An Ancient Everest: Precambrian Basement Terranes of the Williston Basin

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Introduction

The Williston Basin is quite unique, in that the basin lies along three major tectonic zones. These zones are billions of years old and yet they are fundamental to the very lives we lead today. Because of the composition, age, and depth of burial, we identify them as the 'Precambrian basement'. The Precambrian basement beneath the Williston Basin is composed dominantly of one orogenic deformation zone (Trans-Hudson) that separates two cratonic masses (Wyoming and Superior); collectively, the product of continents colliding nearly two billion years ago.

Identifying Basement Terranes

Potential-fields exploration, including magnetic and gravity surveys, are used as an indirect way to 'see' beneath the surface of Earth by measuring/mapping these physical characteristics of deeply buried rocks. These geophysical surveys are relatively inexpensive and can cover very large areas providing a genetic interpretation for rocks not, or minimally, exposed at the surface, and therefore, could not otherwise be studied. Gravity and magnetic exploration are used to locate ancient cratonic masses, terranes, and faults in study/identification of mineral and petroleum resources, as well as ground-water reservoirs (Hill et al., 1995). Aeromagnetic mapping has proven to be particularly useful in identifying Precambrian basement in the Williston Basin area (Sims et al., 2001, 2004; White et al., 2005; McCormick, 2010).

Craton

A craton, also referred to as province (e.g., Superior craton or Province), is an ancient and very stable part of the continental lithosphere of Earth, with the lithosphere consisting of the crust and the upper mantle. Cratons are usually found in the interior of tectonic plates, having survived plate tectonic cycles of converging and rifting continents throughout geologic time. They are composed of thick, continental crust and have lithospheric roots that may extend into the mantle at several hundred kilometers depth. They are generally large, coherent masses that are an end-product of significant tectonic reworking; therefore, cratons consist of separate deformation stages within crystalline igneous and metamorphic rocks. Cratons are typically Archean (2.4–4.0 billion years ago) crustal fragments (e.g., Superior or Wyoming cratons) that were joined during the Proterozoic (1.8–0.6 billion years ago). At the time of joining, deformation was concentrated in adjacent crustal areas called orogens (e.g., Trans-Hudson) that had weaker strength profiles. Therefore, the term craton is generally used to distinguish the more stable portion of the continental crust from regions that are more geologically active and unstable along the craton margins.

Ancient cratonic "shields," dominated by crystalline metamorphic rocks (e.g., Canadian Shield) are present when cratons are exposed. Where younger, weakly deformed/undeformed cover is present above the cratonic mass, these areas are referred to as platforms. Significant rifting events with associated mafic dyke swarms (e.g., The Red Sea), and/or mantle plume activity (e.g., Yellowstone) are needed to break-up cratonic lithosphere. There are approximately 35 Archean crustal fragments on Earth, two of which are the Wyoming and Superior cratons. These likely originated from break-up of larger, transient, Late-Archean supercratons" (Rogers and Santosh, 2003). Therefore, the ensemble of Archean cratons probably originated from the splitting of more than one supercraton, rather than a single Late Archean supercontinent (fig. 1).

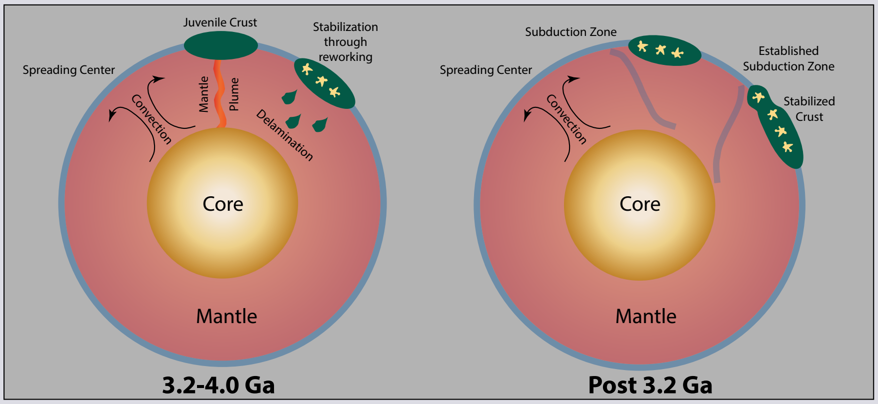

Figure 1. Generalized global Precambrian plate tectonic setting pre- and post-3.2 billion years. Modified from Naeraa et al., 2012.

