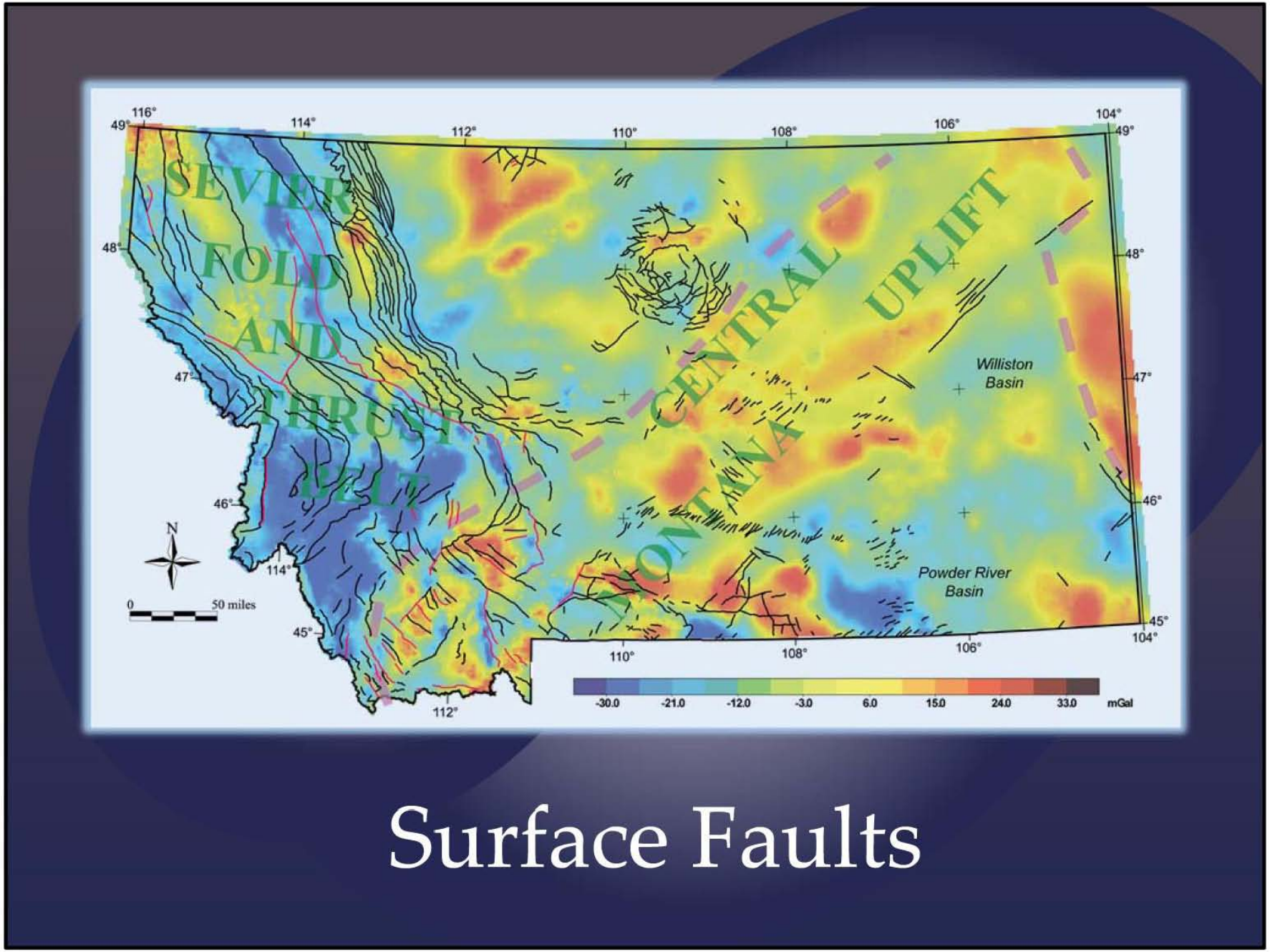
Isostatic Gravity

Presenter's notes: We will start with the isostatic gravity map of Montana shown here.



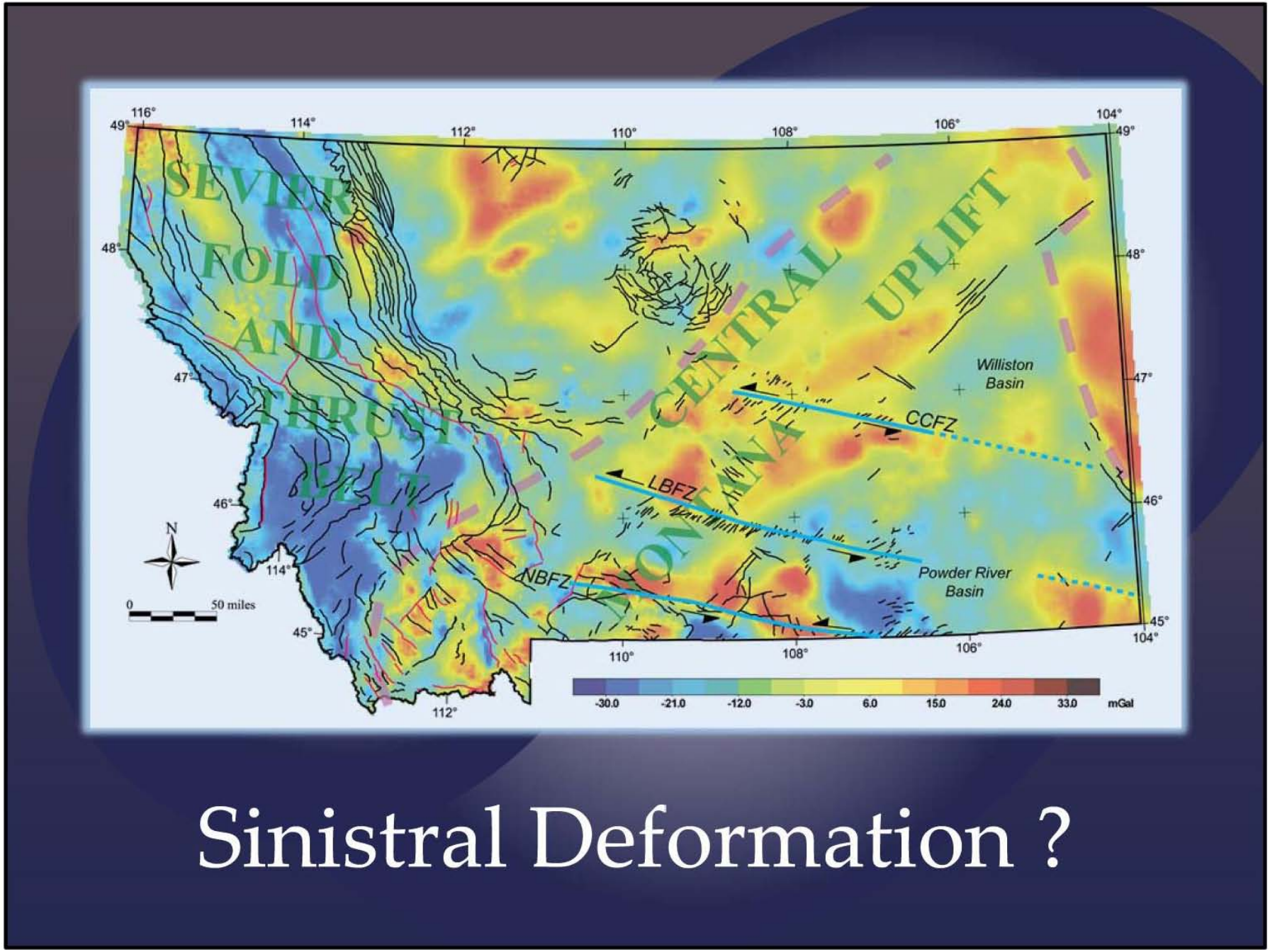
Wyoming Craton

Presenter's notes: Here I have shown the approximate boundary of the Wyoming craton, and you can see the uplift gravity-high clearly extends from south-central Montana to the northeast. The Williston and Powder River Basins are expressed as gravity lows.



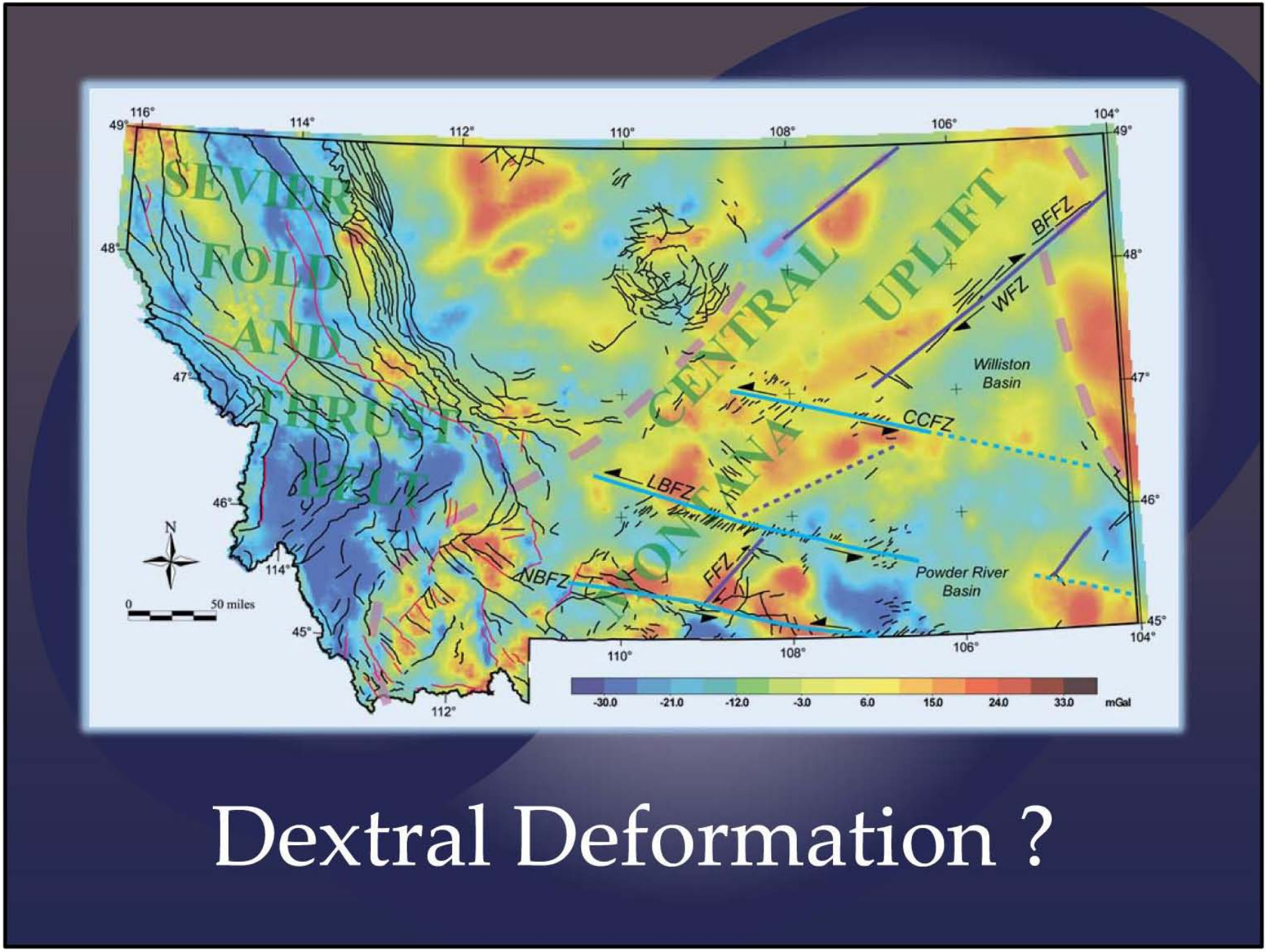
Surface Faults

Presenter's notes: Bringing in the surface faults from the geologic map of Montana, the form of the uplift is now taking shape.



