MOUNTAIN BUILDING: THE OROGENIC EVOLUTION OF MONTANA

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ABSTRACT

The Cretaceous to Paleogene orogenic history of Montana is complex and unique compared to other areas of the Cordilleran foreland to the north and south. This is the result of a variety of tectonic influences that include Precambrian basement terranes, recurrent reactivation of Precambrian fault systems, the enormous thickness and widespread extent of the Mesoproterozoic Belt Supergroup, overlapping contractional and extensional structural regimes, invasion of the plate margin magmatic arc into the actively deforming foreland, and complicated plate boundary interactions involving the Farallon, Kula (or the proposed Resurrection), and North American plates. The lithospheric foundation of Montana is a cryptic collage of Archean and Paleoproterozoic terranes or blocks, with both lateral and vertical variability in composition and rheological strength. The Paleoproterozoic Big Sky orogenic belt, described earlier in the literature as the northeast-trending Great Falls Tectonic Zone, has had a direct influence on subsequent Proterozoic and Phanerozoic tectonic events. Laramide deformation in Montana is not restricted to the southwestern part of the State, but instead steps down in structural relief through central Montana to the Canadian border. Laramide deformation is subdivided into three domains, from the exposed basement-cored arches of southwest Montana (Domain I), to the structurally inverted central Montana platform (Domain II), to low-amplitude basement arches beneath the plains of north-central Montana (Domain II). Similarly, the Sevier fold–thrust belt of western Montana can be subdivided into structural domains that include northwest Montana, the Lewis and Clark Tectonic Zone, the Helena structural salient, and the southwest Montana recess that also incorporates numerous plutons. Thrust sheets within the Helena Salient and southwest Montana recess were intruded by a host of largely synkinematic felsic plutons of Late Cretaceous to Paleogene age, most notably the Boulder and Pioneer Batholiths, which were often emplaced in ramp-top structural positions where accommodation space is created within thrust sheets. Some component of synconvergent channel flow may have occurred within the “Bitterroot to Boulder Batholith magmatic corridor” in western Montana, leading to super-critical taper of the orogenic wedge during Maastrichtian–early Paleocene time. Lithospheric shortening involving Laramide and Sevier styles of deformation, coupled with voluminous magmatic activity within the evolving orogenic wedge, ultimately led to the development of an orogenic plateau, herein named Montanaplano, a northern topographic extension of Nevadaplano in the hinterland of the Sevier orogen farther southwest. The eastern slopes of Montanaplano were likely impacted by a seasonal monsoon from the Western Interior Seaway, resulting in high rates of erosion of poorly consolidated volcanic and volcaniclastic rocks and deposition of one of the thickest foreland basin deposits along the Sevier orogenic front (Livingston Group). Collapse and extension of Montanaplano began ~52 Ma, coincident with the onset of widespread Challis–Absaroka–Kamloops magmatism and extension in the Bitterroot and Anaconda metamorphic core complexes. Huge displacement, east-dipping detachment faults formed on these core complexes, extending to depths of 10–20 km and resulting in the exhumation of rocks from the middle crust. Extensional detachment faults are linked to transverse strike-slip faults in the Lewis and Clark Tectonic Zone, the latter forming an accommodation zone between core complexes in Montana and those to the northwest in Idaho and northeastern Washington, resulting in dextral transtension distributed across the northern U.S. Rocky Mountains. The change at ~52 Ma from regional shortening to transtension and collapse was caused by plate boundary processes involving northward migration of the Kula/Resurrection triple junction with the Farallon and North American plates, in turn resulting in decoupling of Farallon flat-slab subduction and progressive southwestward rollback and/or slab removal beneath the Rocky Mountain foreland. The change in the regional stress/strain field at ~52 Ma is reflected by the length and distribution of radial dikes in the Crazy Mountains Basin.

INTRODUCTION

The geologic evolution of Montana is long and complex owing to numerous tectonic regimes spanning more than three billion years of Earth history. From the Hadean and Paleoarchean to the most recent alluvial sediments deposited yesterday, the "geologic face" of Montana bears the imprint of continental collision, rifting, fault reactivation, and structural inversion caused by spatially overlapping styles of deformation, and many other tectonic signals recorded in the rocks of the northern U.S. Rocky Mountains. This is not to imply that Montana contains a complete, unbroken history of every tectonic event since the early Archean, for that is clearly not the case. However, the breadth of geologic history exposed across Montana (and in the subsurface) is one of the most complete in the western United States. Because of this long geologic history, those not familiar with the geology of Montana might perceive it as unusually complex; indeed, when viewed for the first time, the State Geologic Map of Montana (MBMG, 2007) tends to reinforce this notion through seemingly disorganized outcrop patterns of vastly different rock types and ages (fig. 1).

Some of the reasons for the complexity of Montana's geology include the following. (1) Precambrian tectonic elements (shear zones, basement fabrics, terrane boundaries, etc.) have influenced the geometry and kinematics of many post-Precambrian structures