The Wyoming craton is relatively small and the southernmost North American Archean province. The craton is composed of a gneissic core (3.6–3.0 billion years ago) and sparse supracrustal rocks that have been intruded by potassium-rich granitic rocks (2.90–2.50 billion years ago), as well as low-potassium tonalites and granodiorites (Frost et al., 2006; Mueller and Frost, 2006). The gneissic and granitic rocks occur as alternating belts that are roughly semi-circular in shape around the older central core (Sims et al., 2001). These belts represent several younger magmatic and/or tectonic belts that formed as the older gneissic core was reworked (Houston, 1993). The magmatic and supracrustal belts are younger to the south-southwest, away from the older central core in north-central Wyoming (Chamberlain et al., 2003). Only the northern portion of the craton is present beneath the Williston Basin, and may include the Assiniboia terrane, present in southern Saskatchewan (fig. 2).

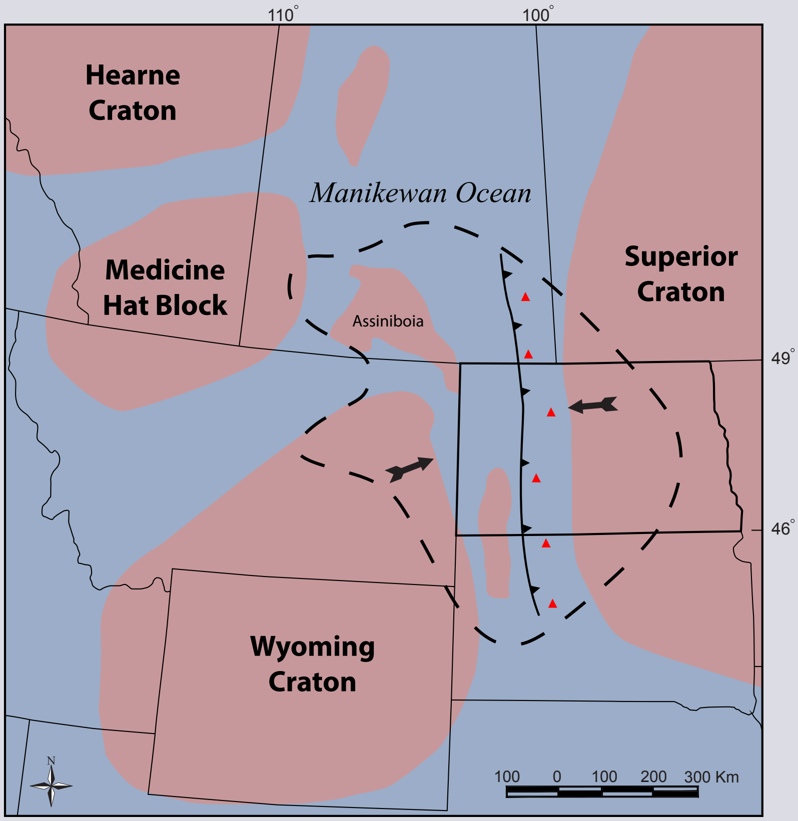

Figure 2. Plate tectonic setting of the Trans-Hudson orogen showing major lithotectonic elements. Dashed line = Williston Basin, sawtooth line = ocean trench with sawteeth on upper plate, red triangles = volcanic island arc chain, black arrows = convergence direction. Modified from Mueller et al., 2005.

The Superior craton is significantly larger (~625,000 square miles) than the Wyoming craton, covering much of central Canada and part of the northern Great Plains of the United States (fig. 2). It forms a large portion of the Canadian Shield (Corrigan et al., 2009). Rocks of the Superior craton consist mostly of metasedimentary rocks, mafic volcanic and plutonic rocks, gneiss, and granitoids in tectonic zones that likely indicate joining of Archean terranes in a plate tectonic setting, likely from 3.2 billion years ago (Naeraa et al., 2012). The NE- to SW-trending belts are oldest to the north at ~3.0 billion years and become progressively younger (2.7 billion years) near the Canadian/US border (Corrigan et al., 2009). However, 3.7 billion year old gneissic rocks are present in the Minnesota River Valley Province, which like Assiniboia, may be an older Archean tectonic fragment caught up in Trans-Hudson suturing at approximately 1.8 billion years ago. The belts are separated by faults that likely have long tectonic histories.