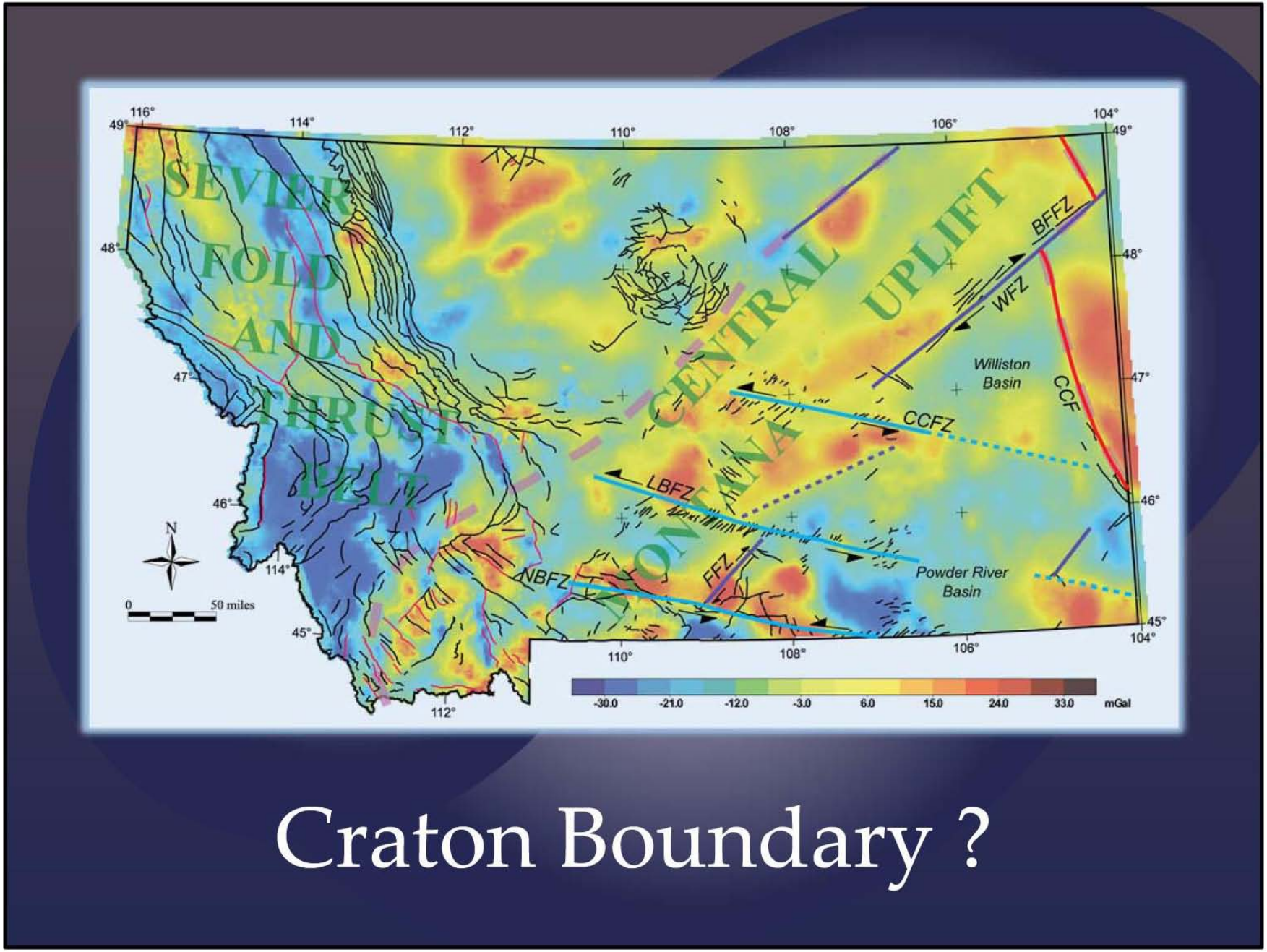
Sinistral Deformation ?

Presenter's notes: First, the proposed sinistral deformation zones striking WNW.

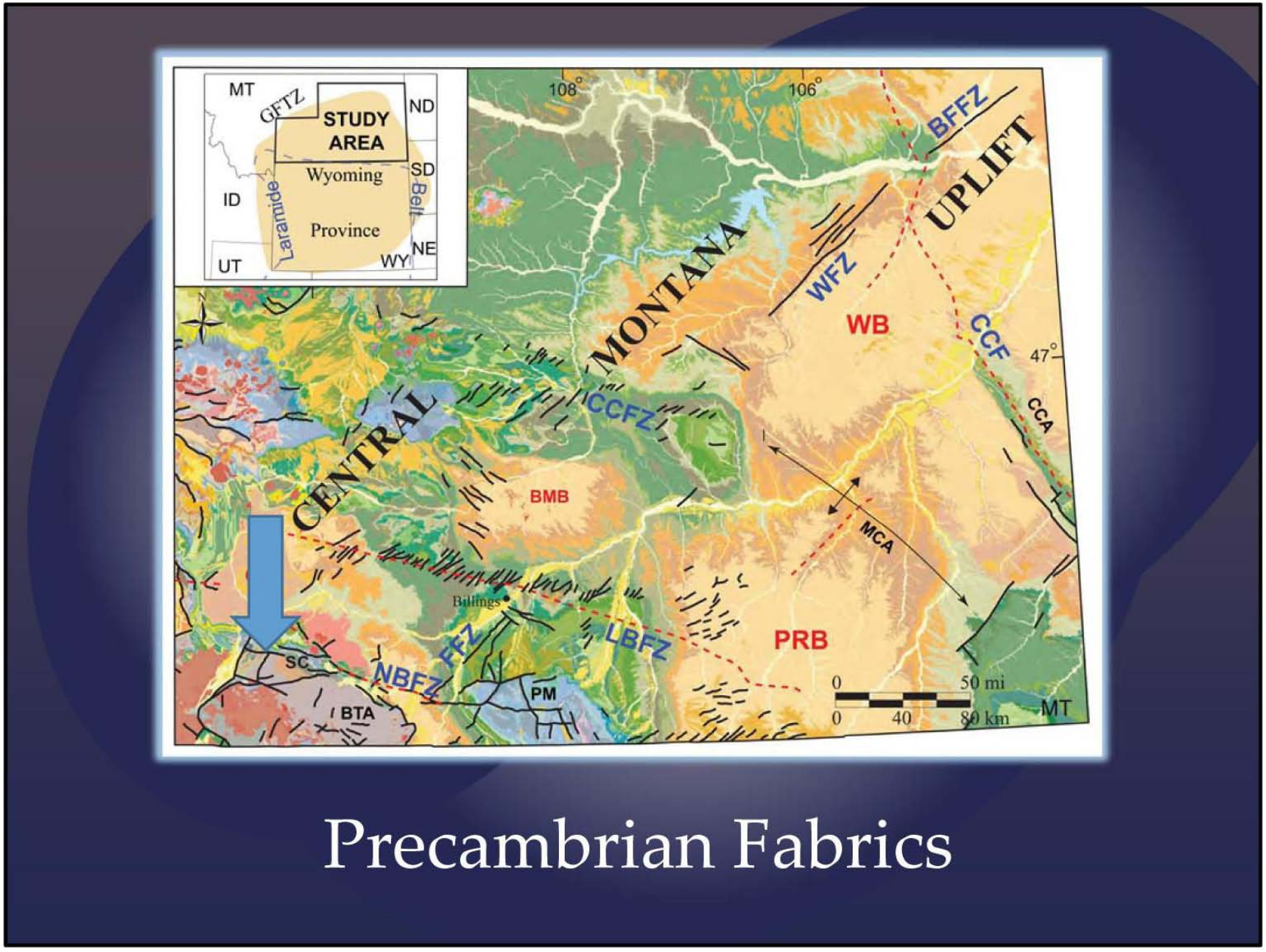


Dextral Deformation ?

Presenter's notes: Next, the proposed dextral deformation zones striking NE.

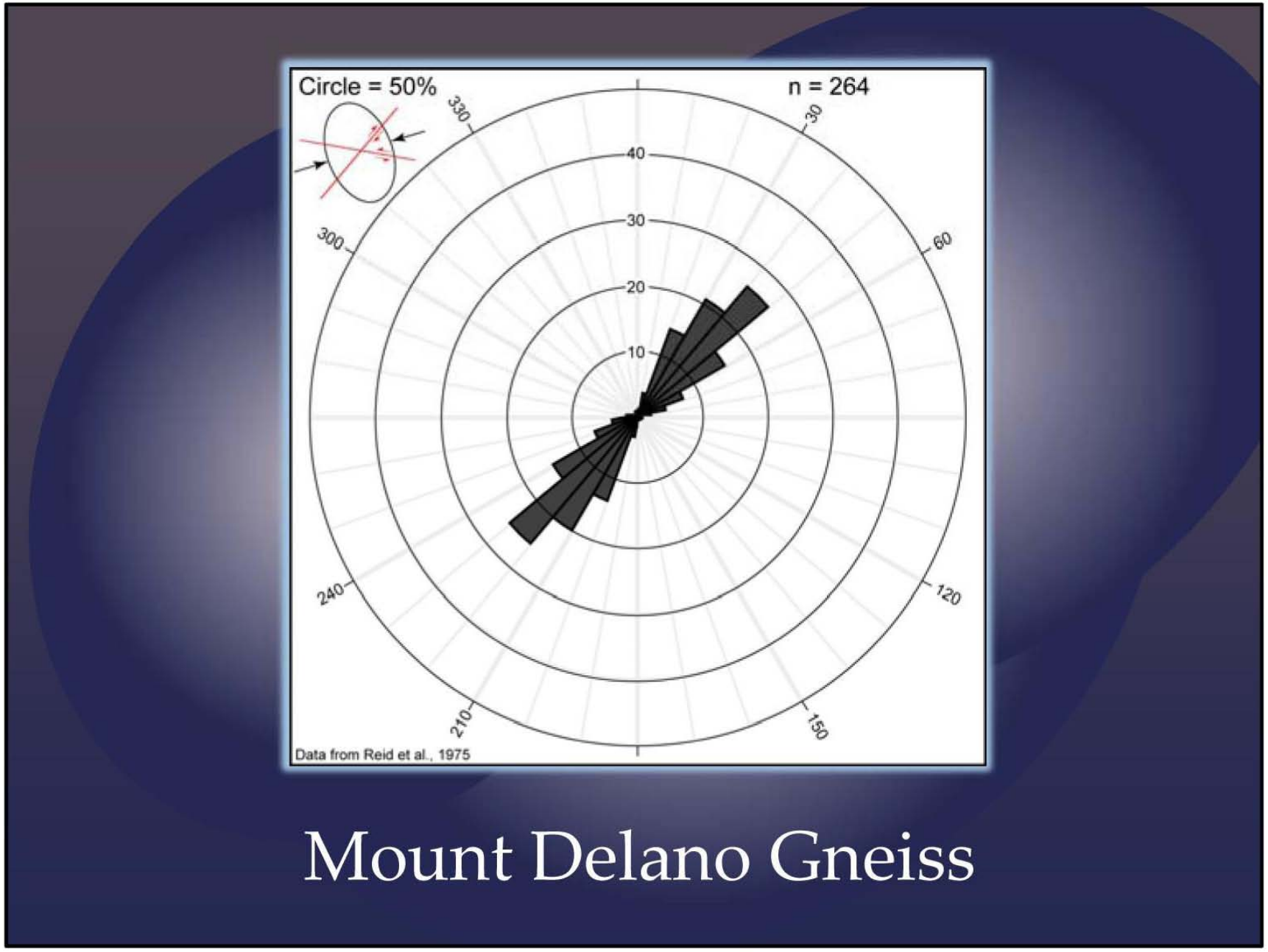


Presenter's notes: and lastly, the proposed craton boundary defined by the Cedar Creek anticline/fault. So just based on the gravity data, we can clearly see the uplift and the well-defined linear zones of deformation, but is this confirmed by basement fabric data?