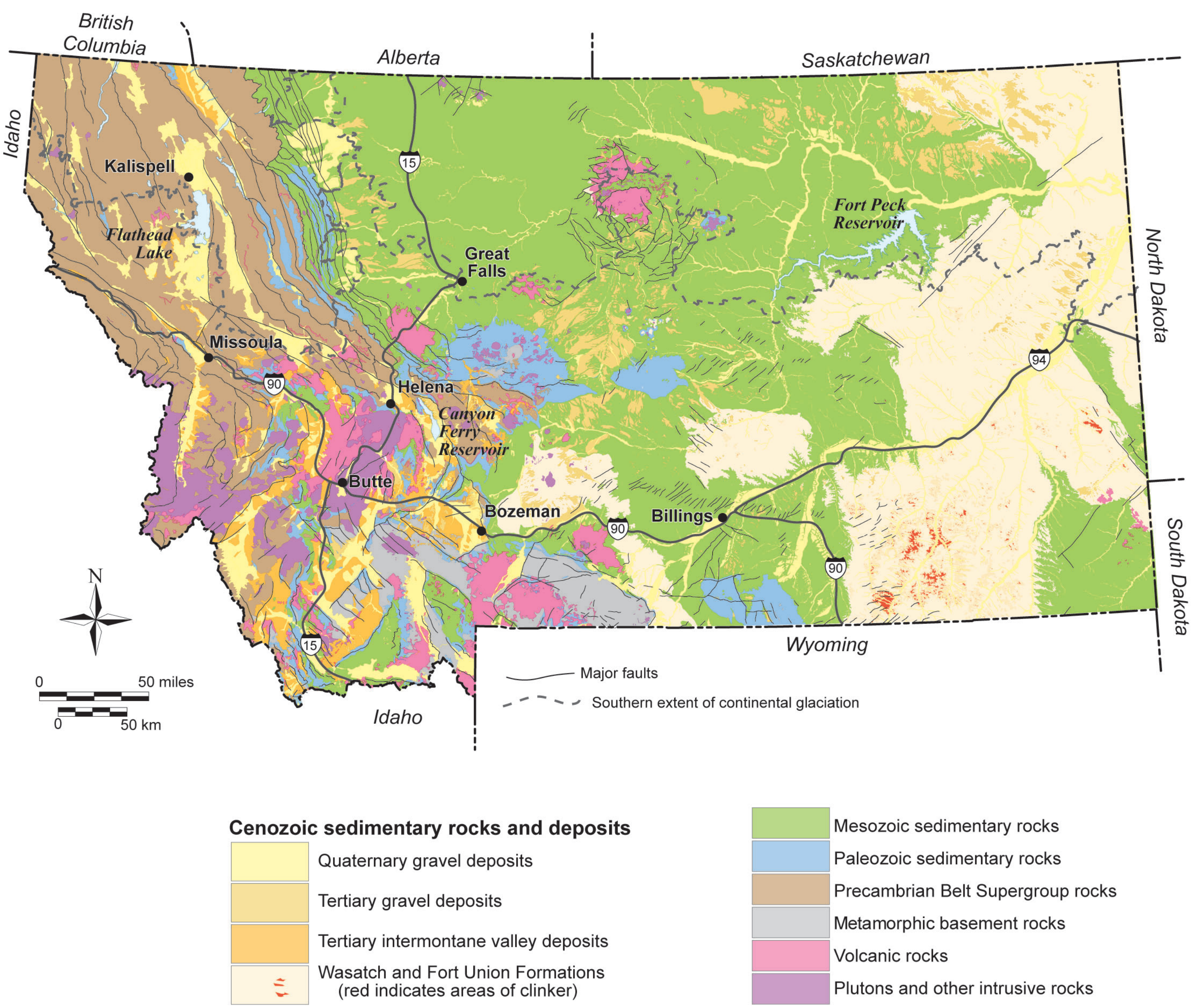

Figure 1. Simplified geologic map of Montana showing increasingly complex surface geology from the Great Plains of eastern Montana to the Rocky Mountains in western Montana. The reader is referred to the State Geologic Map of Montana at 1:500,000-scale for greater detail, as well as other geologic maps available from the Montana Bureau of Mines and Geology (https://www.mbmg.mtech.edu/Information/StoryMaps/GeologicMaps.asp).

and continue to influence Cenozoic lithospheric extension to this day. This is largely because the western margin of Laurentia has experienced the convergence and subsequent rifting of three major supercontinents from the Neoarchean to the Neoproterozoic, including Kenorland/Superia, Columbia/Nuna, and Rodinia (Pesonen and others, 2014), as well as a sustained subduction history of oceanic lithosphere and the accretion of numerous tectonostratigraphic terranes throughout the Phanerozoic (Monger and Price, 2002; Colpron and others, 2007). To varying degrees, these tectonic events have left their mark in the crustal architecture, structural geology, and sedimentary rock record of Montana. (2) Basement-rooted faults have been recurrently active throughout Montana's geologic history, resulting in laterally discontinuous stratigraphic relations in overlying Mesoproterozoic and Phanerozoic rocks that affect structural styles across the region (i.e., lateral and vertical variations in mechanical stratigraphy). As a result of recurrent fault movement, the Phanerozoic stratigraphic section in Montana is relatively thin compared to Wyoming and Alberta, except in areas where accommodation space has been provided by localized extension of the basement (e.g., Mississippian Central Montana Trough; Maughan, 1993). (3) The enormous thickness, lithologic monotony, and wide extent of the Mesoproterozoic Belt Supergroup dominate the geology of westernmost Montana, masking some of the complexity recorded within these rocks (Winston, 1986a,b; see also Geological Society of America Special Paper 522, 2016, and articles therein). In addition, the Belt Supergroup has been rife with stratigraphic confusion and miscorrelations in earlier literature, leading to overly complicated if not incorrect structural relationships on some published maps. (4) As mentioned above, several tectonic domains spatially, and sometimes temporally, overlap across Montana. Relevant to this paper, Montana is a geological hybrid that combines structural styles of the Canadian Rocky Mountain fold–thrust belt to the north and the Wyoming Laramide, basement-involved foreland to the south, all superimposed by several stages of Cenozoic extension. Laramide and Sevier structural styles (i.e., predominantly thick-skinned and thin-skinned, respectively) directly overlap spatially and temporally in many parts of western Montana (e.g., Bridger Range; Lageson, 1989), resulting in tectonic patterns that are not as well differentiated as in Wyoming, where the Sevier fold–thrust belt forms a distinctive salient in the westernmost part of the State. (5) Unlike most areas of the North American Cordillera, the Cretaceous–Paleogene magmatic arc has intruded its own "back-arc" in western Montana, broadly contemporaneously with fold–thrust shortening (Kalakay and others, 2001). (6) The complicated and still uncertain plate configurations involving the triple junction of the Kula, Farallon, and North America plates contributed to onshore tectonic complexity in the evolving northern U.S. Rocky Mountains and southern Canadian Cordillera. Paleogene Montana was near or at the northwest margin of flat-slab subduction of the Farallon plate (Haeussler and others, 2003; Brietsprecher and others, 2003; Humphreys, 2009; Foster and others, 2010), marking a fundamental change from foreland, basement-involved shortening east of the Sevier fold–thrust belt to dominantly thin-skinned shortening northward in the Canadian Rockies and east of a vast collage of accreted terranes in British Columbia (Monger and Price, 2002). (7) Lastly, multiple phases of extension have overprinted the record of contractile deformation in western Montana, resulting in Paleogene metamorphic core complexes and Neogene to Quaternary sedimentary basins with complex geometries, sometimes controlled by underlying, older structures and crustal fabrics (e.g., Madison Range; Kellogg and others, 1995). Fault reactivation and tectonic inversion, documented by different apparent displacements during subsequent tectonic events, have been demonstrated on many range-bounding fault systems in western Montana and seem to be a common theme for the northern U.S. Rocky Mountains.

The recognition of relatively distinct regional tectonic domains across Montana helps to compartmentalize the geology and reduce the apparent complexity as seen on the Geologic Map of Montana (MBMG, 2007). One of the first to do this was William J. McMannis (1965) in his classic paper on the depositional and structural history of western Montana. In this paper, McMannis subdivided western Montana into four broad tectonic provinces (fig. 2). (1) The "Belt Province" of northwest Montana, lying north of the Osburn Fault (now called the Lewis and Clark Lineament), consisting of widespread outcrops of the Mesoproterozoic Belt Supergroup, with the near-absence of large igneous intrusions. (2) The "Batholithic Province," lying south of the Lewis and Clark Lineament and consisting of numerous intermediate to felsic intrusive bodies and thick, largely coeval extrusive accumulations (e.g., Boulder Batholith and the Late Cretaceous Elkhorn Mountains volcanic succession), a thick Belt