Orogen

Orogen is a term that developed from the word orogeny, which literally means 'mountain creation.' An orogeny leads to a large structural deformation of the lithosphere at convergent plate margins (subduction zones) where compression and horizontal shortening create fold and thrust mountain belts (orogen) at collisional (continental-continental crust) or non-collisional (continent-oceanic crust) boundaries. The entire process is collectively called orogenesis. Continent to continent collisions form the most significant deformation zones, such as the modern-day Himalayas.

Orogens may be extremely old (dormant), dating back to the Precambrian, or they may be recent (active), such as the Cascadia orogen in the Pacific Northwest. Together, cratons and orogens of Precambrian age make-up the 'basement' that is present beneath the entire Williston Basin area. This article focuses on the Precambrian Trans-Hudson orogeny that occurred circa 1.8 billion years ago in western North Dakota, and involved the collision of the Wyoming and Superior cratons which formed the Trans-Hudson orogen.

Terrane

Transported units that have migrated into orogens are referred to as tectonostratigraphic terranes, or terranes for short. A terrane is crustal material formed on, or detached from, one tectonic plate and stitched to another tectonic plate at a convergent plate boundary. The distinctive geologic history of the crustal block or fragment is preserved and is usually very different from that of surrounding areas of the suture zone; thus the term "exotic" terrane is commonly used. The suture zone between a terrane and the crust to which it is attached is usually defined by a fault. Terranes are further characterized as being allochthones (formed far away) or autochthones (formed nearby). Terranes may also be referred to as internides, and may be further subdivided into belts, zones, and domains (McCormick, 2010).

The core of the North American continent began forming in the Paleoproterozoic (~2.0–1.8 billion years ago) through plate collisions of larger Archean microcontinents (e.g., Hearne-Superior), as well as smaller Archean continental fragments that included the Wyoming craton (Whitmeyer and Karlstrom, 2007). Proterozoic oceanic crustal terranes included island arc volcanic and plutonic rocks, back-arc volcanic and sedimentary rocks, and fore-arc oceanic crust, sedimentary, and metamorphic rocks. These juvenile volcanic belts eventually were caught and deformed between the two converging Archean cratons (fig. 2) during the terminal collision phase of the Trans-Hudson orogeny, creating a deformation zone similar in scale to the Himalayas. These early collisions would continue to 1.1 billion years ago, forming the Precambrian core of North America, Laurentia (Whitmeyer and Karlstrom, 2007).

Plate Tectonic Assemblage of North America in the Precambrian

Earth is approximately 4.6 billion years old and was a molten mass during the Hadean until about 4.0 billion years ago when the planet had cooled enough to form a proto crust (fig.1). During the earliest Archean (4.0 billion years ago), Earth likely consisted of relatively thin, continuous veneer of crustal material (Naaera et al., 2012). By the Mesoarchean, several small proto continents (Archean terranes) had formed, but Earth was dominantly water to 3.2 billion years ago, when the modern processes of plate tectonics and subduction probably started. At ~3.2 billion years, subduction became more prevalent and several of these small Archean terranes began to develop into larger continental cratonic masses such as the Wyoming and Superior cratons (Corrigan et al., 2009). However, by the beginning of the Paleoproterozoic (~2.4 billion years ago), they were still surrounded by oceans and more importantly oceanic crust (fig. 1). At the end of the Paleoproterozoic (~1.8 billion years ago), the Manikewan Ocean was present in central North America and separated the Wyoming craton from the Superior craton (fig. 2); however, these cratons were converging, as island arcs developed along subduction zones between the two continental masses (Mueller et al., 2005). Collectively, the island arcs, as well as fore-arc, and back-arc basins of the island arcs were eventually 'trapped' when the two cratons collided, forming the Trans-Hudson orogen and our present-day Precambrian basement. This important docking of land masses also set the stage for development of the present-day Williston Basin.