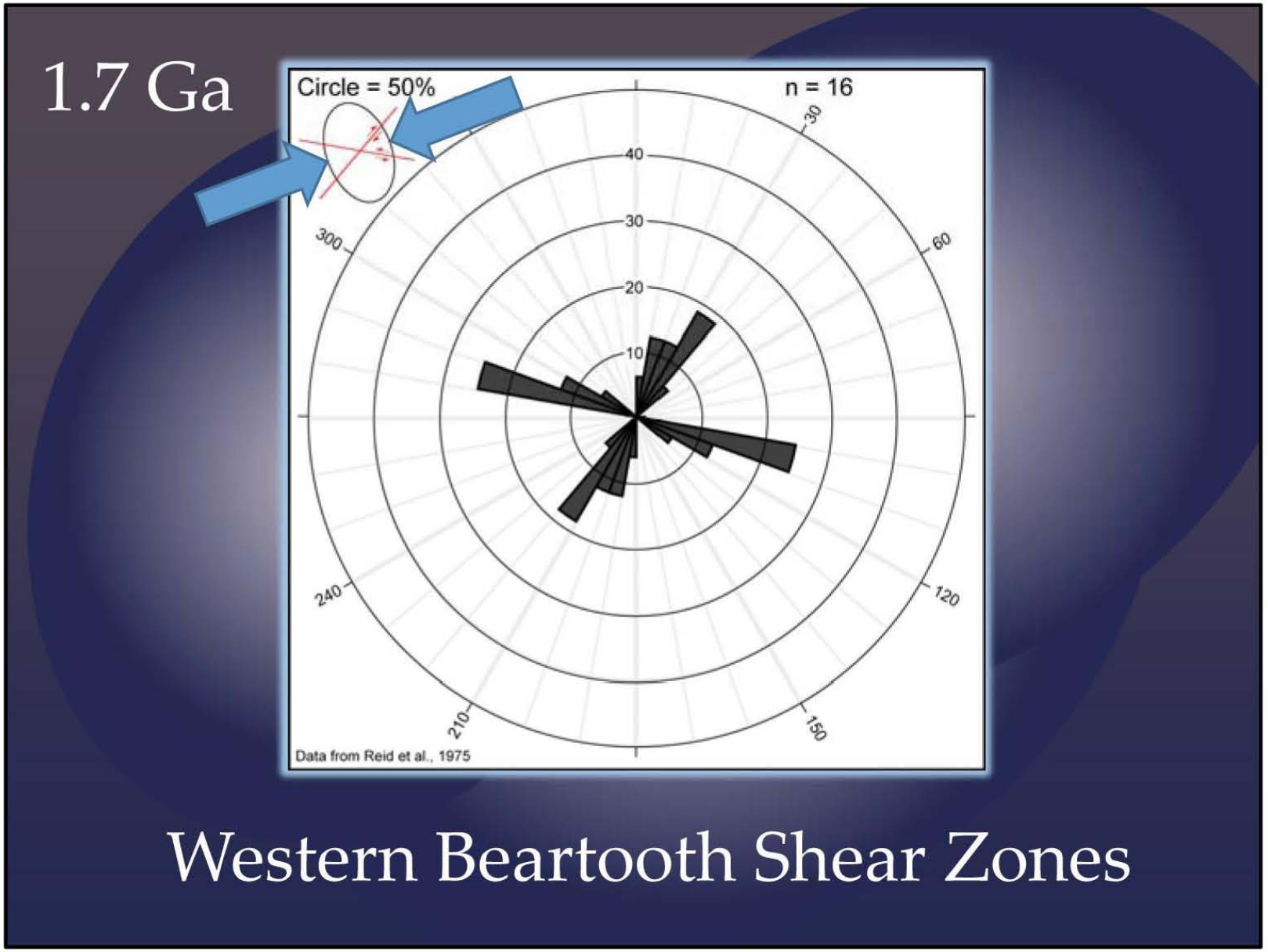
Precambrian Fabrics

Presenter's notes: Unlike north-central Wyoming, Precambrian basement is not exposed in the Central Montana uplift. However, some data was available from the Western Beartooth Mountains near the Stillwater Complex.

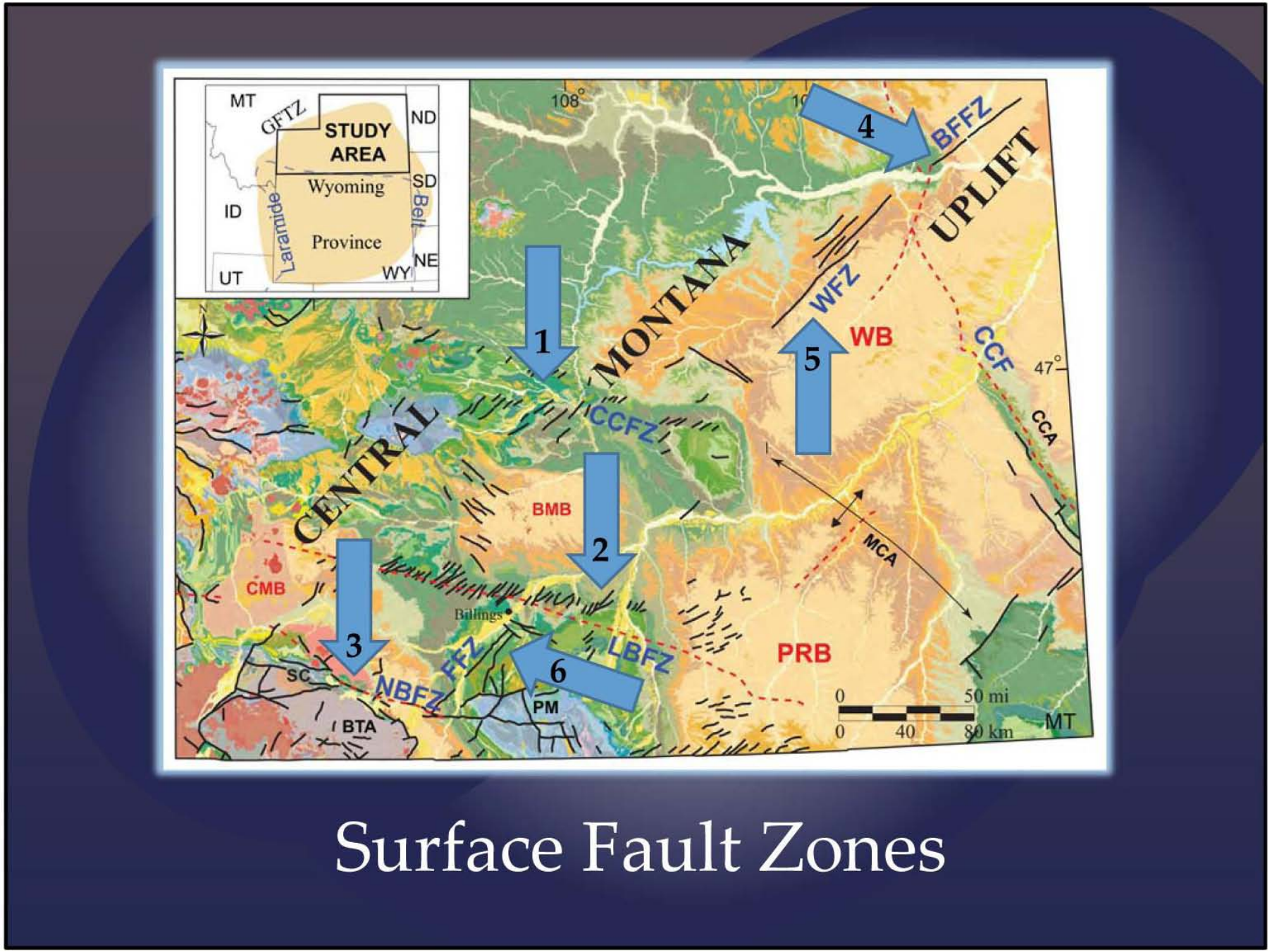


Mount Delano Gneiss

Presenter's notes: Pervasive foliations in the Mount Delano gneiss were measured by Reid and others (1975), shown on this rose diagram. The foliations show a unimodal pattern of approximately N45E, which is subparallel to the NE-striking faults zones at approximately N40E, and consistent with pure shear from the ENE.

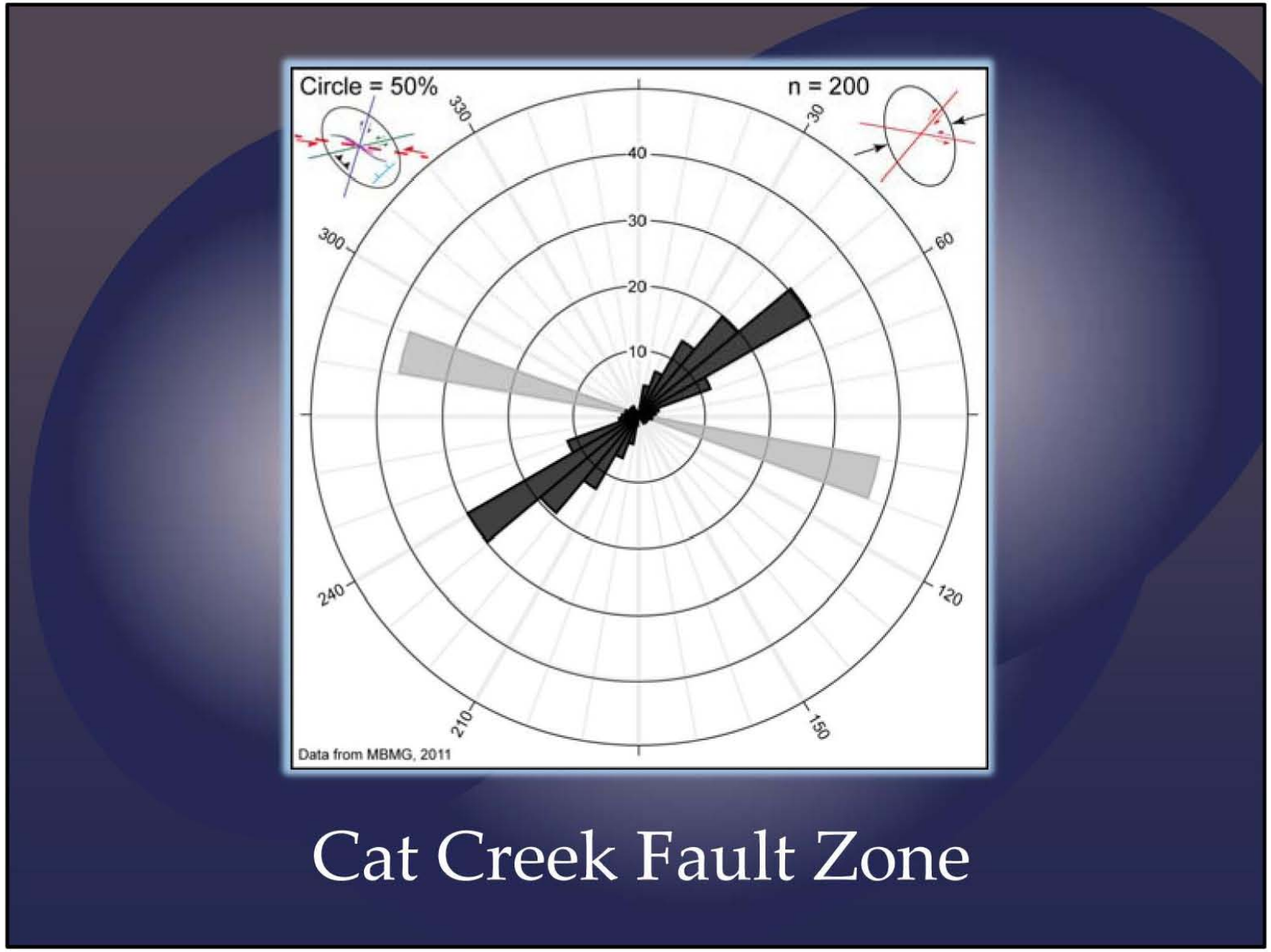


Presenter's notes: Shear zones in the same area of the Beartooths, also from Reid and others (1975), show a bimodal pattern, with the similar NE strike we just saw, and also a WNW strike of N75W, subparallel to the WNW-striking surface fault zones at approximately N80W. Reid's group interpreted these shear zones as forming from NE convergence in the Paleoproterozoic at 1.7 Ga. Therefore, the data from the western Beartooths support the presence of Precambrian anisotropies oriented WNW and NE, and pure shear from the ENE. So how does that fit with the surface fault zones of Laramide age?