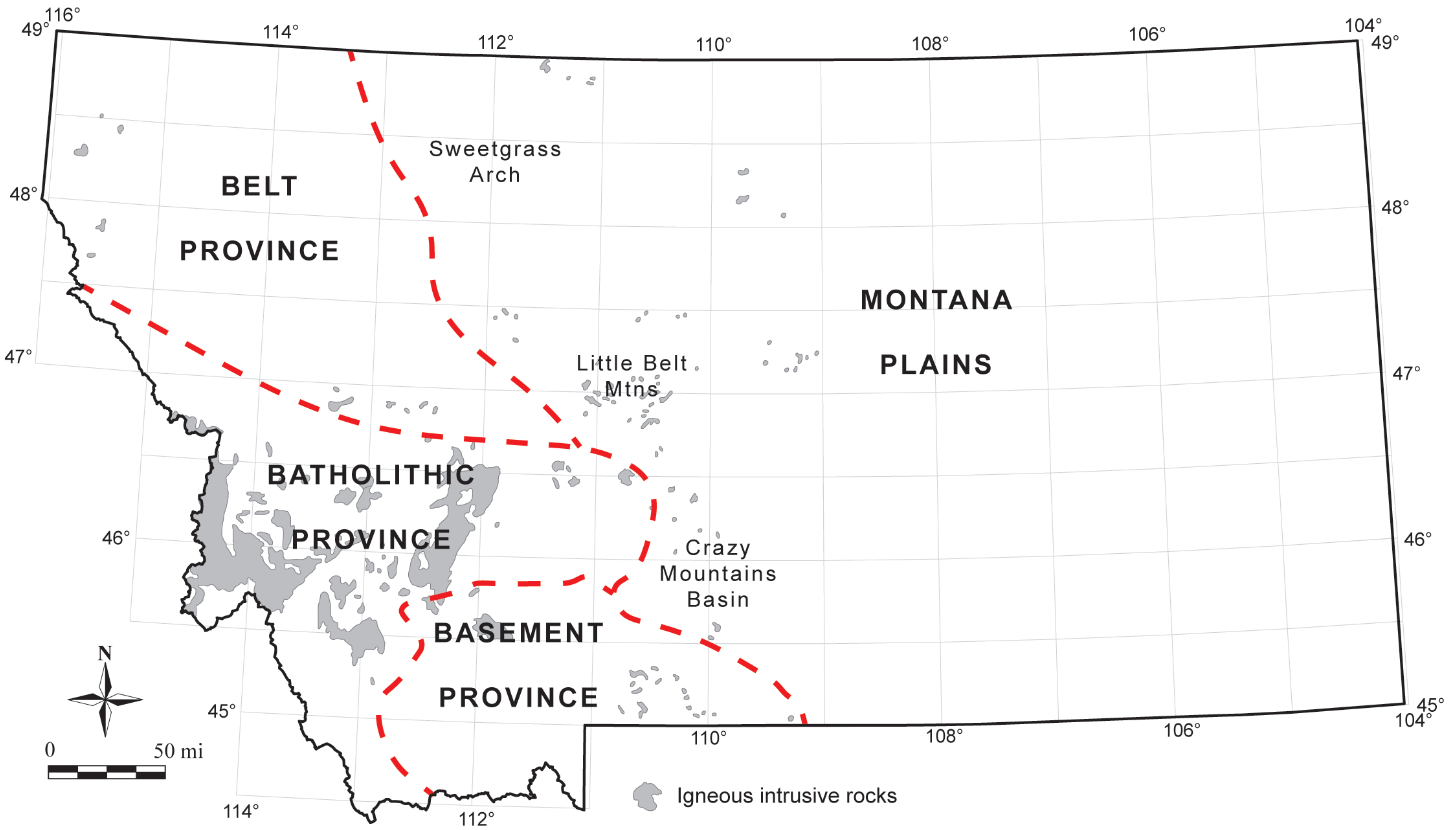

Figure 2. Tectonic provinces of Montana as envisioned by McMannis (1965). This was one of the first papers to "bring order out of chaos" in terms of the regional geology of western Montana.

sedimentary succession, and exceedingly complex structure. (3) The "Basement Province," characterized by pre-Belt basement (Archean) rocks exposed in Laramide and younger uplifts, overlain by a generally thin Paleozoic–Mesozoic sedimentary succession and abundant Cenozoic basin-fill deposits. The tectonic provinces envisioned by McMannis (1965) are simplifications of the regional geology as we have come to understand it in recent decades, but his provinces were a first step toward understanding this complex region by identifying tectonic domains based on the predominant rock assemblage. More recently, tectonic and other maps in the booklet that that accompanies the 1:500,000-scale Geologic Map of Montana (MBMG, 2007) further clarify and organize the geologic complexity of Montana.

The remainder of this review will discuss the Cretaceous to early Paleogene contractile orogenic history of Montana, followed by a discussion of the Paleogene collapse of the thickened orogenic wedge. At the end, we discuss broader, regional-scale tectonic factors and propose some ideas that might stimulate future research. Throughout, we strive to make clear the distinction between stress and strain, by using strain terminology (e.g., contraction and extension) and avoiding stress-related terminology (e.g., compression), except when discussing proxy indicators of paleo-stress orientation.

PRECAMBRIAN (PRE-BELT SUPERGROUP) FOUNDATION OF THE OROGEN

This section is not intended to be a thorough review of the continental lithosphere that underlies Montana. Mogk and others (2020, this volume) provide a detailed, chronological review of the evolution of the pre-Belt basement in Montana. However, we do want to emphasize the important role that crustal architecture has played in the tectonic development of the northern U.S. Rockies (Montana–Idaho). Tectonic events that spatially overlap through geologic time can have vastly different orientations of stress/strain. Even for a single tectonic event, the axes of stress/strain can vary through time during progressive deformation, producing superimposed structural fabrics in rocks. The resulting structural and lithological heterogeneity of the Precambrian basement can, in some but not all cases, be a factor in controlling the distribution and geometry of younger structures, a fact recognized by many early field geologists in Montana (e.g., Chamberlin, 1945). Quoting Chamberlin (1945, p. 99) from Mudge (1972, p. B7):

The more these mountains are studied, the more it becomes evident that preexisting structures in the underlying basement rocks, developed long before our present Rockies started to form in Laramide times, have had great influence in determining the areal pattern of some of the present ranges and basins and likewise the modes of yielding under the compressive stresses.

Exposures of basement rocks and related structures occur in several Laramide and younger uplifts across southwest Montana, namely the Beartooth, Madison, Gravelly, Tobacco Root, Highland and Ruby Ranges (fig. 3; see Mogk and others, 2020, this volume). These rocks represent the exposed north margin of the Archean Wyoming Province (craton), which underlies all of southern and southeastern Montana (Mogk and others, 2020, this volume; Foster and others, 2006, 2012). In this paper, we define *basement rocks* in Montana as a heterogeneous assemblage of low- to high-grade metamorphic and igneous rocks, all entirely pre-Belt in age.

The first major stage in the formation of felsic meta-igneous basement rocks occurred at 3.5–3.1 Ga as horizontal plate tectonics with subduction became the dominant mode of geodynamics. This time period marks the earliest foundation of the Wyoming Province (fig. 4), in the sense of forming a thick, semi-stable tectosphere (Mogk and others, 2020, this volume and references therein). Subsequently, Late Archean magmatic rocks (~2.9–2.8 Ga tonalite, trondhjemite, and granite) and quartzofeldspathic gneiss dominated the basement assemblage in the Beartooth and Bighorn Ranges, comprising the Beartooth–Bighorn magmatic arc/terrane, or BBMT (Mogk and others, 1992a). To the west in the Madison, Gravelly, and Blacktail Ranges, metasedimentary rocks mixed with trondhjemitic gneiss become more abundant, constituting the Montana metasedimentary terrane, or MMT (Mogk and others, 1992a). These two terranes appear to have experienced "a separate and distinct geologic history since at least 3.6 Ga" until their juxtaposition or suturing in the Late Archean (Mogk and others, 1992a). However, similarity in isotopic signatures suggests that they were part of larger crustal province or "supercraton" at this time, most likely a part of Superia (Bleeker, 2003). Smaller lithotectonic terranes are also found within the northern Wyoming Province, such as two distinct metasupracrustal terranes separated by a 0.5-km-wide shear zone in the northern Madison Range (Mogk and others, 1992b) and several high-grade metamorphic suites in the Tobacco Root Mountains (Harms and others, 2004). The Wyoming Province finally "stabilized" as a coherent craton following a major, Late Archean (2.7–2.6 Ga) crustal growth event that involved the accretion of these smaller terranes and crustal blocks (Harms and others, 2004, and references therein). This Late Archean crustal growth event was very likely associated with the assembly of Kenorland/Superia, the earliest, well-vetted, large supercontinent, at ca. 2.7 Ga (Williams and others, 1991).