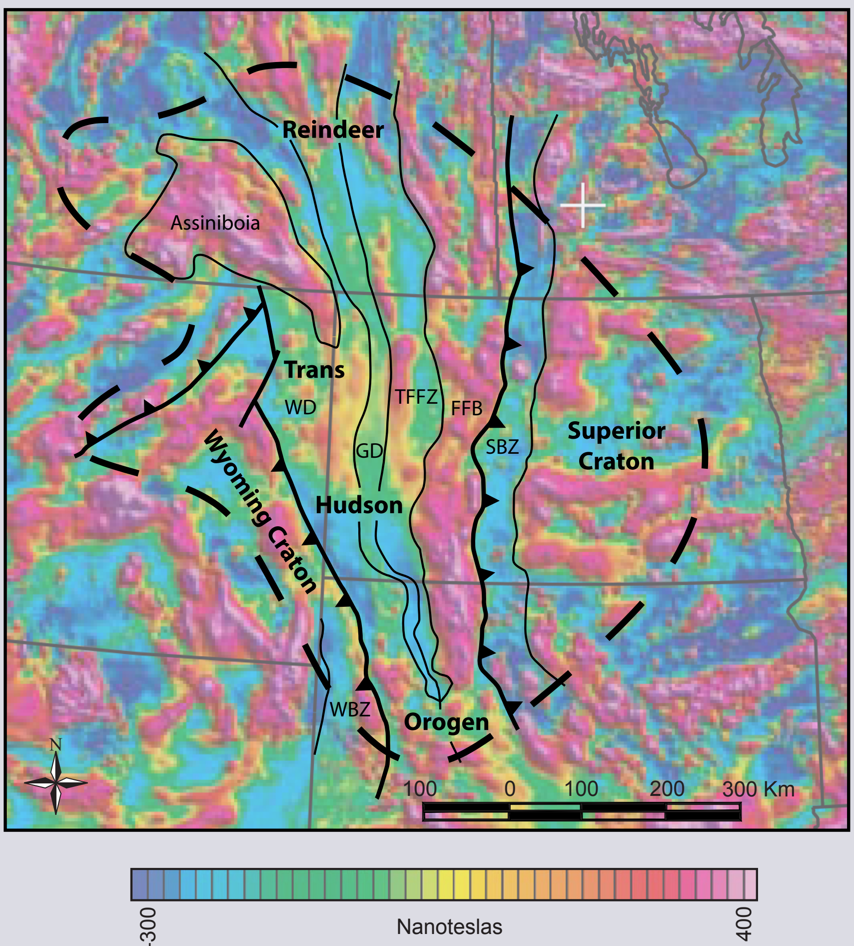

Figure 3. Aeromagnetic map of the Williston Basin and environs showing the configuration of basement terranes across North Dakota, as well as surrounding U.S. states (MT, WY, SD) and Canadian Provinces (SK, MB). Previously published interpretations of Precambrian terranes are shown for Montana and Wyoming (Sims et al., 2001, 2004), South Dakota (McCormick, 2010), and Saskatchewan and Manitoba (White et al., 2005). FFB = Flin Flon belt, GD = Glennie domain, SBZ = Superior boundary zone, TFFZ = Tabbernor fold and fault zone, WBZ = Wyoming boundary zone, WD = Williston domain.

Aeromagnetic Mapping

The magnetic field of Earth is measured in nanoteslas (nT) and ranges from 25,000 nT at the magnetic equator to 70,000 nT at the magnetic poles (Hill et al., 1995). This magnetic field is strong enough to magnetize certain kinds of rocks that contain iron. Therefore, magnetic anomalies are caused by variations in magnetization of crustal rocks, and can be mapped. Sedimentary rocks are generally not magnetic; whereas igneous rocks that are commonly rich in iron minerals are very magnetic. Metamorphic rocks show a wide range of magnetic susceptibilities. Precambrian terranes are commonly composed of certain rock type or combinations of rock types; thus they can be recognized on aeromagnetic anomaly maps.

A magnetic anomaly map is generated from flight-line measurements across the mapped area after the magnetic field of Earth has been removed (fig. 3). The data are gridded converting flight-line magnetic data to a representative map of the crustal magnetic field at evenly spaced locations along and between flight lines. Magnetic anomaly maps are typically shown as color maps—with warm colors (reds and oranges) indicating areas of higher magnetism and cool colors (blues and greens), indicating lower magnetism.