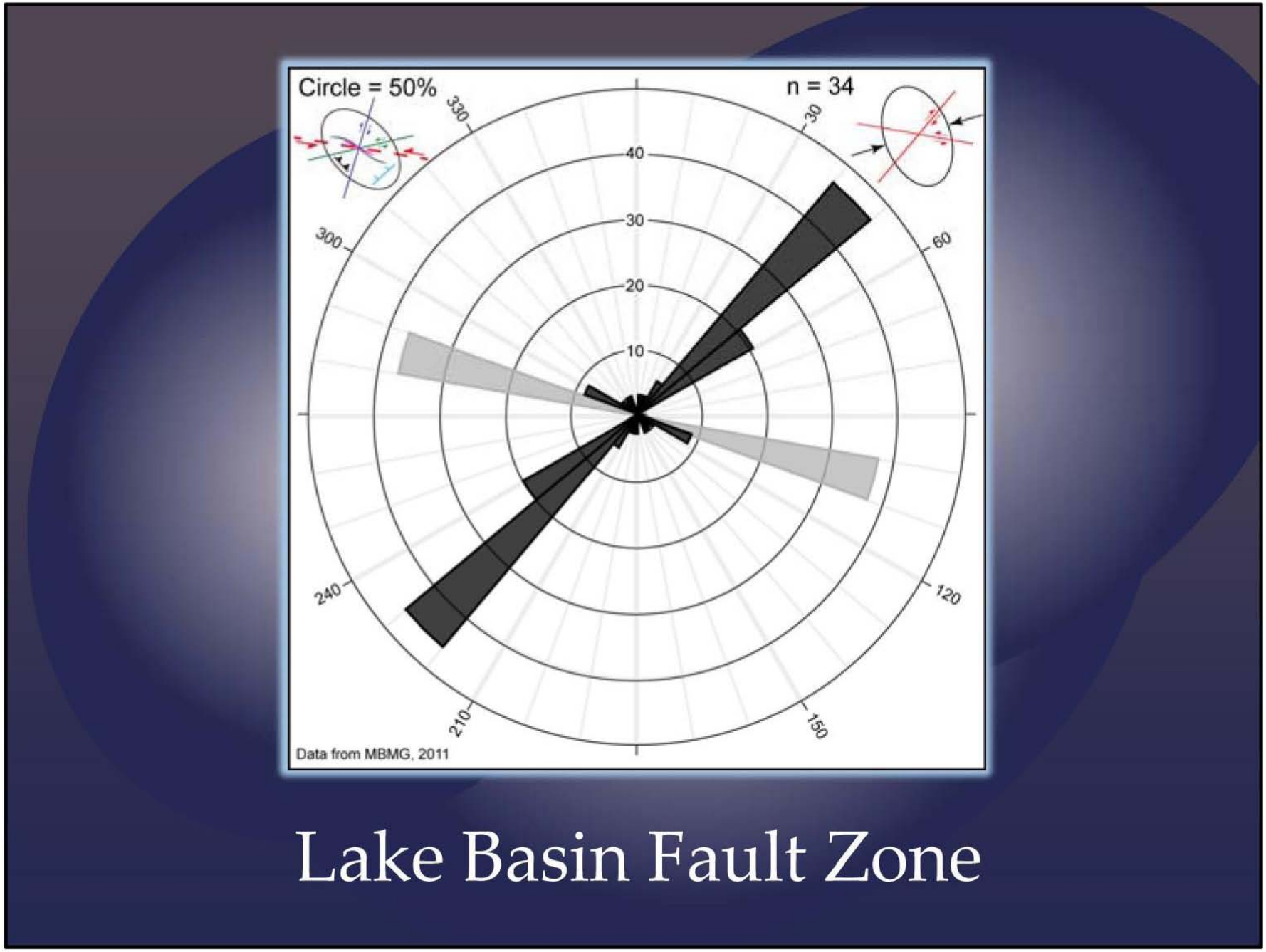


Surface Fault Zones

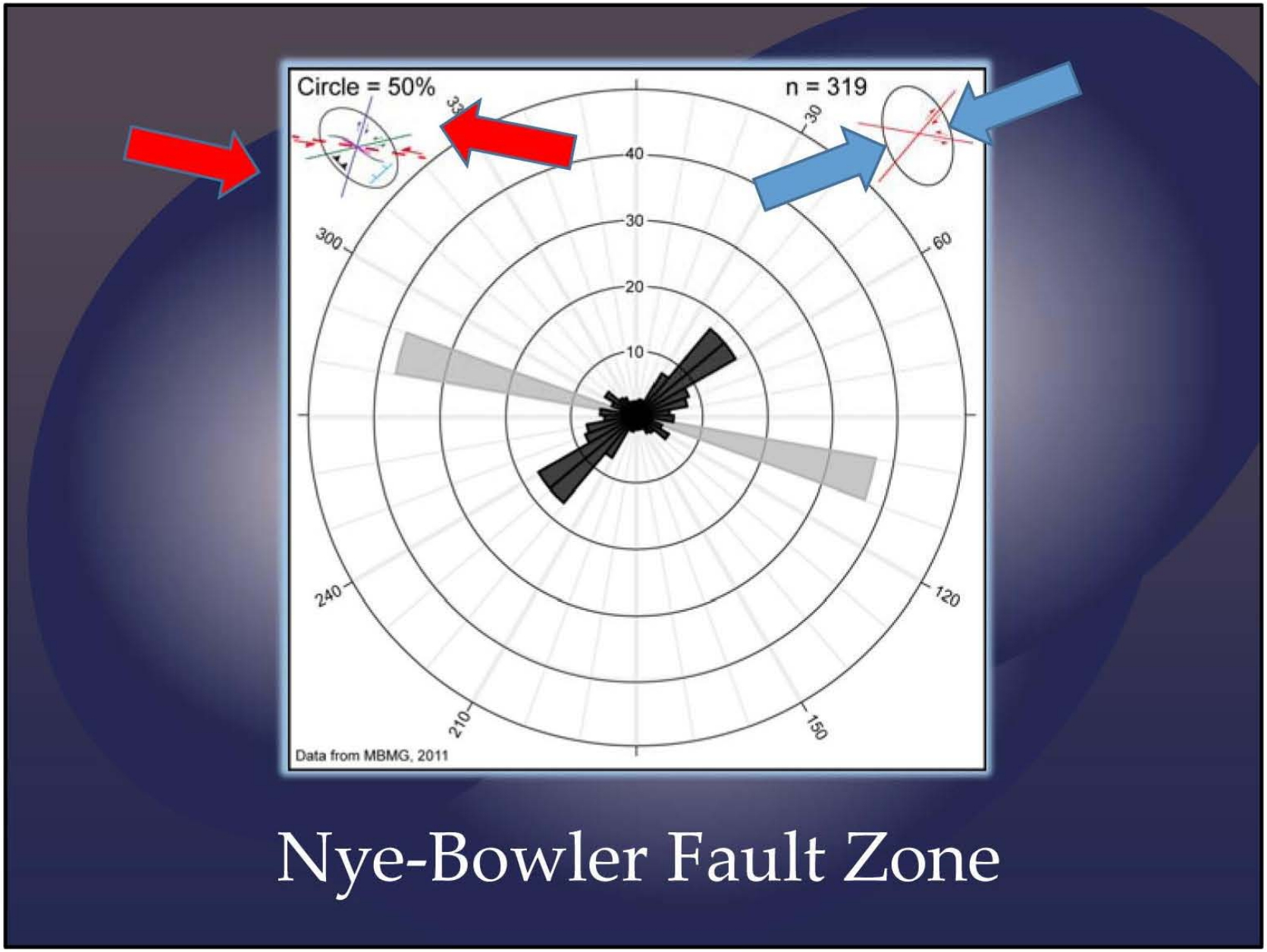
Presenter's notes: Here again we see the six rectilinear fault zones mapped by the MBMG; 3 WNW and 3 NE (MBMG, 2011).



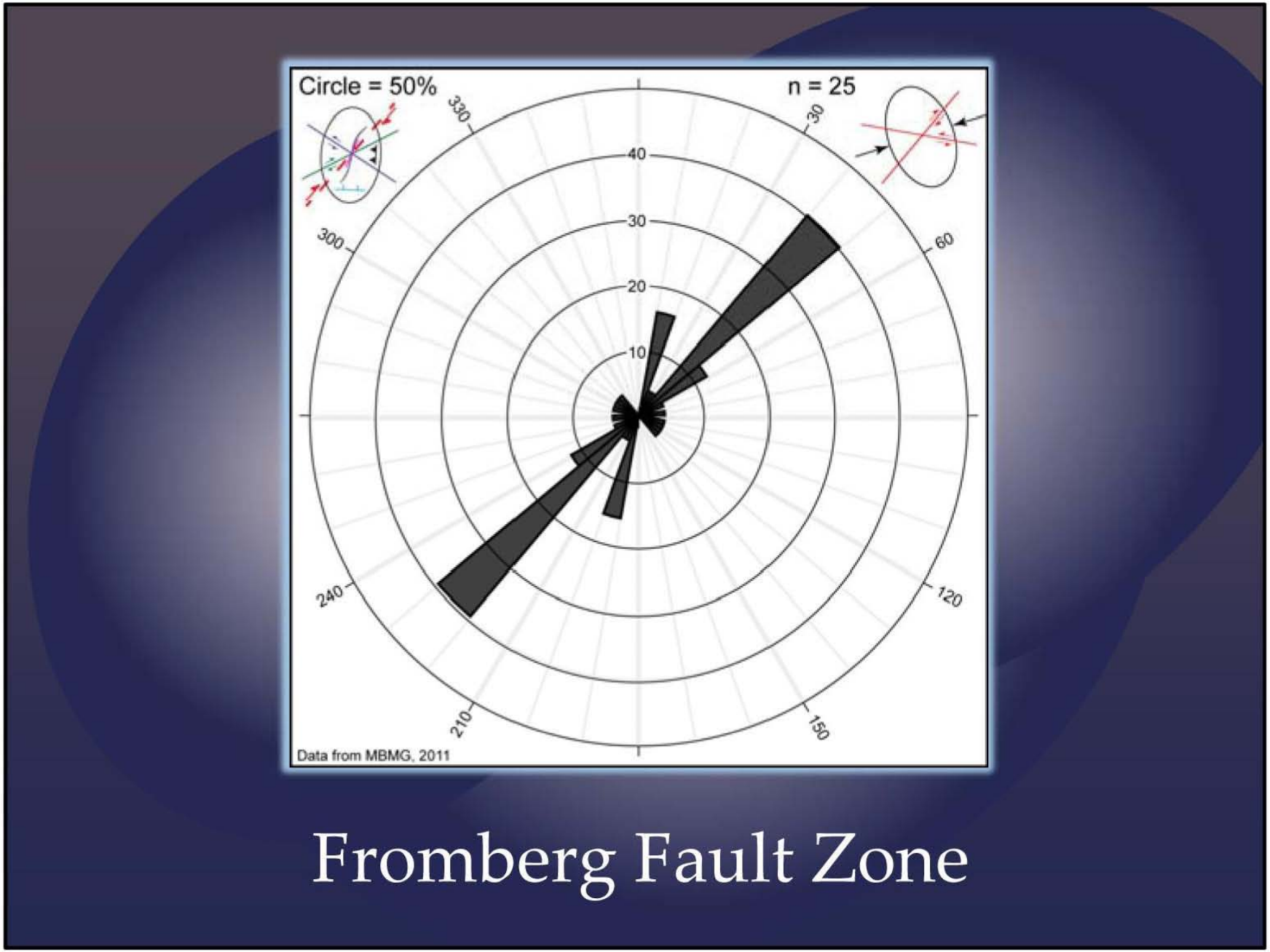
Presenter's notes: Let's start with the WNW zones. Fault strikes were measured from MBMG 100K maps, plotted on rose diagrams, and compared to a proposed master fault strike of N80W, shown in gray. The faults of the Cat Creek zone show a distinct unimodal distribution consistent with dominantly normal faults of a sinistral system as seen by the strain ellipse for a sinistral wrench fault. Therefore, the en echelon and right-stepping mapped faults of the Cat Creek zone compare very favorably with the data and are also consistent with a pure-shear origin, based on the strike of the proposed master fault; formed in the Precambrian, reactivated during the Laramide.