It was recognized many years ago that the Wyoming Province was affected by 1.8–1.7 Ga thermotectonism, resulting in the so-called "Giletti Line" along its northern margin (see Harms and Baldwin, 2020, this volume). This "line" is actually a broad zone where K-Ar ages in Late Archean rocks were reset (Ar loss), resulting in Paleoproterozoic post-metamorphic cooling ages (Giletti, 1966). This thermotectonic event, variously called the Big Sky orogeny (Harms and others, 2004, p. 228), Great Falls orogeny (Gifford and others, 2018), or Trans-Montana orogeny (Gu and others, 2018), culminated at ca. 1.78 Ga when the Medicine Hat craton (or block, as some authors refer to it) and a magmatic arc accreted to the northern margin of the Wyoming Province (Foster and others, 2006; Gifford and others, 2018). The arc rocks are best exposed in the Little Belt Mountains in central Montana (referred to as the "Little Belt arc"), having intrusive ages of about 1.86 Ga (ranging from 1.87 to 1.80 Ga) based on U-Pb and Pb-Pb dating of zircons (Mueller and others, 1996, 2002; Vogl and others, 2004; Foster and others, 2006). Oblique collision with the Medicine Hat craton along the north margin of the Wyoming Province at 1.78 Ga followed the end of arc-type magmatism. Condit and others (2015) demonstrated at least two phases of Big Sky deformation in the northern Madison Range, as well as a progressive southeastward-younging of high-grade deformation away from the core of the Big Sky orogenic belt. Condit and others (2015) suggest that the spatial and temporal pattern of thermotectonism for the Big Sky orogeny across southwest Montana reflects: (1) multiple collisions of small terranes, (2) a single protracted collision, and/or (3) superimposed post-collision collapse of the orogen.

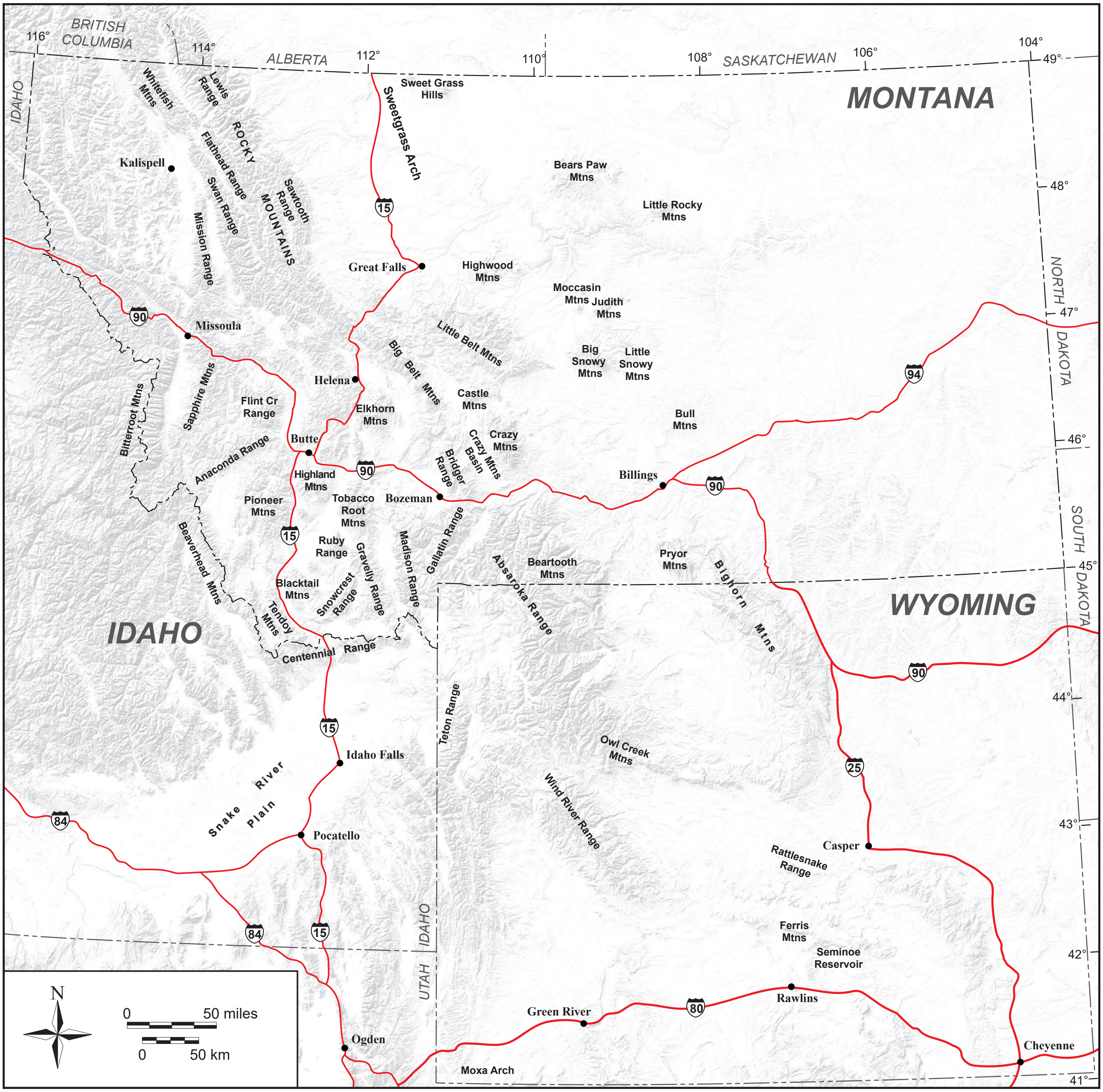

Figure 3. Geographic features referred to in text.

The Archean Medicine Hat block, and Hearne Province to the north, lie to the northwest of the Big Sky orogen (fig. 4), making up the basement beneath northwest Montana and the Western Canada Sedimentary Basin (Ross and others, 1991). Deep Probe investigations (Gorman and others, 2002) reveal these to be separate and distinct Archean blocks from the Wyoming Province that were joined in the Paleoproterozoic as intervening basins were closed through subduction. Two prominent northward-dipping reflectors in the velocity structure of the lithospheric mantle project up-dip to the north and south crustal boundaries of the Medicine Hat block (Vulcan structure and Great Falls Tectonic Zone, respectively), interpreted to be fossil subduction zones (fig. 5; Gorman and others, 2002, p. 389). If so, these upper mantle velocity anomalies would mark the remnants of two ocean basins that separated the Medicine Hat block from the Hearne Province to the north, and the Wyoming Province to the south. Therefore, by 1.7–1.6 Ga, a broad collage of

