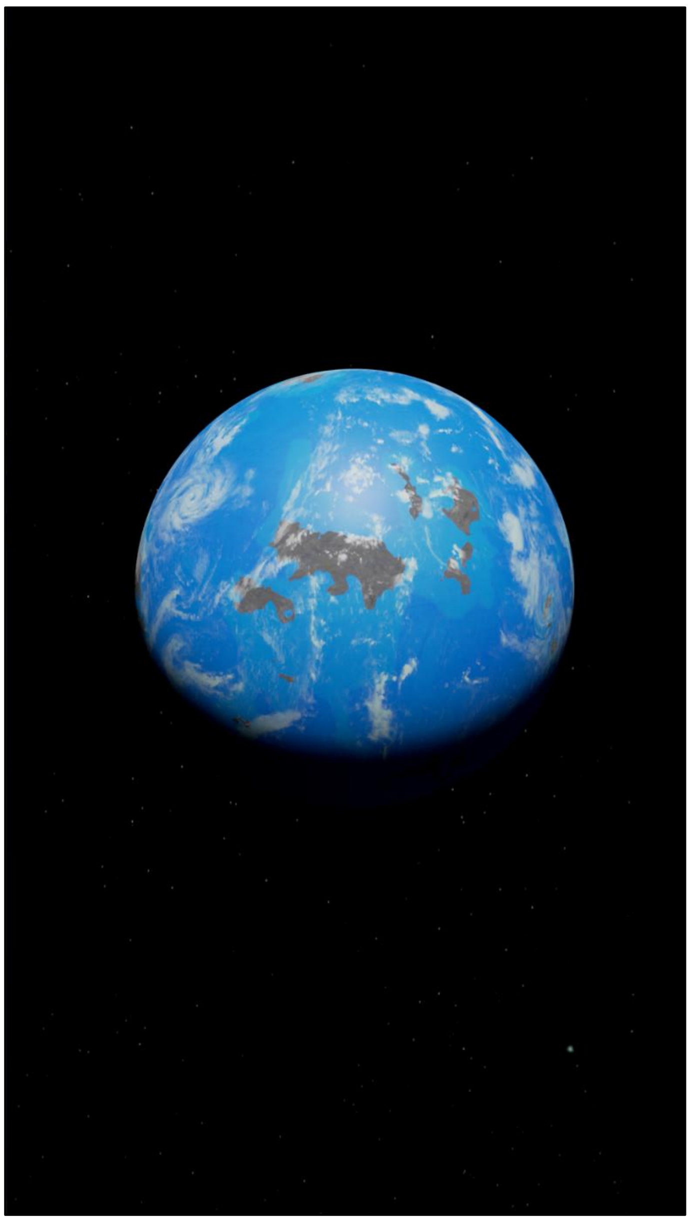
Assembling Laurentia

Precambrian Compressional Tectonics in North Dakota and Surrounding Areas

By
Jeffrey W. Bader



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Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
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Cover Photo: What Earth may have looked like in the Archean at 3.8 billion years ago (bing.com)

INTRODUCTION

As citizens of North Dakota, each day we leave our homes and venture outside into the prairie flatlands of the Northern Great Plains. We generally don't consider that we are situated in the middle of a major rock mass of planet Earth: the continent of North America. It is important to know that this geographic arrangement was not always so. In fact, it is difficult to comprehend that western North Dakota was once the edge of the continent approximately 2 billion years ago. The state was then located along an open ocean that eventually closed and the edge of the state was then dominated by Everest-like mountains (Mueller et al., 2005; Bader, 2019a). Indeed, the fundamental geologic process behind our surroundings, plate tectonics, is generally not part of our daily musing, especially for those of us riding along in the middle of tectonic plates. However, as geologists, the tectonic history related to growth of the North American continent is critical in understanding the geology of our state, and more specifically, the evolution of the Williston Basin and generation of geologic resources such as petroleum. Integral to this understanding are the rocks that form the foundation or "basement" below which we stand. In North Dakota, these are three rock masses: one orogenic deformation zone (Trans-Hudson Province), and two major cratons (Superior and Wyoming Provinces) (Bader, 2019a). The Superior Province underlies the eastern portion of North Dakota, with the western side dominated by Trans-Hudson rocks. The Wyoming Province barely extends into southwestern North Dakota. However, because the continent initially grew from the southwest, the origin and evolution of the Wyoming Province is integral to understanding the specifics of the Precambrian history of North Dakota, and in general, how the North American craton of Laurentia formed.

TRIAXIAL COMPRESSION

For continental masses to grow, crustal material must accrete to the continental margins through convergent events at accretionary or collisional boundaries (subduction zones). Compressional forces at these convergent boundaries are dominant and significant (Sylvester, 1988). Testing of such compression on rocks is generally performed through triaxial compression tests that mimic rock behavior on Earth (Fig. 1A), generally with a small core of homogenous rock. The force exerted in this test is pure shear, that is, non-rotational stress, with the principal horizontal stress (PHS) being dominant and parallel to the surface of Earth. Rocks break in a predictable manner (conjugate shear fractures) as shown on Figure 1B, with nominal variations in fracture angles generally related to rock type and heterogeneities. These tests have been applied to larger rock masses to better understand stress/strain relationships that may affect our planet. But, at what scales do the tri-axial tests apply? Recent studies of the Rocky Mountains of Wyoming and Montana suggest that such testing may be applied at continental-scale levels (Bader, 2019b, 2019c) and thus may be applicable to basement rocks of North Dakota.