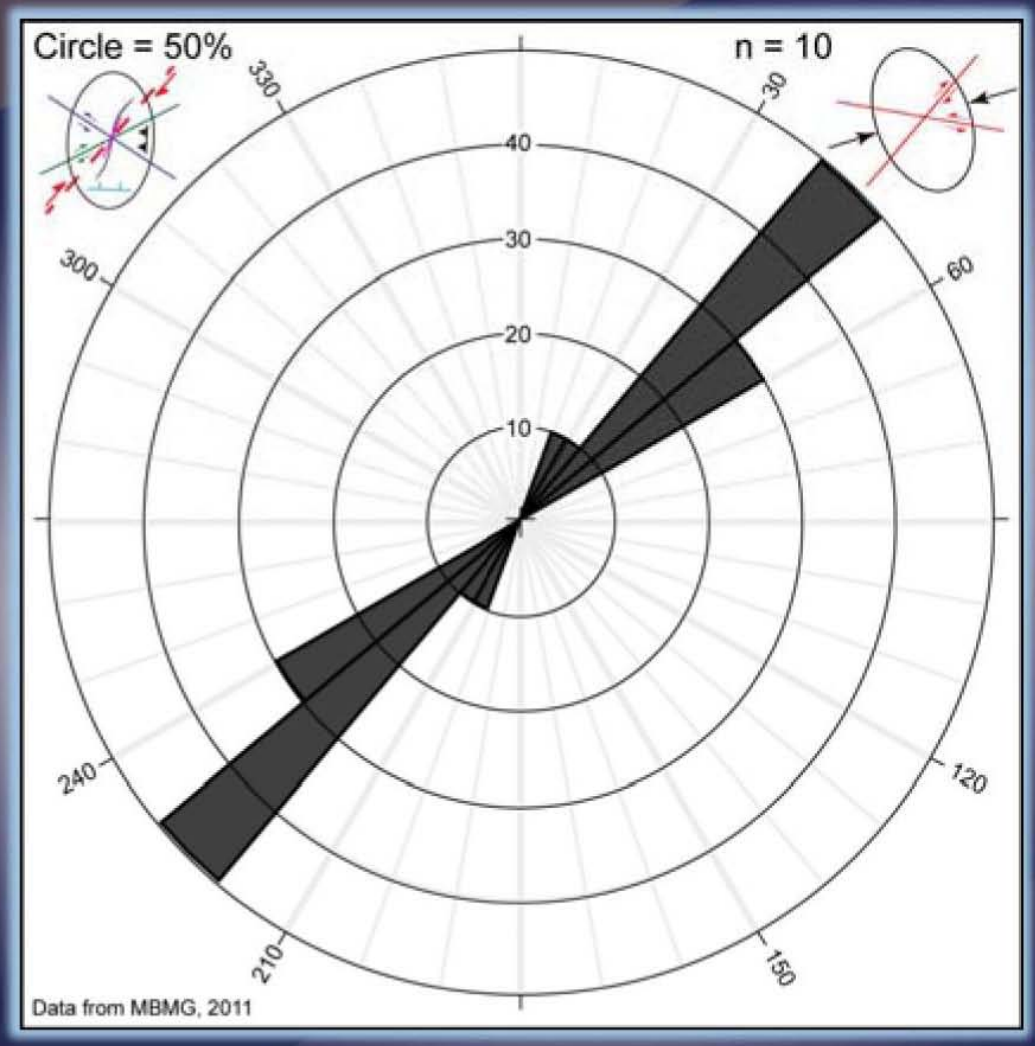
Presenter's notes: Similar for the Lake Basin zone, with some different subsidiary faults.



Presenter's notes: and the Nye-Bowler zone as well, with even more subsidiary faults. Therefore, the data support the interpretation that these fault zones are indeed related to transcurrent movement on high-angle, basement-rooted faults that deformed the sedimentary cover during the Laramide. Again, pure shear origin, Laramide simple-shear reactivation.

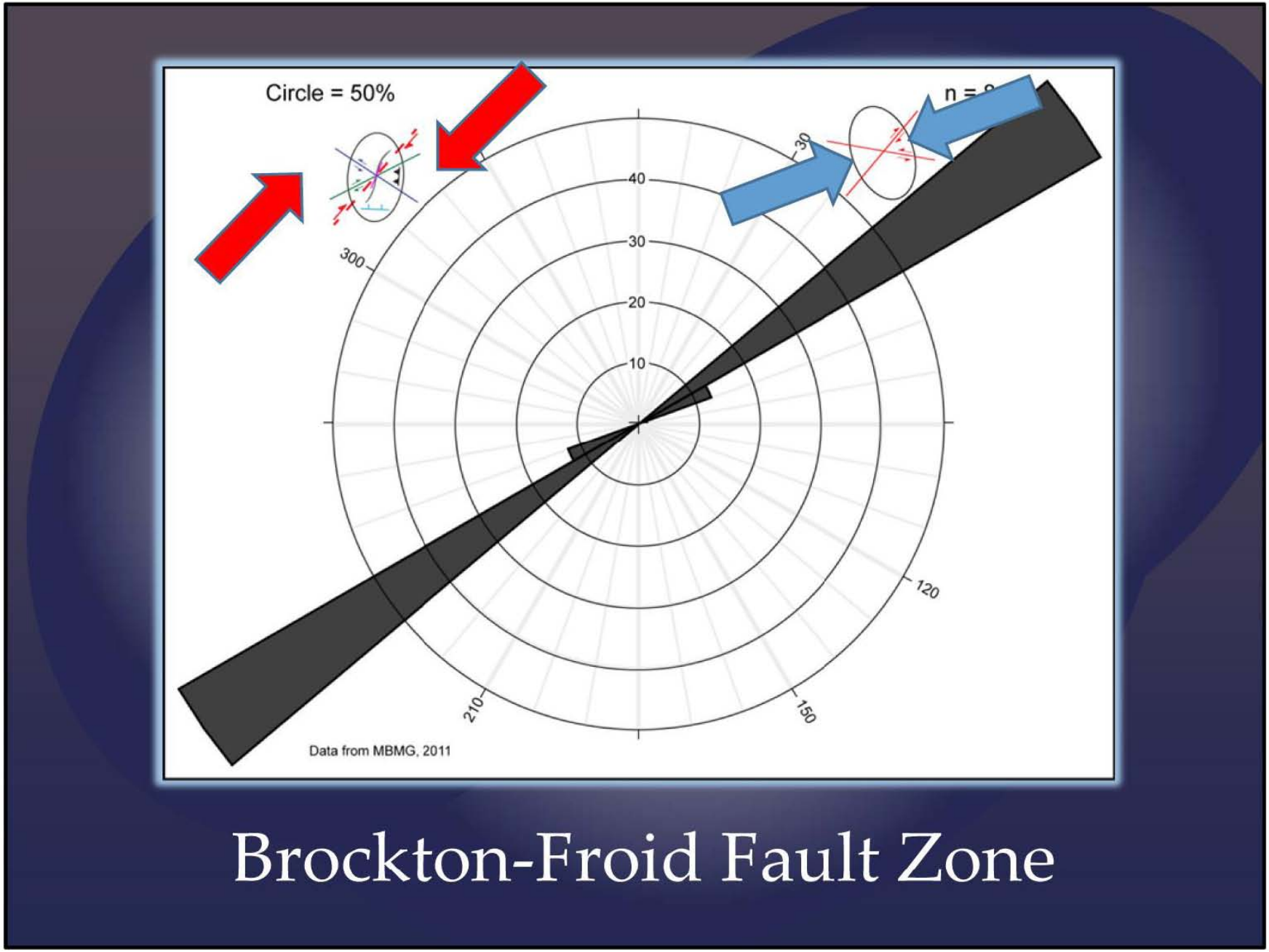


Presenter's notes: and we see similar relationships for the proposed dextral zones such as the Fromberg; however, subsidiary faults (reverse/synthetic) are minimal suggesting that the master fault may be near the surface and had minimal movement.