Interpretation

Archean Cratons

Both the Wyoming and Superior cratons are recognizable on aeromagnetic maps (fig. 3). These areas, by definition, have undergone little or no modification since the Precambrian. The Superior craton is defined by a distinct east—west tectonic grain as compared to adjacent terranes to the west.

This tectonic grain defines several Subprovinces in both Canada and South Dakota. The Superior craton can be mapped from southern Manitoba to north-central South Dakota and is generally characterized by aeromagnetic highs, especially along the western margin. This margin defines the east side of the Superior boundary zone (White et al., 2005; McCormick, 2010), again mapped in both Manitoba and South Dakota, and easily correlated across North Dakota. The western margin defines the major suture between Proterozoic Trans-Hudson rocks on the west, and the Superior boundary zone. This boundary zone is defined by aeromagnetic lows and likely consists of Archean Superior craton margin and Proterozoic rocks that have undergone significant deformation and reworking during continental collision (McCormick, 2010), as evidenced in South Dakota by NW—SE shear/fault zones and NE/SW faults. Rocks in South Dakota from this zone include schist, granite, diorite, granodiorite, gabbro, and quartzite and range in age from 1.7—1.9 billion years, with one granodiorite also dated at 2.5 billion years (McCormick, 2010).

The Wyoming craton boundary is less definitive on the aeromagnetic map, but the boundary zone is well defined in Wyoming, North Dakota, and South Dakota (fig. 3; McCormick, 2010). A steep transition from aeromagnetic highs to lows occurs along the strike of the Cedar Creek anticline, a significant surface structure. This transition defines the craton boundary/suture at depth (Cedar Creek fault). The Wyoming boundary zone is again Archean Wyoming craton margin and Proterozoic rocks that have undergone significant deformation and reworking during continental collision on the west side of the Trans-Hudson orogen.

Proterozoic Terranes

Proterozoic terranes are also readily identified in Precambrian rocks of the Williston Basin (fig. 3). These include: the Flin Flon belt, the Tabbernor fold and fault zone, and the Glennie domain of southern Canada and South Dakota (White et al., 2005; McCormick, 2010), and the Williston domain of South Dakota (McCormick, 2010). Boundaries between these units can again be traced through North Dakota based on aeromagnetic signatures, as well as supporting gravity data (McCormick, 2010).