GEOLOGIC SETTING

The origins of the Wyoming Province extend to beyond 3 billion years ago (Archean), when proto continents initially formed on Earth (Corrigan et al., 2009; Bader, 2019a). At this time, the craton was a thin sliver of rock that was located a great distance from its present-day position (Fig. 2), along with other proto continents spread across the globe, separated by dominantly vast oceans and oceanic crust of early Earth.

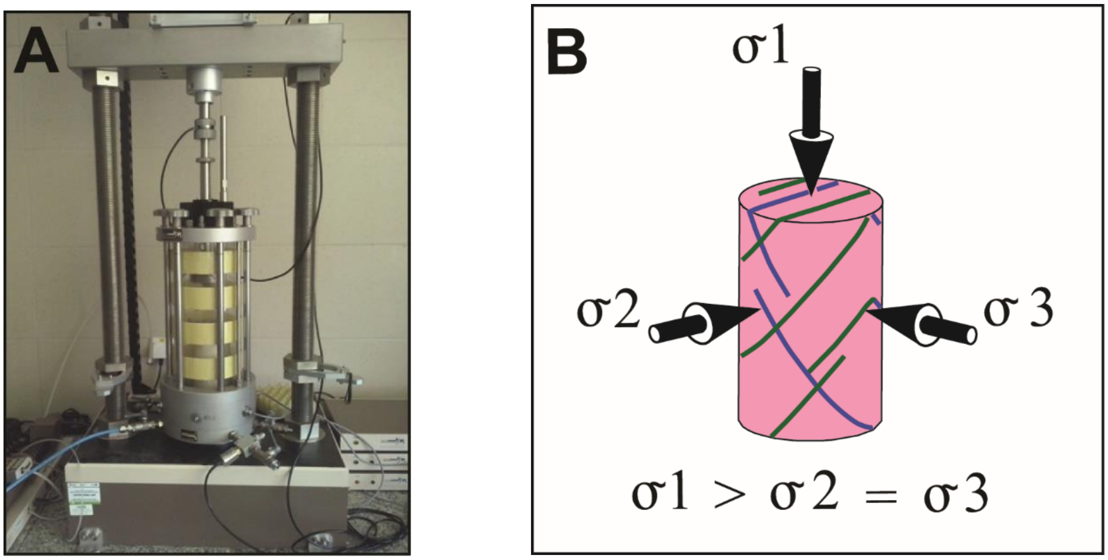

Figure 1. (A) Apparatus used for triaxial compression rock deformation experiments. (B) Schematic of stress states for triaxial deformation. σ–sigma.

Precambrian Plate Tectonics

The Wyoming Province, at 3 billion years old, has been postulated to have had active margins along the northeastern and southwestern sides of the proto craton (Frost et al., 2000; Chamberlain et al., 2003; Frost et al., 2006; Bader, 2019b). To the northeast, some of the earliest forms of subduction as we know it, may have initiated the formation of the present-day Bighorn Mountains, whose basement rocks may represent the roots of ancient volcanoes that developed along the northeast margin of the craton in the Neoarchean (Fig. 2). To the southwest, and likely from approximately 2.6 to 2.9 billion years ago, subduction was forming volcanic arcs and the roots of the Wind River Mountains. Accretion of perhaps large Archean terranes on the northeast (northern accreted terranes) and southwest (southern accreted terranes) margins likely took place throughout the Neoarchean, forming the present-day Wyoming Province (Fig. 2; Chamberlain et al., 2003).

By about 2 billion years ago, the Wyoming Province was near the geographic position it occupies today (Fig. 3). It was part of a group of small Archean cratonic blocks that were present proximal to much larger Archean provinces (Superior and Hearne) to the north and northeast. At this time, these smaller cratonic blocks were merging from the southwest and northeast (Mueller et al., 2005) and docking with the larger blocks in a series of continent to continent collisions that lasted millions of years. The Manikewan Ocean may have opened and closed several times during this time frame (Fig. 4). The terminal closure culminated the Trans-Hudson orogeny at approximately 1.76 billion years ago, developing the initial basement architecture of western North Dakota.

Deformational Events (D1–D4)

Deformation of the basement in Wyoming and eastern Montana is postulated to be dominated by pure shear stress and resulting strain, as reflected by the presence of conjugate shear zones across the entire Wyoming Province (Bader, 2019b, 2019c). Such deformation has been explained through a convergent deformation system (CDS) model that considers the geomechanical configuration of basement-rooted fault zones across