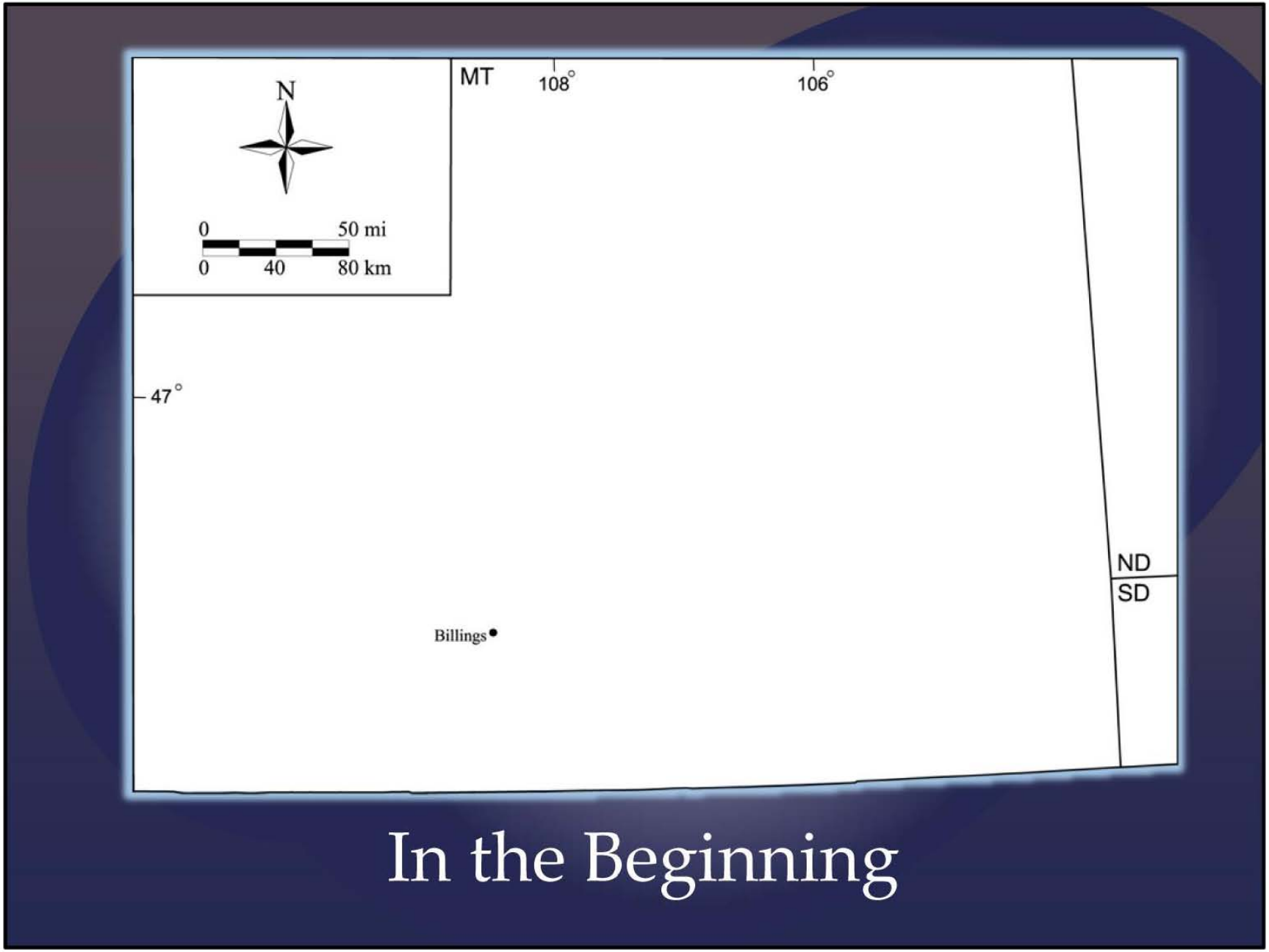


Weldon Fault Zone

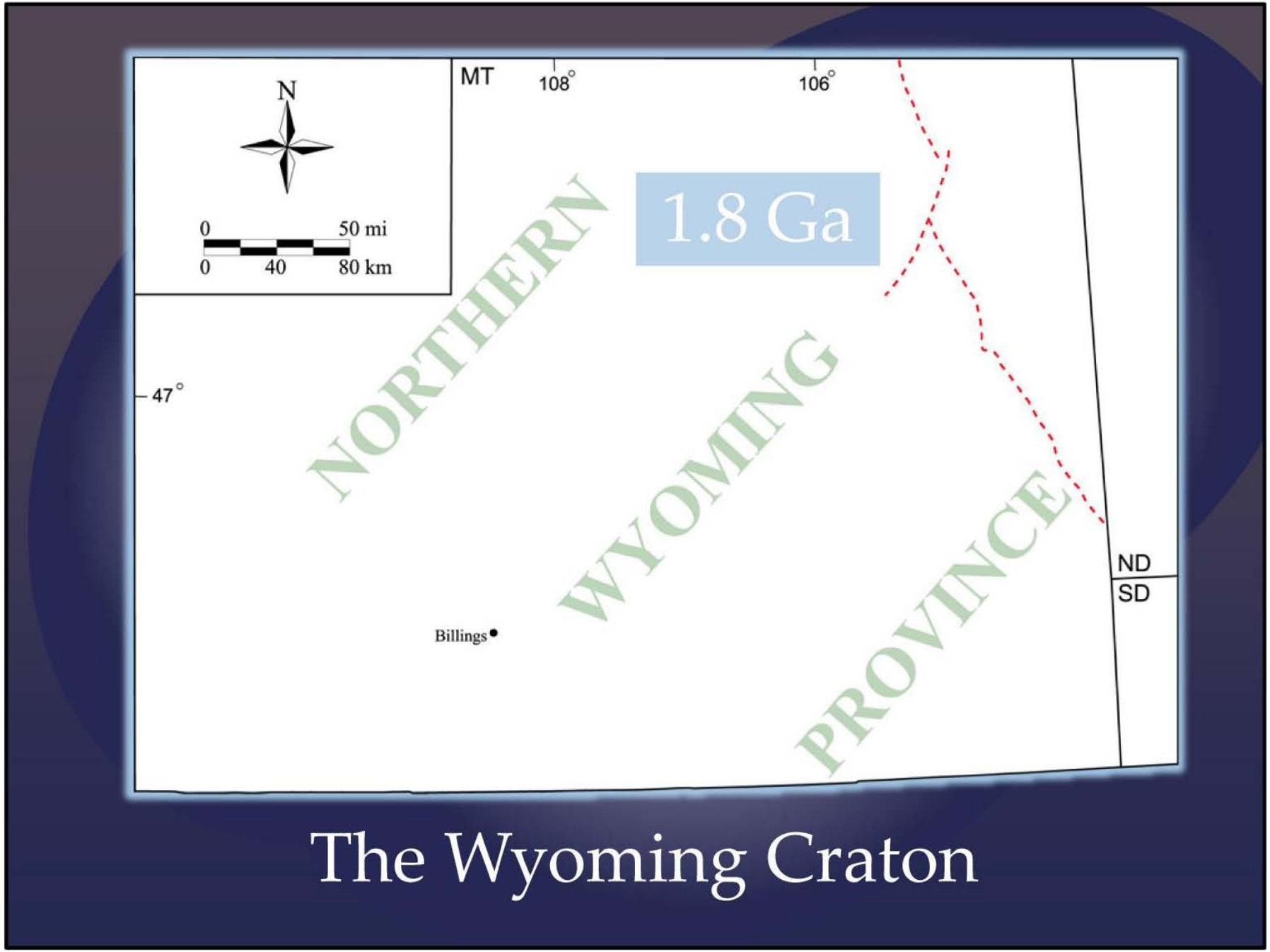
Presenter's notes: More so for the Weldon zone.



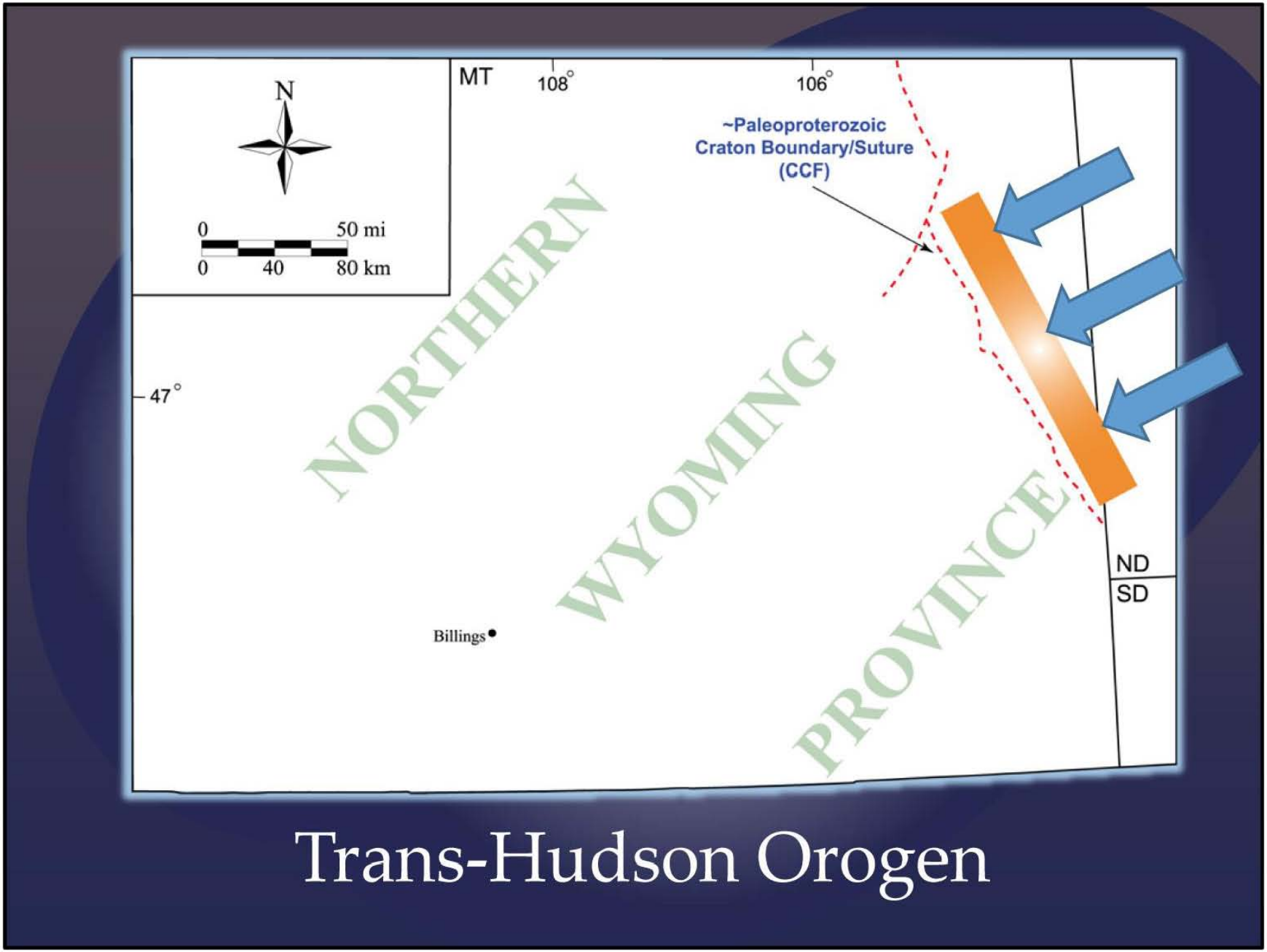
Presenter's notes: and the Brockton-Froid as well, pretty much seeing the strike of the master fault and synthetic splays. Again, evidence for pure shear origin in the Precambrian and simple-shear reactivation in the Laramide.



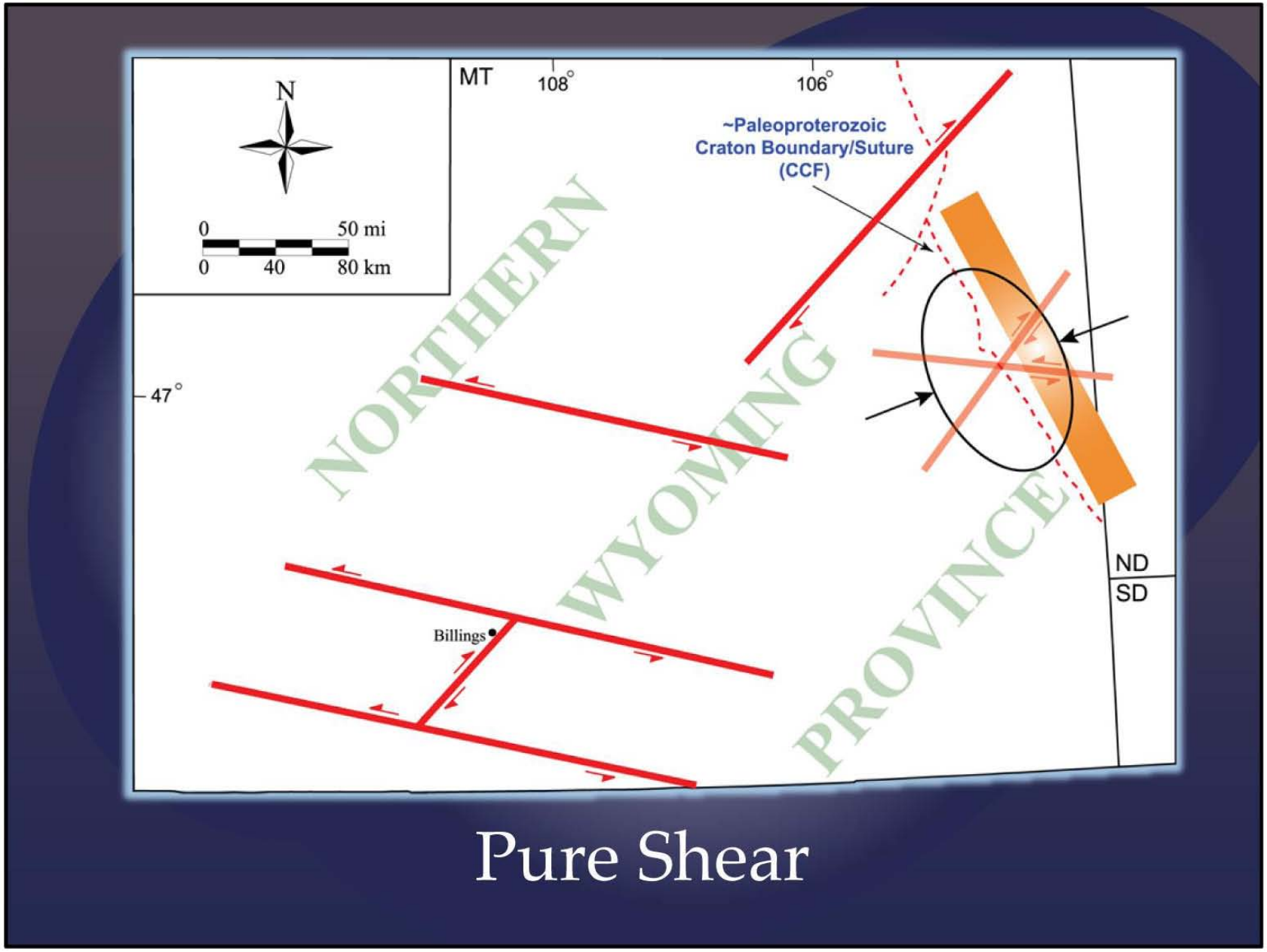
Presenter's notes: So what does all this mean? Actually, it is quite simple. Precambrian fracturing of the basement rocks then reactivation of the anisotropies during the Laramide, as I will briefly step through it. So, in the beginning there was,…… there was Billings.