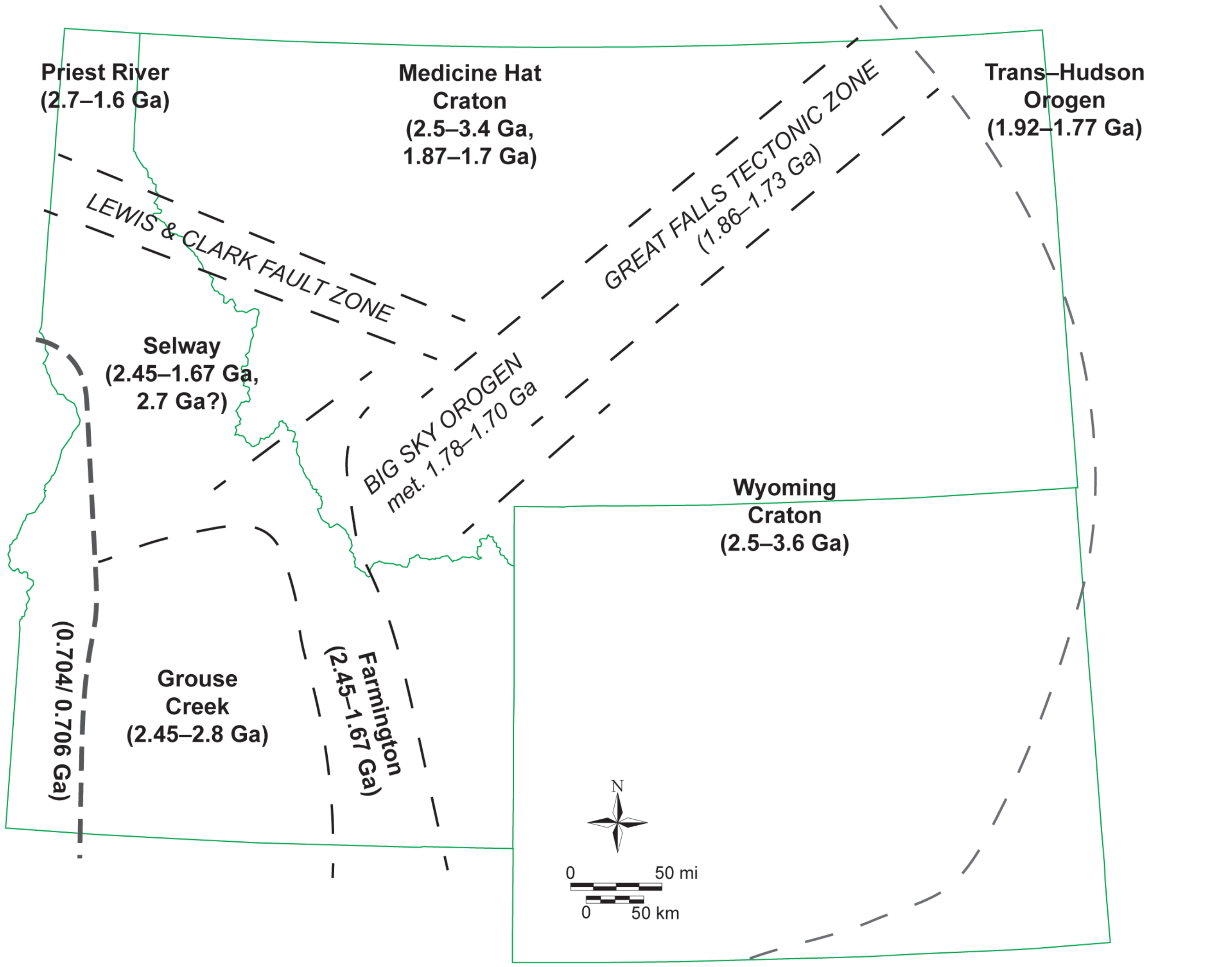

Figure 4. Map showing the distribution of Precambrian cratons, transecting fault zones, and orogenic belts. Modified from Foster and others (2006) and Gifford and others (2018). The two major Archean cratons are Wyoming (to the south) and Medicine Hat (to the north), sutured along the northeast-trending Big Sky/Great Falls orogenic zone. Rocks within the Paleoproterozoic orogens, such as the Big Sky/Great Falls, include reworked Archean crust from Medicine Hat and Wyoming cratons along with juvenile crust.

accreted Archean basement blocks and Paleoproterozoic arc terranes had assembled to form the basement complex of a large part of western Laurentia (e.g., Whitmeyer and Karlstrom, 2007). These collisional/accretionary events were broadly coincident with the Paleoproterozoic assembly of one of Earth's largest supercontinents, Columbia/Nuna (fig. 6; e.g., Meert, 2012; Verbaas and others, 2018).

In southwest Montana the Big Sky orogeny resulted in several northeast-striking mylonite shear zones and related structures, such as the Madison, Snowy, Mirror Lake, and Big Brother shear zones (Mogk, 1992). The Madison mylonite (Erslev, 1982) is a top-to-the-southeast thrust parallel to, and on the foreland side of, the Big Sky orogenic belt (Erslev and Sutter, 1990; Harms and others, 2004). Along-strike to the northeast, the Madison mylonite zone is coincident with a thick, steeply dipping mylonite zone that structurally and topographically defines the northwest margin of the Laramide Beartooth Uplift and the Eocene to Recent Paradise Valley (Kalakay and others, 2018). The Emigrant normal fault, marked by Holocene fault scarps (Stickney and others, 2000), is superimposed on this mylonite zone and defines the southeast flank of the Paradise Valley (Locke and others, 1995).

The northeast-trending tectonic grain of the Big Sky orogenic belt produces strong potential field lineaments with parallel trend in the Precambrian basement beneath central Montana, as seen on aeromagnetic and gravity maps (e.g., McCafferty and others, 1998; USGS, 2002; Gorman and others, 2002, their fig. 2). However, recognition of northeast-trending lineaments and faults across central Montana occurred long before conception of the Big Sky orogenic belt, such as the

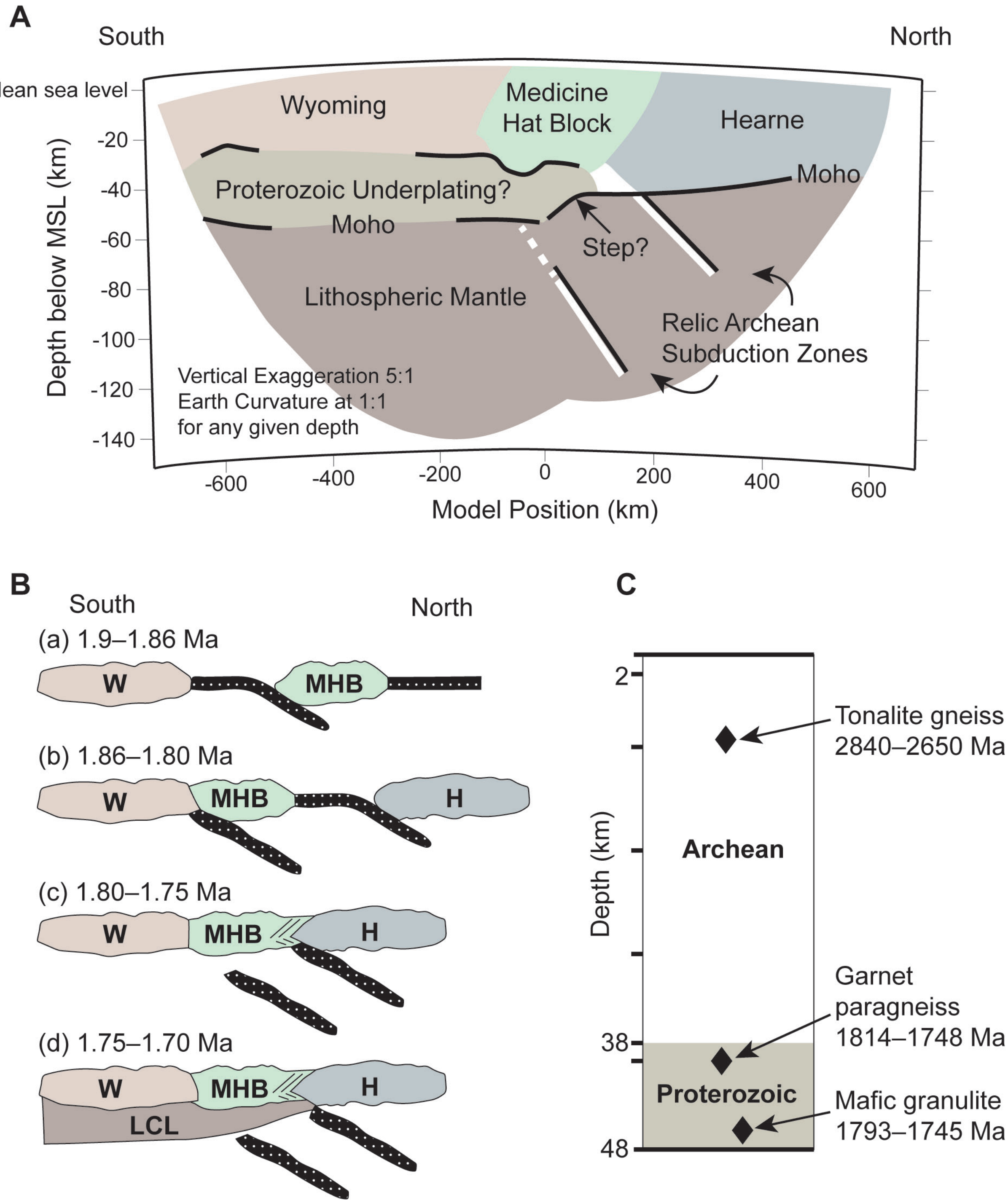

Figure 5. (A) Structural interpretation of the Deep Probe seismic refraction velocity profile from the Wyoming craton to the Hearne craton, with model positions in kilometers indicated north (+) and south (-) of the Canada/U.S. border. Reflective boundaries are indicated by solid black lines, two of which are interpreted to be traces of Late Archean subduction zones. (B) Paleoproterozoic cratonic assembly of western Laurentia, showing inferred paleo-subduction zones based on Deep Probe seismic data. W, Wyoming Province; MHB, Medicine Hat Block; H, Hearne Province; LCL, "lower crustal layer" underplated to the Wyoming Province. (C) Xenolith ages and source depths from the Sweetgrass Hills, showing interpretation of the Archean/Proterozoic crustal boundary from Deep Probe model at the Canada/U.S. border. Modified from Gorman and others (2002). Note that the suturing of the Medicine Hat Block to Wyoming Province was thought to be Archean by Gorman and others (2002); this is now considered a Paleoproterozoic event (see fig. 4).