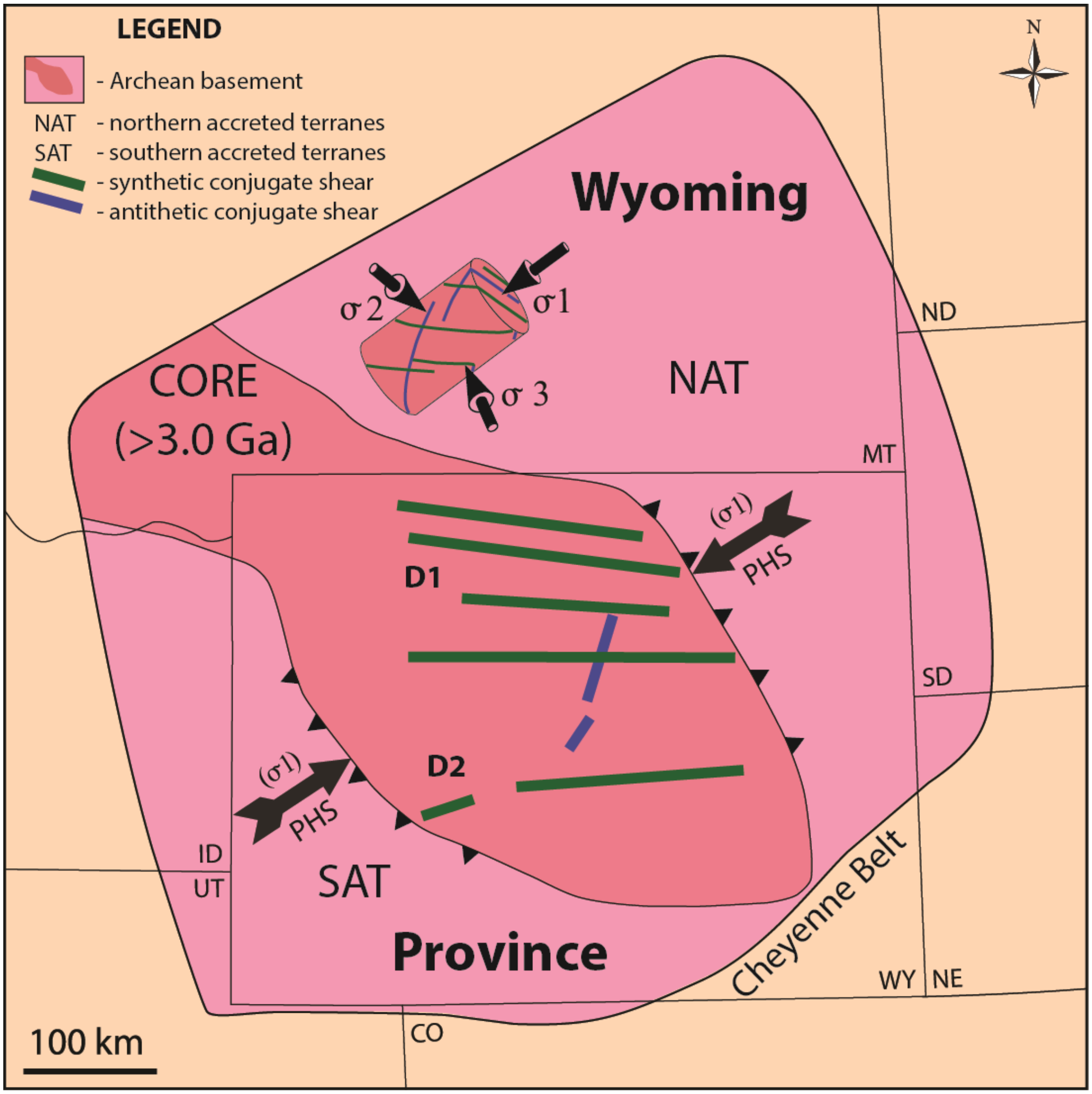

Figure 2. Proposed convergent deformation system at ~3.0 billion years ago. PHS–principal horizontal stress, σ–sigma.

the craton, as well as the temporal constraints for Precambrian tectonism in both the Neoarchean and Paleoproterozoic. These events, as described here, are defined as D1 (oldest)–D4 (youngest).

The D1 event corresponds to convergence from the northeast along the northeastern margin of the proto-Wyoming Province at approximately 3.0 billion years ago (Fig. 2). Subduction at this active margin likely developed volcanic arcs oriented parallel to the continental margin, and deep-seated shear zones across north-central Wyoming oriented north-northwest. In addition, conjugate shears likely developed in-board of the continental margin, as reflected by basement-rooted fault zones that were last active during the Laramide orogeny from approximately 80 to 40 million years ago, and possibly during post-Laramide tectonism (Bader, 2019b, 2019c). Similarly, the D2 event resulted in conjugate shears along the southern craton margin later in the Neoarchean. The northern accreted terranes (NAT) and southern accreted terranes (SAT) were likely assembled during the 3.0-2.5 billion-year time frame.