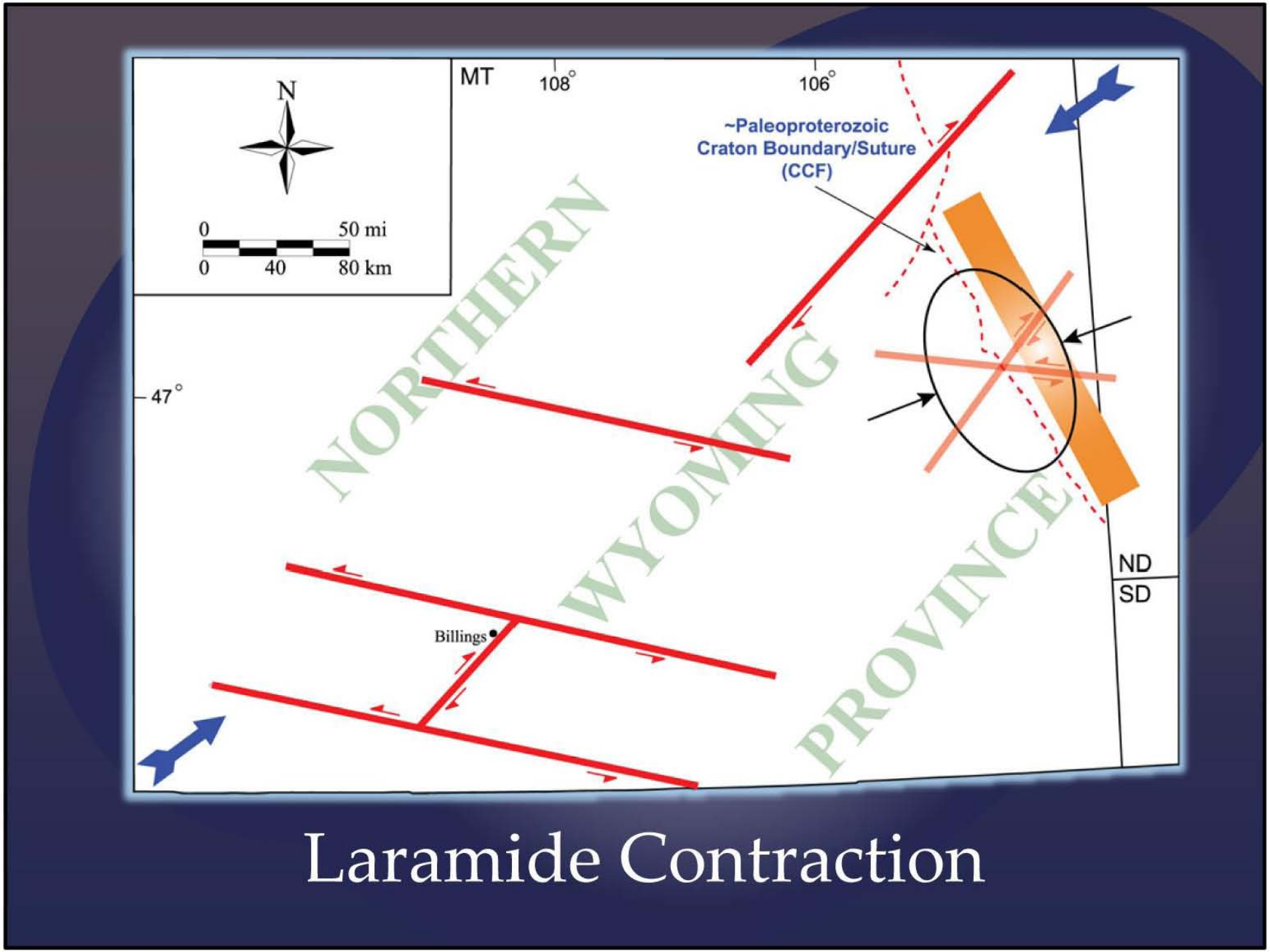
Presenter's notes: By circa 1.8 Ga, the Wyoming craton was situated approximately as shown here with the NE boundary here in NE Montana.



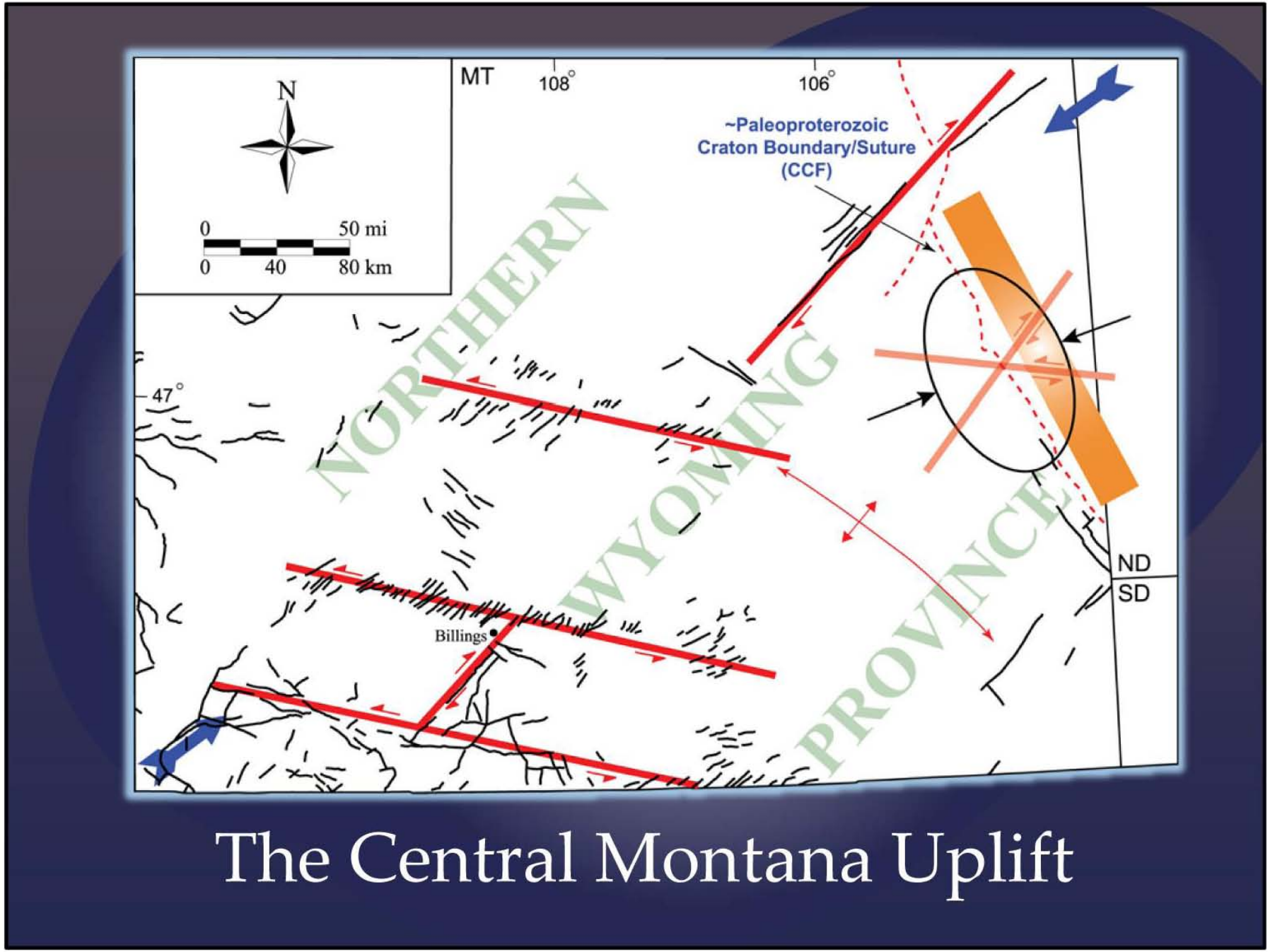
Presenter's notes: Then the beginning of the Trans-Hudson orogeny, with Proterozoic terranes and perhaps Archean fragments accreting to the stable craton at the suture zone, defined today by the Cedar Creek fault.



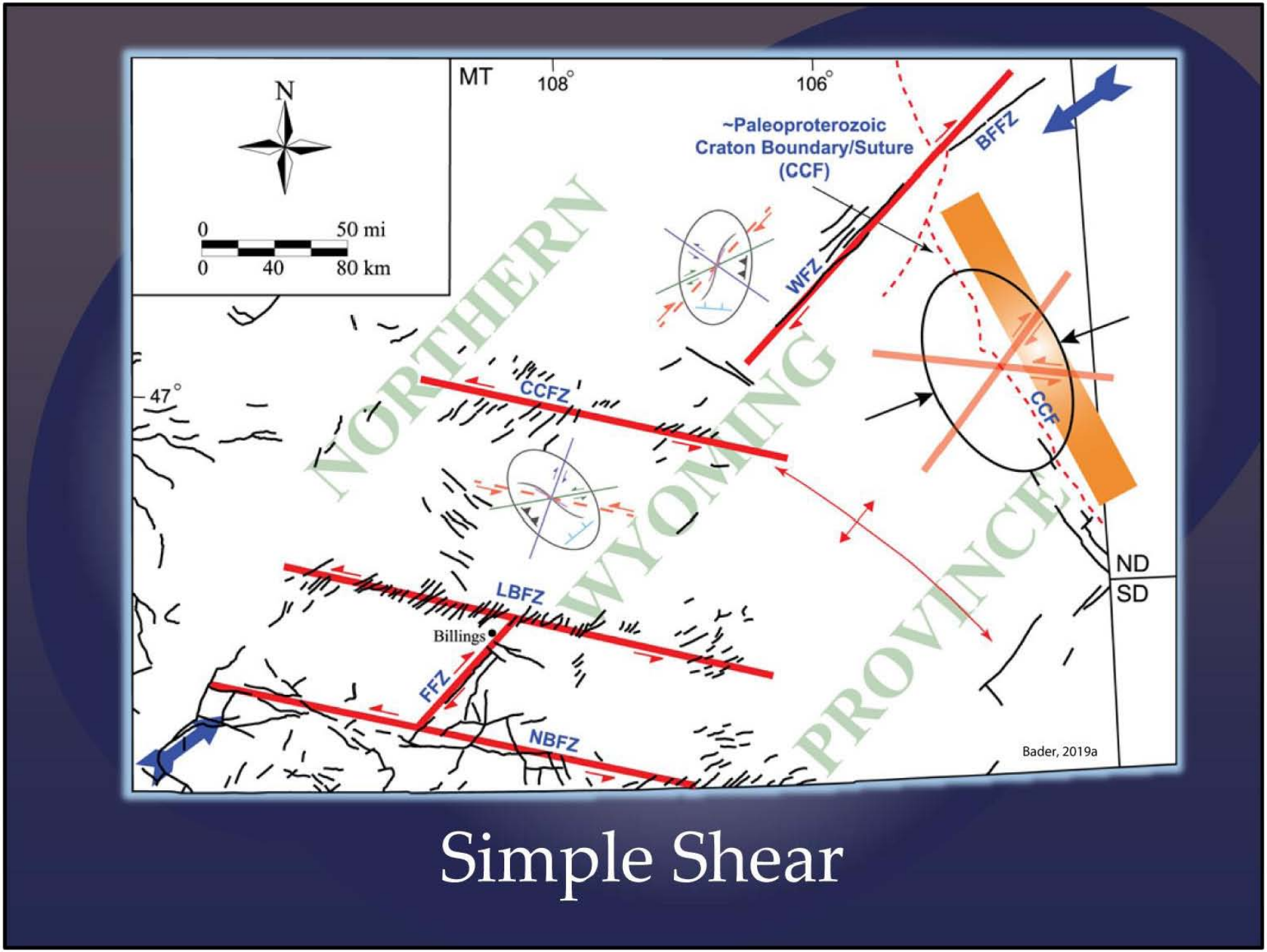
Presenter's notes: These collisions from rigid indenters are proposed to have fractured the craton in a very systematic, fundamental manner during pure shear. So much so that these major anisotropies appear to "dwarf", "overprint", "predominate", and/or "control" other less significant polyphase deformations (rifting events/Cat Creek/Central Montana trough, etc.) that have surely taken place since the Precambrian.