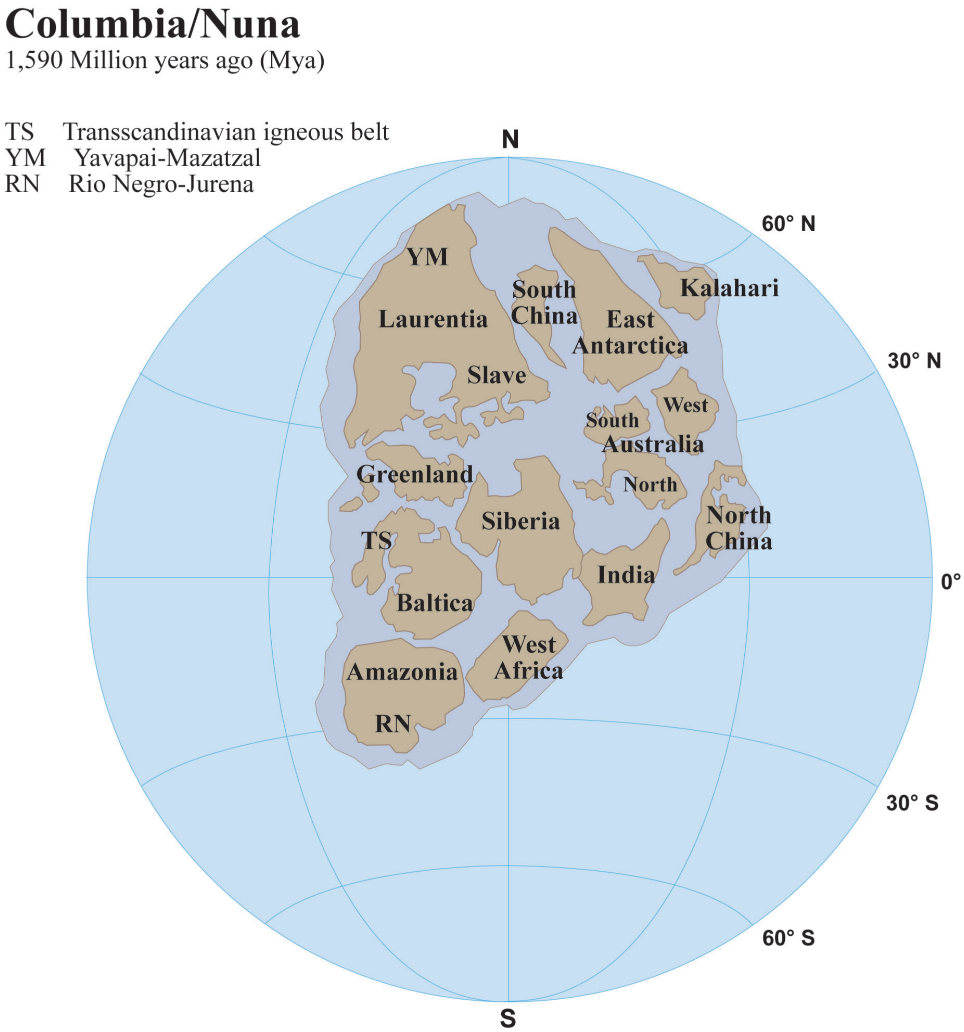

Figure 6. Global map showing interpreted paleogeography of the Proterozoic supercontinent Columbia/Nuna approximately 1,590 million years ago, after accreted Archean basement blocks and Paleoproterozoic arc terranes had assembled to form the basement complex (tectonic collage) across a large swath of western Laurentia. Modified from: https://en.wikipedia.org/wiki/Columbia_(supercontinent).

Scapegoat–Bannatyne trend and Pendroy Fault east of the Sawtooth Range ("Disturbed belt"), as well as other structures in eastern Montana with a similar northeast trend (Mudge, 1972, p. B7). O'Neill and Lopez (1985) defined a broad zone of semi-parallel geologic features extending northeastward from the Idaho Batholith in east-central Idaho, to southwestern Saskatchewan and beyond (~200 km wide, >1,500 km long); they called this the Great Falls Tectonic Zone (GFTZ; fig. 4). The GFTZ marks the alignment of high-angle faults and shear zones, Late Cretaceous and Paleogene igneous centers, Phanerozoic isopach patterns, linear gravity and magnetic anomalies, and linear topographic features. Even on the 1:500,000-scale Geologic Map of Montana (MBMG, 2007), the GFTZ jumps out as a wide swath of semi-aligned, diverse geologic features that trends northeast–southwest across central Montana. Today we broadly correlate the GFTZ with the Big Sky orogenic belt, but in 1985, the recognition of the GFTZ was a brilliant, seminal work of tectonic synthesis by O'Neill and Lopez.

The pre-Belt basement has played an important role in influencing the distribution and in some cases the geometry of later structural and tectonic features in Montana. As will be amplified in subsequent sections, field studies have shown that Archean basement fabrics have controlled, or at least influenced at shallow crustal depths, the geometry of much younger Phanerozoic structures (Lageson, 1987a; Miller and Lageson, 1993). In central Montana, the crustal fabric of the Paleoproterozoic Big Sky Orogen (GFTZ) strongly influenced the structural development of the Mesoproterozoic Belt Basin (Helena embayment), which in turn influenced the Cretaceous–Paleogene Sevier fold–thrust belt (Helena salient) and the spatial distribution of Cretaceous igneous provinces (Foster and others, 2006, 2012). In addition, the projection of the Vulcan structure and GFTZ to the southwest beneath the fold–thrust belt is reflected in overlying structures, even though the regional structural grain of the thrust belt strikes almost orthogonal to the Big Sky Orogen (Burberry and Palu, 2016; Price, 1996; O'Neill and Lopez, 1985). Basement crustal structures and lithospheric province boundaries influenced the Phanerozoic structural development of Montana because of variations in the strength of the lithosphere (particularly in Cretaceous time), the composition of the basement in terms of the potential for partial melting, the proximity of basement structures to major structures of the Mesoproterozoic Belt Basin, and the relative proximity of the Archean Wyoming craton edge to the growing orogenic plateau that advanced generally from west to east. At the same time, we caution against overinterpretation of the role of the basement in controlling the geometry and orientation of younger structures, because there are also examples in which the influence of basement terranes and fabrics on younger structures is unclear.