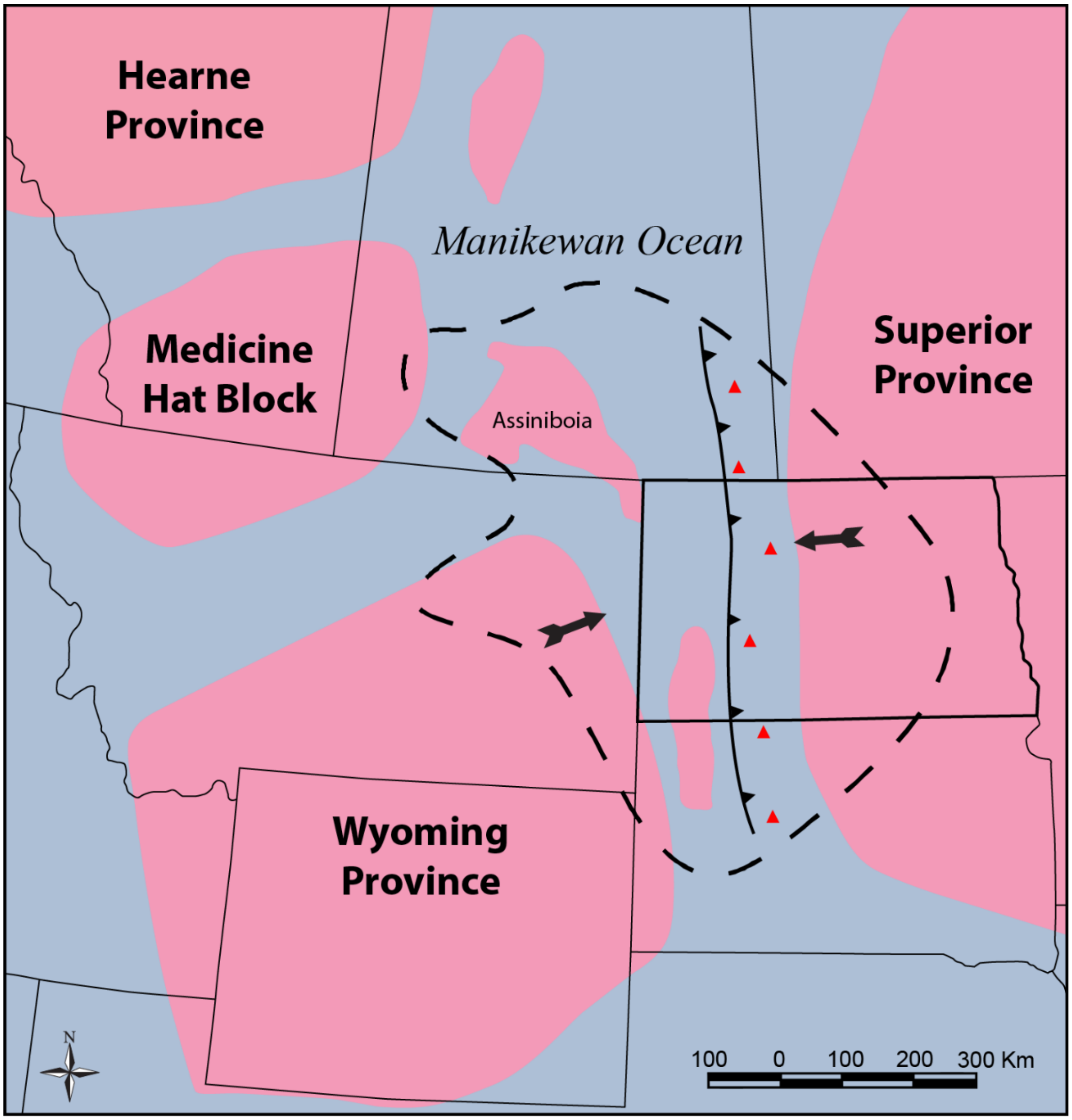

Figure 3. Plate tectonic setting of the Trans-Hudson orogen showing major lithotectonic elements. Dashed line–Williston Basin, sawtooth line–ocean trench with sawteeth on upper plate, red triangles–volcanic island arc chain, black arrows–convergence direction. Modified from Mueller et al. (2005).

The D3 event corresponds to initial Trans Hudson orogenesis as the Manikewan Ocean began to close at approximately 1.8 billion years ago (Figs. 4 and 5; Mueller et al., 2005; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009; Bader, 2019c, 2021). Evidence for a significant landmass, likely a large Paleoproterozoic island arc system, is apparent on isostatic gravity maps of the western Dakotas and eastern Montana (Bader, 2020a). Initial docking of this terrane as well as docking of the Grouse Creek block from the southwest is postulated to have fractured the NAT and SAT, as well as reactivating sinistral conjugate shears within the core of the Wyoming Province. Reactivated Laramide basement-rooted shear zones of eastern Montana and Wyoming provide indirect evidence for this event (Bader, 2019b, 2019c).