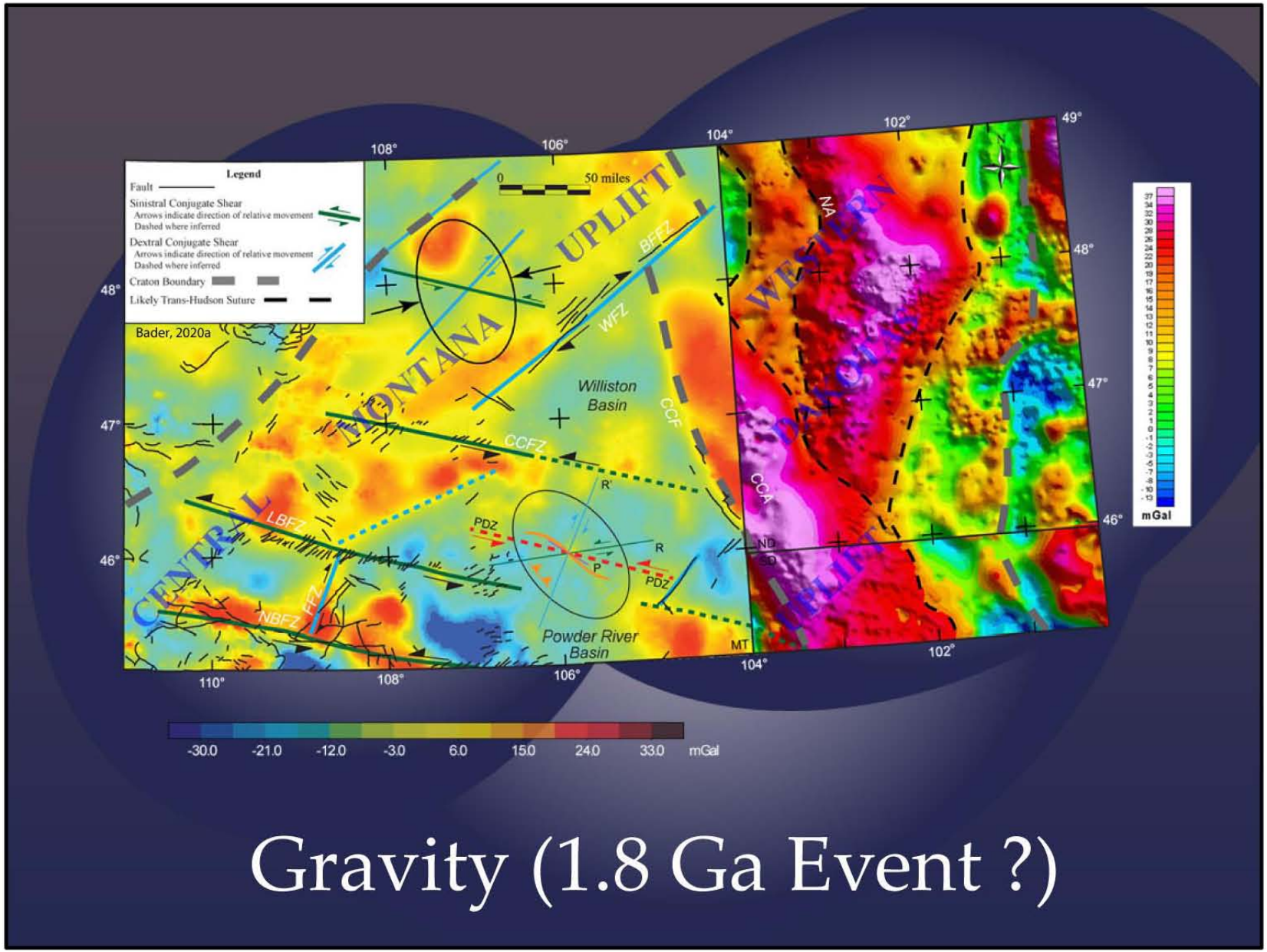
Presenter's notes: Then, once they are there, easily reactivated if the stress regime is conducively aligned, as during the Laramide when the ENE PHS was very similar to that of the Precambrian allowing the faults to be reactivated as simple shears.



Presenter's notes: As seen here with the surface fault zones shown, sinistral zones predominate, but dextral zones are also significant.

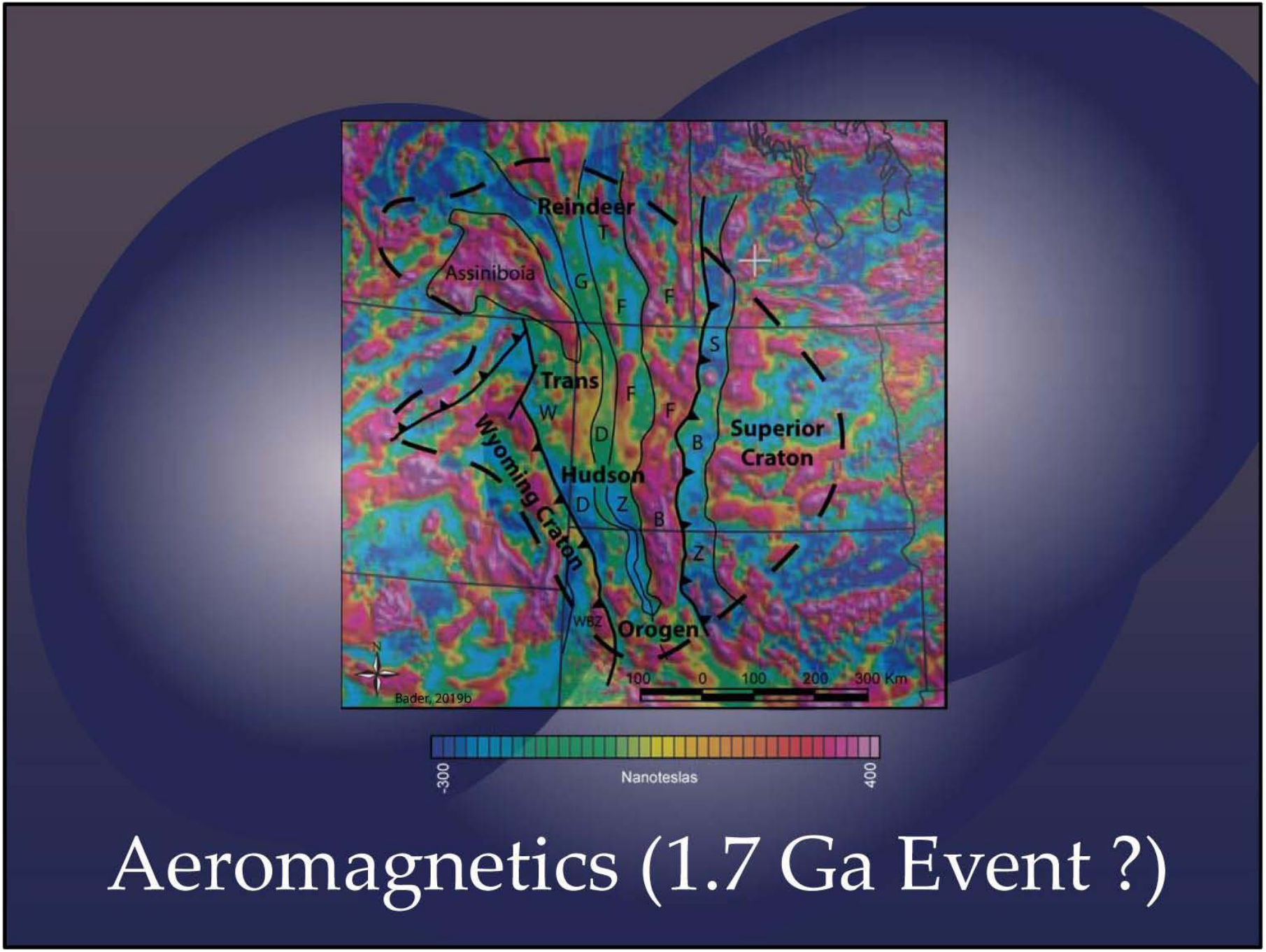


Presenter's notes: As seen here with comparison to the strain ellipse, the Cat Creek fault zone for example, dominantly normal faults and en echelon, curvilinear folds present across the entire length of the rectilinear deformation zone.



Gravity (1.8 Ga Event ?)

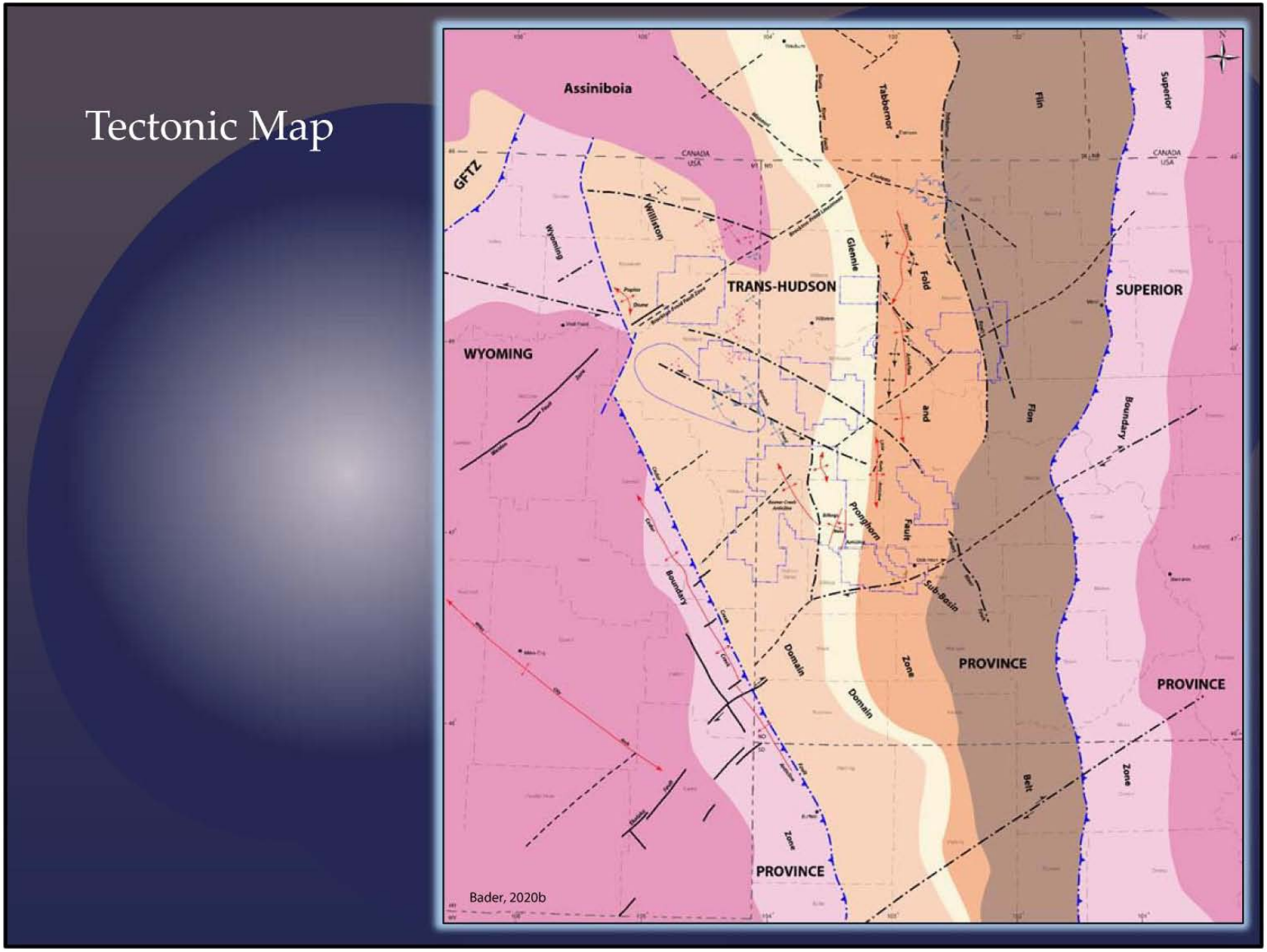
Presenter's notes: We can see evidence of these events on residual isostatic gravity with the interpretedlarge island arc terrane in southwest North Dakota into eastern Montana represented by a significant gravity high. This feature, along with interpreted N-S sutures in North Dakota, create what I am calling the Western Dakotas uplift.



Aeromagnetics (1.7 Ga Event ?)

Presenter's notes: Magnetics tend to paint the overall final docking with the Superior Province circa 1.7 Ga, imprinting that N-S structural grain.

Tectonic Map



Presenter's notes: Finally, this takes us into my present work putting together a tectonic map of the Western Dakotas uplift and surrounding areas. Here I have used all available data to make this map, including older oil and gas field maps, oil and gas fields maps from the 60s, lineaments, gravity and magnetic data, published papers/maps, etc. Here again we see our trifecta with N-S structures representing the basement sutures, and then what may be conjugate sets (NW/SE and NE/SW) at the appropriate angle to the E-W direction of PHS at final docking of the Superior craton.

Conclusions

- Development of conjugate shears in Precambrian
  - Paleoproterozoic convergence = Trans-Hudson orogeny
  - Pure shear
- Reactivation of conjugate shears during the Laramide
  - Contraction due to shallow-angle subduction
  - Simple shear
  - Basement involved deformation = northern extension of Laramide belt
  - Consistent with Bader (2018)
- Nature of Neoarchean and Paleoproterozoic anisotropies along active Precambrian continental margins
  - Preexisting and primary basement heterogeneities controlled subsequent deformational events in the northern Laramide belt
  - Insight into Neoarchean terrane amalgamation and later Paleoproterozoic convergent episodes related to the development and possible final assembly of Laurentia

Presenter's notes: In conclusion, we have development of conjugates shears in eastern Montana due to pure shear in the Paleoproterozoic. Then these features are reactivated as simple shears in the Laramide, which includes the basement; therefore, the Central Montana uplift is the northern extension of the Laramide belt. This work not only agrees mechanically with Bader (2018) but is also temporally consistent. It also has implications for the tectonic and structural development of western North Dakota and southern Saskatchewan. Finally, this model also provides insights into Precambrian and Laramide plate tectonics and role of basement weakness in controlling Laramide orogenesis.

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