LARAMIDE DEFORMATION

The Laramide orogenic belt refers to the Rocky Mountain foreland region from New Mexico to Canada, typified by basement-involved uplifts and basins that formed during the Cretaceous and early Paleogene, hundreds of kilometers inboard from the plate margin (Snoke, 1993; Yonkee and Weil, 2015). The term "Laramide" derives from J.D. Dana's (1895) "Laramie Series" in the Laramie Basin of southern Wyoming, in turn derived from F.V. Hayden's coal-bearing "Lignitic Series," later called the Montana Group. These non-marine rocks overlie marine Cretaceous strata throughout the Rocky Mountain foreland, unconformably overlain by the Paleogene Fort Union and Eocene Wasatch Formations and equivalents (Snoke, 1993, p. 21). Like most names given to protracted orogenic events across a broad region, the term "Laramide" has enjoyed a long history of varied use and abuse. For example, the "Laramide" has been used in reference to tectonic events in other parts of the North American Cordillera during the Late Cretaceous/Paleogene that bear no similarity to Rocky Mountain Laramide structures, and even to orogenic events during this interval of geologic time on other continents. Furthermore, some authors refer to *"Laramide time,"* supposedly in reference to Late Cretaceous/early Paleogene deformation anywhere in the world. However, the global geologic time scale is well established and does not include a time unit named for the Laramide (e.g., Cohen and others, 2018, International Chronostratigraphic Chart; GSA Geologic Time Scale). Therefore, in this paper, Laramide or Laramide orogeny refers to basement-involved deformation of the Rocky Mountain foreland east of the Cordilleran fold–thrust belt, but locally overlapping with thin-skinned fold–thrust structures, which involved shortening of the continental lithosphere into a series of broad uplifts (basement-cored arches) and basins from New Mexico to the Alberta border during the Late Cretaceous and early Paleogene. In other words, we specify: (a) a structural style that occurred, (b) in a specific geographic region, and (c) during a specific interval of geologic time.

Laramide Structural Style

The historic debate over the predominant structural style of the Laramide foreland province has been resolved for over 30 years. This debate centered largely on the issue of fault geometry within the basement and the nature of causative stress fields acting on the lithosphere, as reflected in two schools of thought, namely "vertical uplift" along high-angle faults (e.g., Stearns, 1978) versus "horizontal shortening" along reverse and thrust faults (e.g., Blackstone, 1940, 1981, 1983, 1986, 1987, 1990, 1991; Brown, 1993). The debate has been resolved resoundingly in favor of horizontal crustal shortening based on data from industry and academic deep-reflection seismic profiles (Smithson and others, 1978), subsurface oil well logs, deep drilling through Laramide range-front "basement overhangs" (Gries, 1983a,b; Skeen and Ray, 1983; Stone, 2002), constraints imposed by regionally balanced cross-sections (particularly those coupled to the Sevier fold–thrust belt), and detailed geometric and kinematic field studies. Excellent summaries of the history of the "Laramide debate" and of our current understanding of Laramide structural style are in Brown (1993) and Snoke (1993), and references therein.

It is now widely accepted that horizontal crustal shortening across the Laramide foreland was regionally accommodated by long-wavelength, basement-involved arches and basins, and on a local scale by modified versions of fault-propagation folding whereby basement shortening was accommodated along one or more imbricated reverse/thrust faults, with folding of overlying Phanerozoic strata ahead of fault tips. Shortening was transferred up-dip from the basement fault array into an overlying fold, thus maintaining overall structural balance, a process of up-dip displacement transfer. Erslev (1991) presented a kinematic model of fault-propagation folding called "trishear," whereby a triangular region of ductile deformation develops ahead of a propagating fault tip. The zone of trishear strain moves upsection through rock layers as the fault tip propagates in an up-dip direction; folding ceases after the fault has cut through overlying layers (Fossen, 2016, p. 200). The popular trishear fault-fold model has wide applications for both contractile and extensional tectonic regimes, but seems particularly well suited to Laramide foreland structures where substantial fault offset (throw) of the Precambrian basement has folded the overlying Phanerozoic stratigraphy (fig. 7). From a historical perspective, Blackstone's (1940) cross-sections of the Pryor Mountains in southern Montana are an excellent geometric example of the trishear model of Laramide deformation, presaging modern thinking by several decades (Snoke, 1993, p. 23). Also, de Sitter's (1964, p. 197) cross-section of a monocline above a basement reverse fault, in reference to the Colorado Plateau, was way ahead of its time relative to modern Laramide fault-fold trishear models, lacking only in kinematic rigor.

As folds evolve in the hanging wall of basement-rooted faults, forelimbs can often become vertical to overturned in the trishear zone, a feature commonly seen along many Laramide uplifts in southwest Montana (e.g., Bridger Range; Skipp and others, 1999). Steeply dipping to overturned forelimbs at the level of the Precambrian basement require that rigid basement rocks somehow accommodate the fold geometry of overlying sedimentary rocks, a topic that has received much attention in the literature on Laramide structural geology. Miller and Lageson (1993) demonstrated that one of the key factors involved with Laramide basement folding is the angular discordance of metamorphic foliation in basement rocks relative to the basement–cover interface, or Cambrian nonconformity. In areas where the pre-Laramide angle of discordance is low, <25^{o} (e.g., Bridger Range anticlines and Canyon Mountain Anticline), the basement folded congruently with cover rocks via localized flexural-slip on micaceous foliation surfaces, very similar to flexural-slip folding in layered sedimentary rocks to produce parallel folds. In other areas where the angle of discordance is high and/or complex fold patterns in the basement impeded flexural-slip folding along micaceous foliation surfaces, the basement was segmented into rigid, macrogranular blocks that were displaced relative to one another along cataclastic zones, a style commonly referred to as "passive-slip" folding (Donath and Parker, 1964). In passive-slip folding (sometimes called passive-shear folding), layering has no mechanical significance and slip occurred on high-angle, foliation-oblique, small displacement reverse faults spaced several meters apart, thus producing an overall "folded" (but non-rotated) geometry of the basement/cover interface through macrogranular displacements of rigid blocks—not flexural-slip. This style of basement folding in the core of Laramide anticlines was documented at Storm Castle Creek in the western Gallatin Range (Miller and Lageson, 1993). Schmidt and others (1993) discuss other mechanisms of Laramide basement deformation based on a study in the central Madison Range, Montana.

Debate over the underlying causative processes that drove Laramide compression and shortening of the Rocky Mountain foreland has occurred for decades. One problem is that the pattern of Laramide arches and basins across the Rocky Mountain foreland is somewhat variable (most trend north–south, curving to northwest–southeast into southwest Montana); also, there are several east–west zones marked

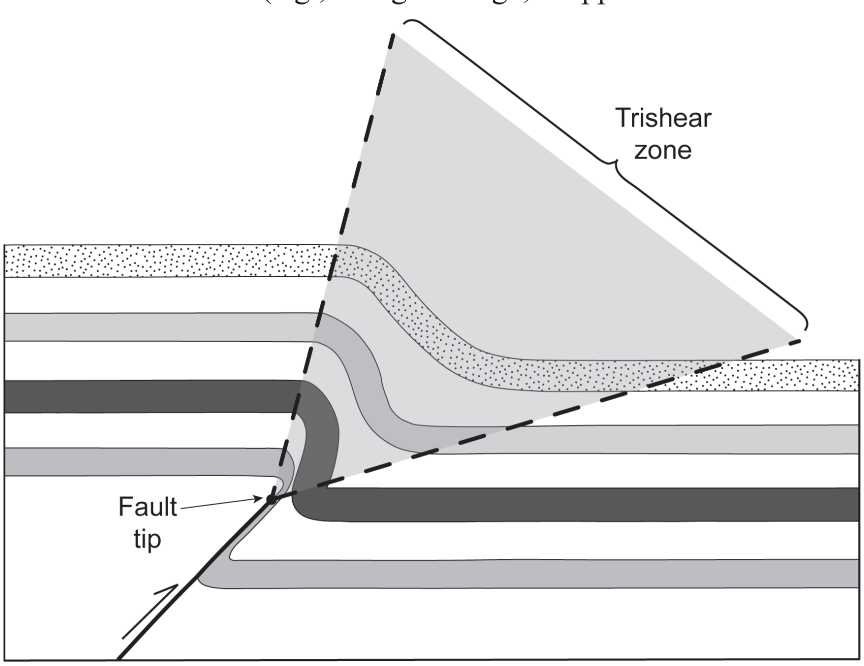

Figure 7. Simplified structural geometry of the "trishear" fault-propagation model of Erslev (1991), as applied to Laramide foreland uplifts. Earlier workers presaged this model (e.g., Blackstone, 1940), albeit lacking in kinematic/modeling rigor. From van der Pluijm and Marshak (2004, p. 464).