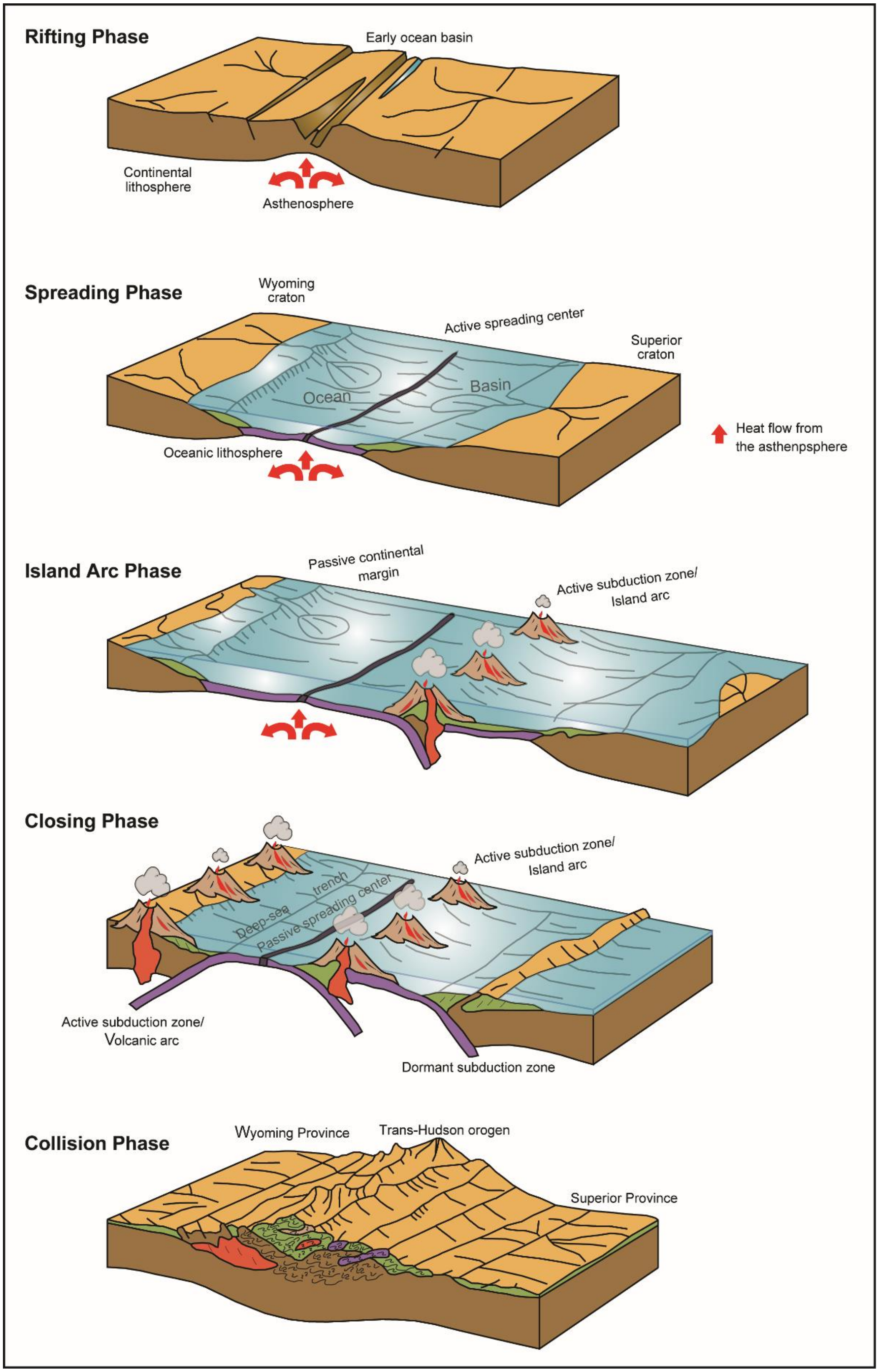

Figure 4. Schematic of possible Wilson cycle for Wyoming Province, Superior Province, and Trans-Hudson orogen. From Bader (2019a).