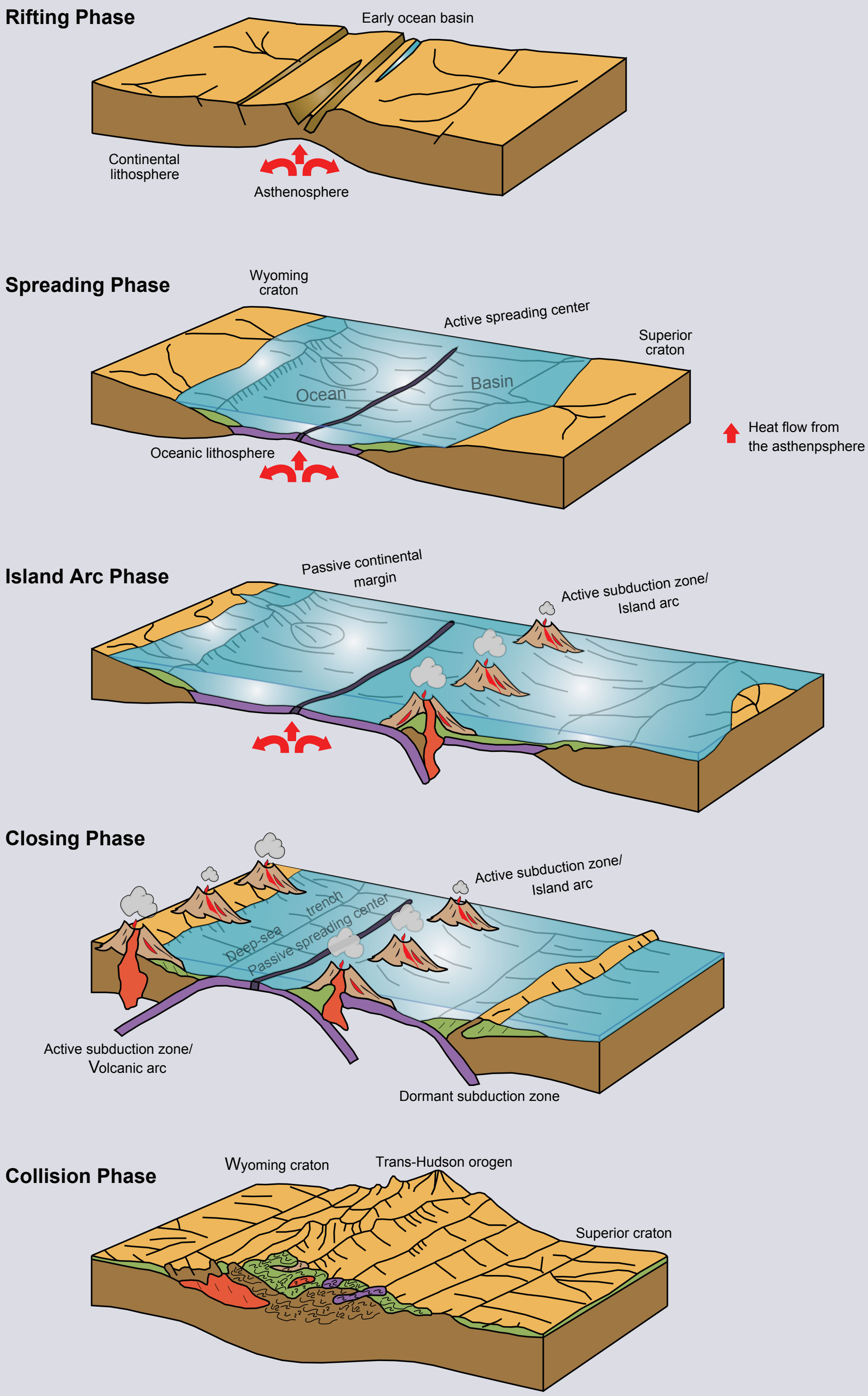

Figure 4. Schematic of possible Wilson cycle for Wyoming–Superior cratons and Trans-Hudson orogen.

The Flin Flon belt is characterized by gravity highs that trend distinctly N—S from SW Saskatchewan to NW South Dakota (fig. 3). Green et al. (1985) interpreted this belt to consist of Proterozoic island arcs in Canada and northern North Dakota, and possibly cordilleran-type arc massifs of Archean age in southern North Dakota/northern South Dakota, as suggested by Klasner and King (1986) and McCormick (2010). Rock types in South Dakota include granite and quartzite with radiometric dates of approximately 1.8 billion years for the granites.

The Tabbernor fold and fault zone is a major N—S-striking feature that extends form SW Saskatchewan into NW South Dakota (fig. 3) and consists of significant zones of deformation (McCormick, 2010). It is characterized by subdued magnetic relief in Canada, but includes elongate and discontinuous aeromagnetic highs in NW North Dakota. These highs correspond to the major near-surface deformations of North Dakota including the Nesson anticline. In the Williston Basin, it separates the Glennie domain on the west from the Flin Flon belt on the east.

The Glennie and Williston domains are highly reworked oceanic crust likely formed in fore-arc and/or back-arc basins of an island arc setting (White et al., 2005). Rocks from the Glennie domain include mafic volcanic and igneous packages and metasedimentary rocks were the only materials identified in cores (McCormick, 2010).

Summary

Within the Trans-Hudson orogen, a relatively complete Wilson-Cycle is preserved, from early 2.5–1.9 billion years old rift-to-drift sedimentary assemblages deposited along Archean craton margins, to formation of 2.0–1.9 billion years old oceanic and pericratonic arcs and back-arc basins, as well as younger (1.88–1.83 billion years) continental arcs, foredeep and collisional basins, with eventual terminal collision at ~1.8 billion years forming an orogenic zone with peaks on the scale of Mount Everest and K2 (Fig. 4; Ansdell, 2005; Corrigan et al., 2009). The importance of understanding the Precambrian basement is critical to many aspects of the evolution of the Williston Basin throughout the Phanerozoic, most importantly structure and tectonics, basin evolution, sedimentation, and petroleum accumulation (Bader, in press).

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