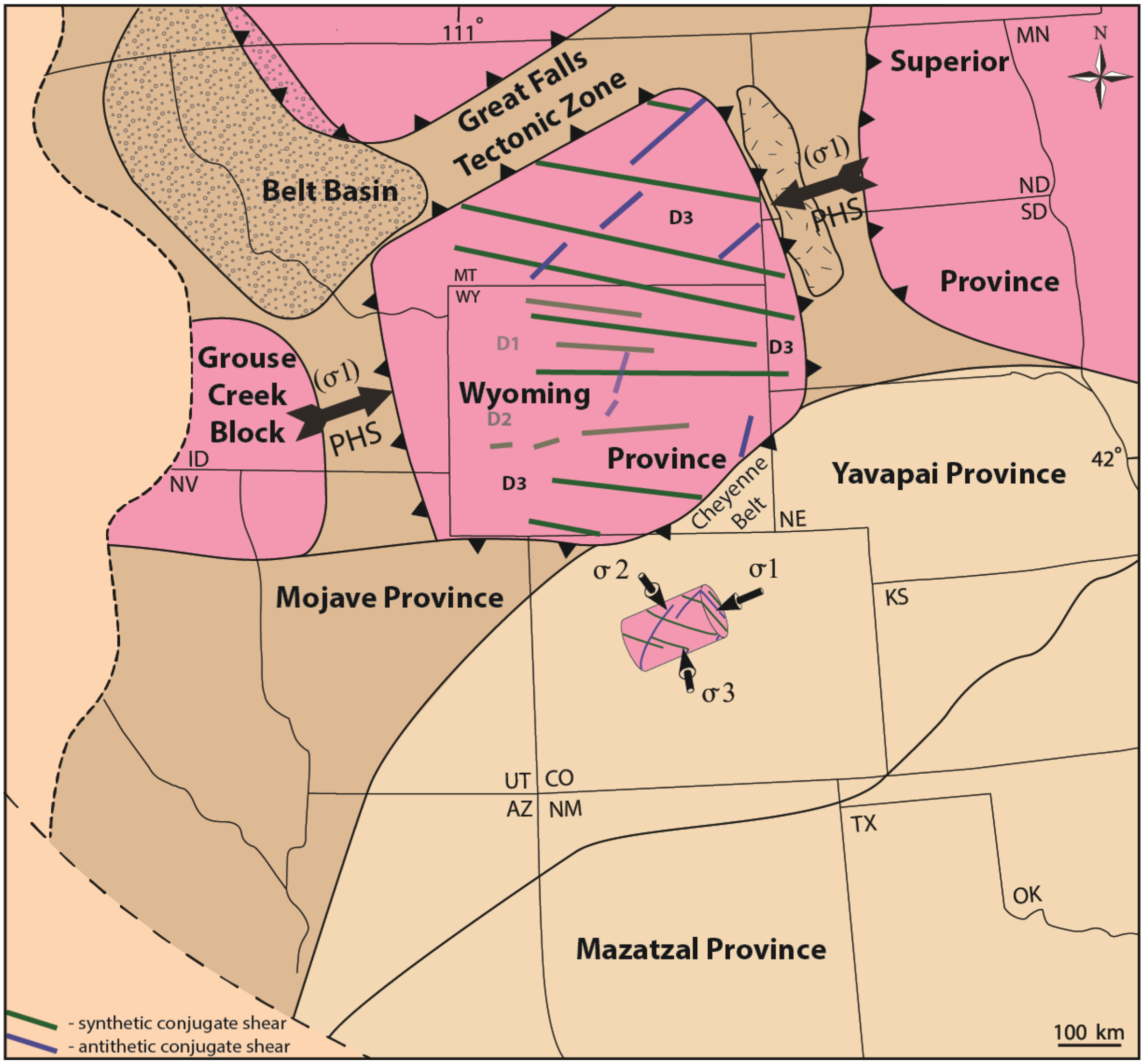

Figure 5. Proposed convergent deformation system at ~1.8 billion years ago. PHS–principal horizontal stress, σ–sigma.

Finally, the D4 event represents final closing of the Manikewan Ocean and terminal collision at the end of Trans-Hudson orogenesis at approximately 1.76 billion years ago. Structures observed on the tectonic map of the Western Dakotas uplift (Fig. 6; Bader, 2020b) reflect this event. At that time and post-D3, convergence was more east-west directed, with north-south sutures likely reflecting convergence events across the orogen as the Manikewan ocean opened/closed. The juvenile crust of the Trans-Hudson orogen was also likely fractured into conjugate shear zones striking northwest and southeast during the terminal docking event (Fig. 7; Anderson, 2011; Bader, 2020b). Again, such fracturing is consistent with a PHS directed from the east, as is indicated by the orientation of the western Superior Province boundary.

The Wyoming Province and Laurentia

The basement core of North America is the Canadian shield. It developed in the Archean from 4.0–2.5 billion years ago (Fig. 8; Whitmeyer and Karlstrom, 2007). Trans-Hudson orogenesis included plate collisions of large Archean continents, such as the Superior Province, along with smaller Archean continental fragments such as the Wyoming Province, among others, as described above. The resulting

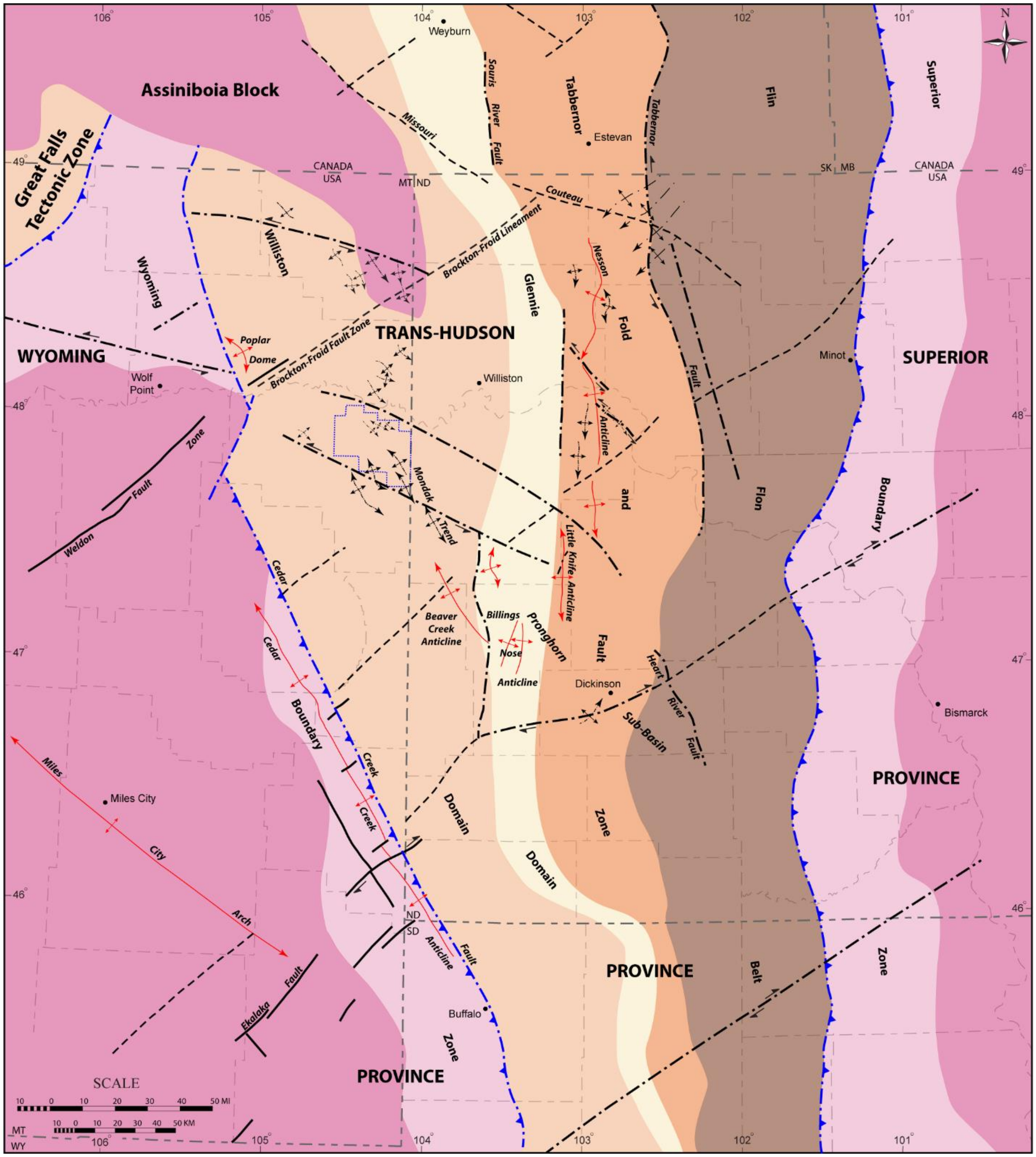

Figure 6. Tectonic map of Western Dakotas uplift and surrounding areas. From Bader (2020b).

collisional belt was similar in scale to the modern Himalayas (Bader, 2019a), with a significant convergent deformation zone (CDZ) developed across Idaho, Utah, Wyoming, Montana, South and North Dakota, at the southwest edge of Laurentia. Such collisional orogenesis may be considered triaxial compression on a continental scale, beginning in the Neoarchean and continuing through Trans-Hudson orogenesis.

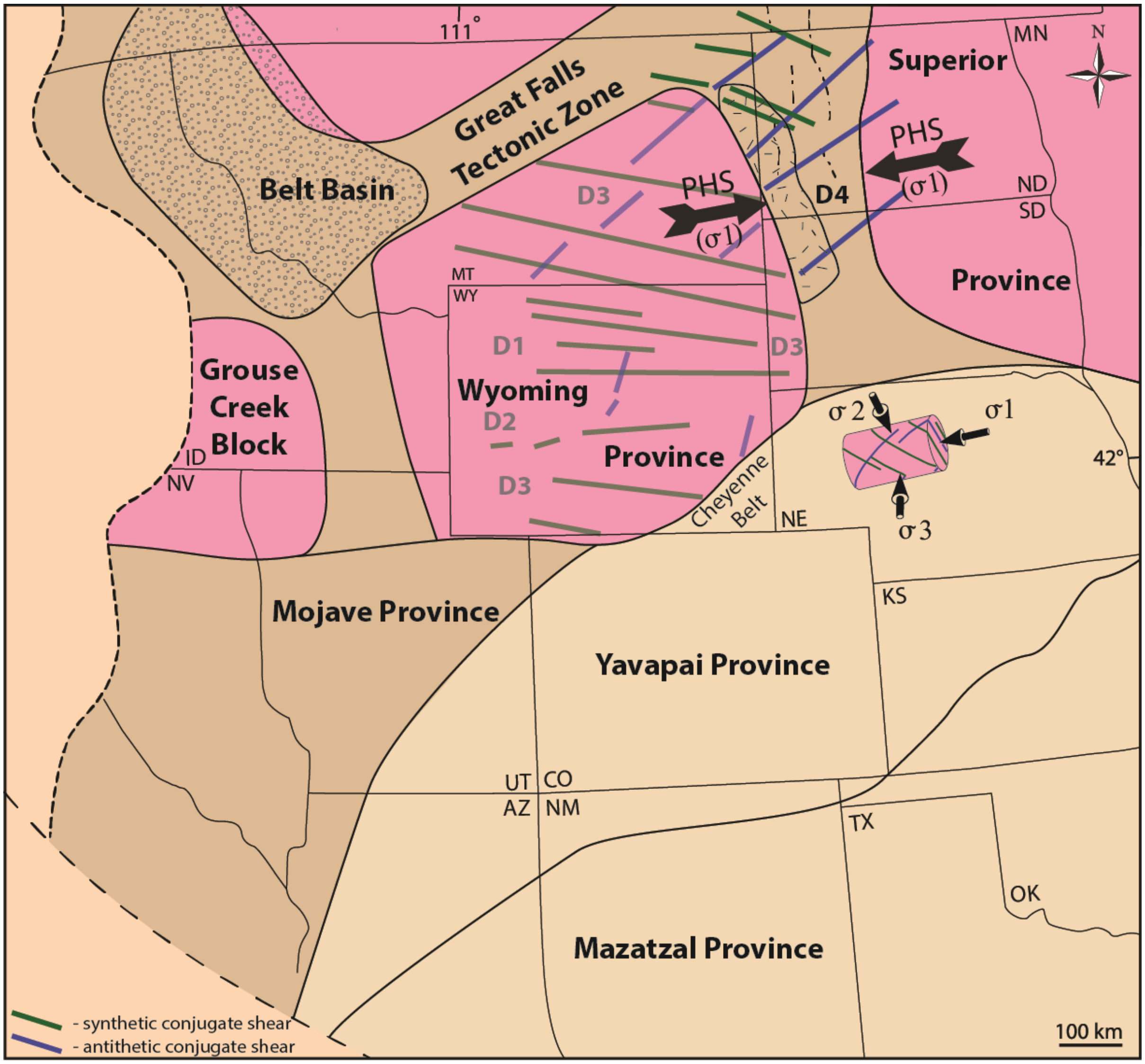

Figure 7. Proposed convergent deformation system at ~1.76 billion years ago. PHS–principal horizontal stress, σ–sigma.

DISCUSSION

Finally, what does all this have to do with North Dakota? Firstly, the Wyoming Province is considered basement rock present in the state of North Dakota, regardless of the "Wyoming" name. Secondly, because Laurentia grew from southwest to northeast, evolution of the Wyoming Province is integral to development of basement rock in western North Dakota. Lastly, commonalities between tectonic events in the Archean and Proterozoic in Wyoming and Montana give insight into structures observed in basement rocks of North Dakota. Such Precambrian structures formed in basement rocks can be reactivated millions of years later under stress that is conducive to such movement. This stress can deform the sedimentary rocks that overlie basement rocks forming traps for petroleum accumulation. Therefore, even though the Wyoming Province barely underlies North Dakota, its tectonic history as part of a Precambrian convergent deformation system undergoing pure-shear compression has had long-lasting effects on our state continuing to the present day.

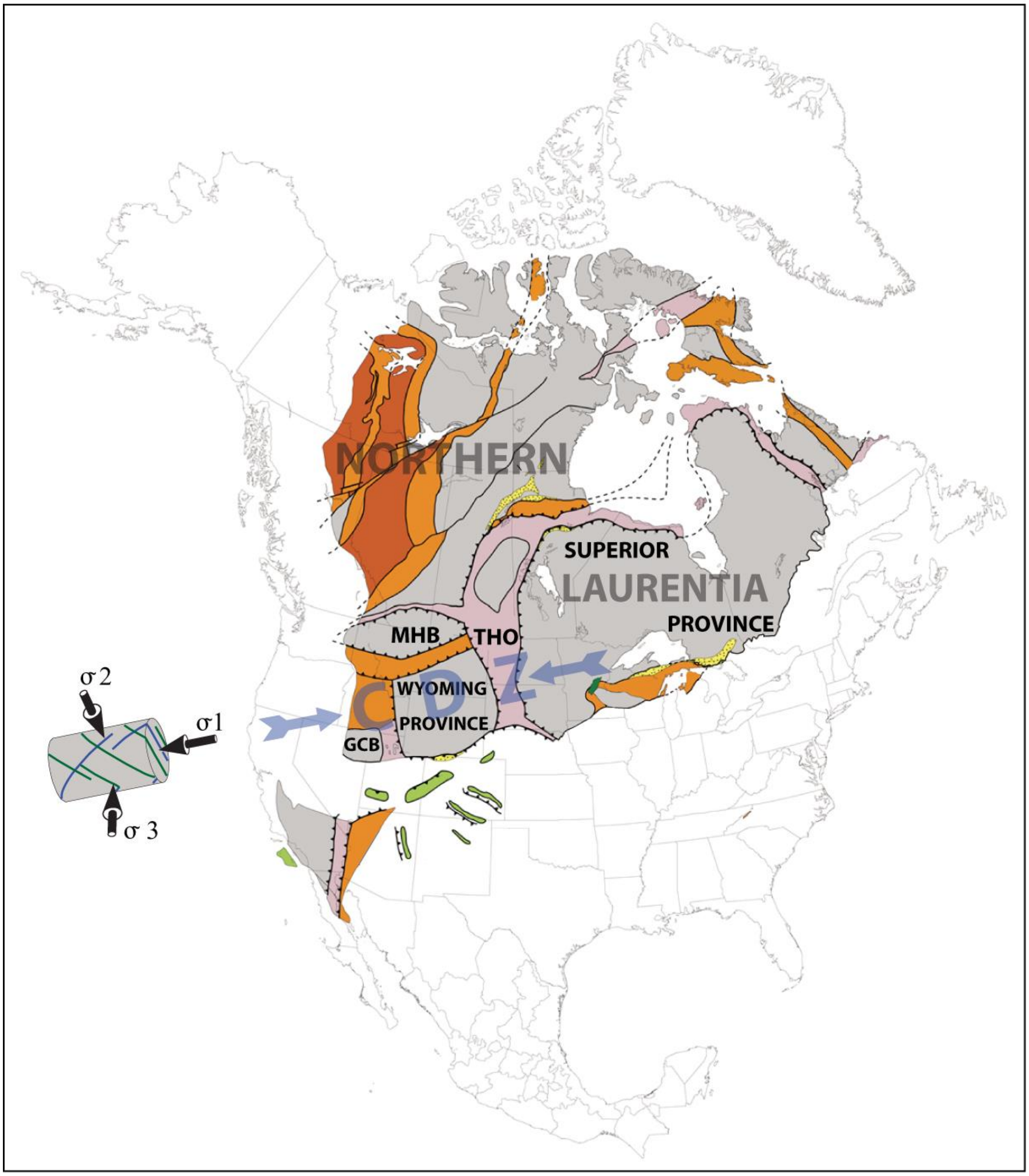

Figure 8. Laurentia and Convergent Deformation Zone. Areas in gray are Canadian Shield. Large blue arrows–general direction of principal horizontal stress in the Neoarchean and Paleoproterozoic. σ–sigma, CDZ–convergent deformation zone, GCB–Grouse Creek block, MHB–Medicine Hat block, THO–Trans-Hudson orogen. Modified from Whitmeyer and Karlstrom (2007).

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