by *en echelon* uplifts, all of which have led to varied tectonic interpretations. In the past, some authors have used the regional variability in orientation of Laramide structures (in map view) as an argument against a regionally coherent stress field that led to crustal shortening, i.e., east–west compression of the lithosphere (Stearns, 1978), or to argue for major changes in the orientation of the regional Laramide stress field (Gries, 1983a). However, these studies lacked kinematic data and assumed dip-slip on major bounding faults, and therefore, conclusions drawn about regional Laramide dynamics were weak, if not invalid. Also, basement heterogeneities and reactivated faults are another factor that can cause variability in the orientation of Laramide structures, thus invalidating conclusions about Laramide paleo-stress based primarily on orientation data. More recent structural studies of the Laramide foreland have incorporated robust kinematic and paleomagnetic data into detailed geometric analyses to produce convincing conclusions about the dynamic stress field that drove Laramide orogenesis (e.g., Weil and Yonkee, 2012; Weil and others, 2014). Brown (1993) compiled a vast amount of structural data into a geometric, kinematic, and dynamic model of the central Rockies (Wyoming), in which he concluded that the overall direction of regional Laramide horizontal compression (RHC), or σ_1, was oriented northweast–southwest (~040/220^o; fig. 8). Koenig and Erslev (2009) combined over 20,000 minor fault slip data with vector means of Laramide arches and fold

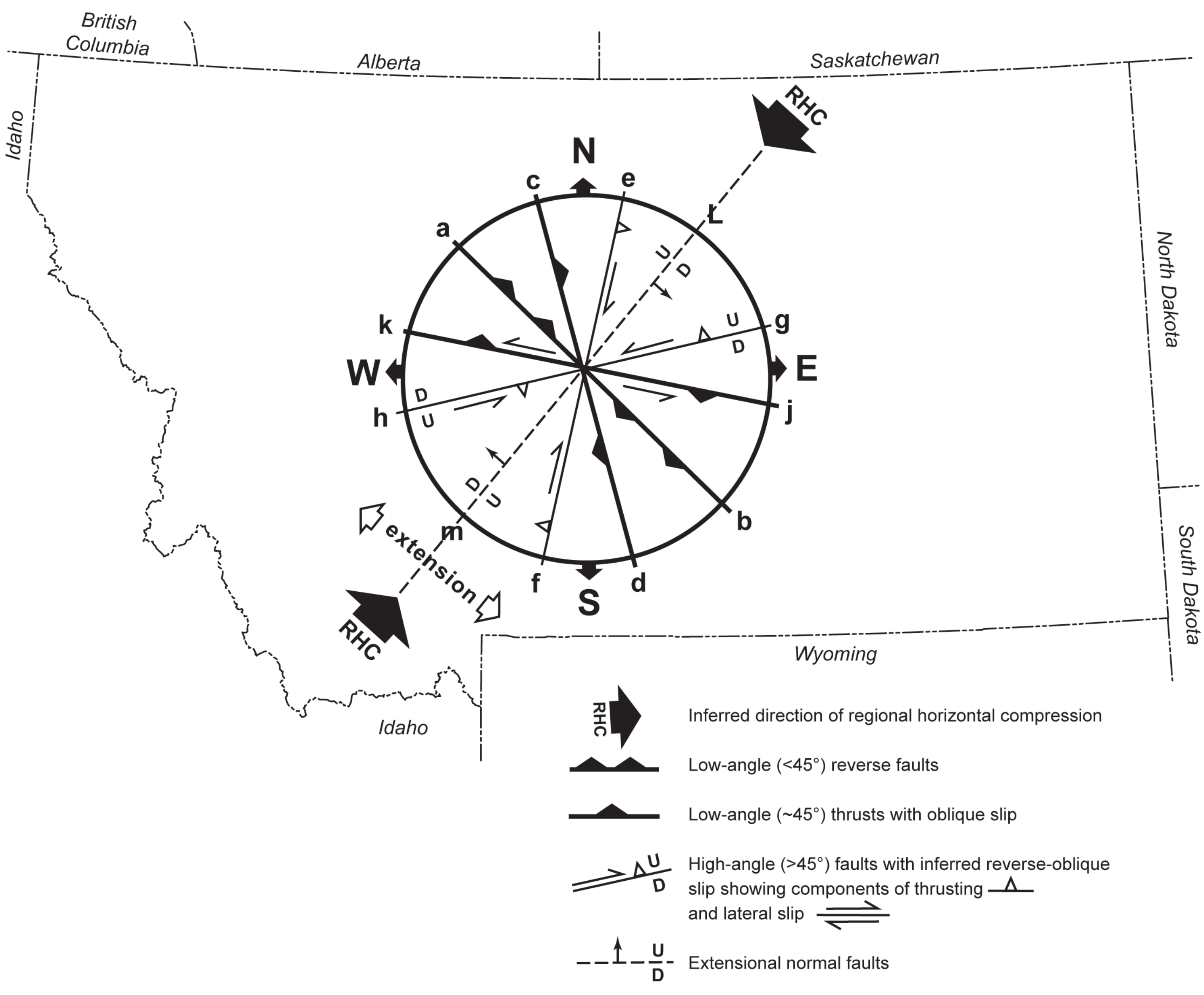

Figure 8. Regional stress field (RHC, regional horizontal compression) during the Laramide Orogeny across the Central Rockies (Wyoming) and southern Montana. Fault and fracture arrays are labeled as a–b (reverse/thrust faults with predominantly dip-slip motion); c–d and j–k (thrust faults with components of oblique-slip); e–f and g–h (oblique-slip faults); and L–m (normal oblique-slip faults). From Brown (1993, p. 355).

axes to calculate average N. 66° E–S. 66° W. shortening and compression directions for the Laramide Orogeny. Brown (1993) estimated approximately 50 km (~13–15%) of crustal shortening accommodated by major uplifts and basins across the central Rockies from the Green River Basin to the Powder River Basin, but not including smaller-amplitude structures like the Moxa Arch or the Black Hills. More recent workers have also concluded that WSW–ENE, layer-parallel regional shortening occurred across the Laramide foreland based on integrated structural, anisotropy of magnetic susceptibility (AMS) data, and paleomagnetic data (Weil and Yonkee, 2012; Yonkee and Weil, 2015). Beaudoin and others (2012) also documented northeast–southwest shortening at Rattlesnake Mountain in the Bighorn Basin, northern Wyoming, based on fracture, fault-slip, and calcite twinning paleopiezometry data. Tikoff and Maxson (2001) studied regional-scale lithospheric "buckle folds" (broad mountain arches) across the southern Rockies and concluded that horizontally directed end-loading of the western margin of North America was required, through flat-slab subduction and/or terrane accretion. However, the buckling interpretation may be incorrect because the Moho is not folded along with the upper crust beneath the Wind River (Brewer and others, 1980; Groshong and Porter, 2019) and Bighorn Mountains (Yeck and others, 2014; Worthington and others, 2016). Regardless, it is reasonable to assume that the Laramide regional horizontal compressive stress field for the central and southern Rocky Mountains, well documented by various techniques, models, and structural studies, also affected the crust of Montana during Paleocene to early Eocene time.

Most workers ascribe Laramide deformation to flat-slab subduction of the Farallon plate (e.g., Coney and Reynolds, 1977), leading to strong dynamic coupling with the overriding North American plate. Flat-slab subduction was probably induced by accelerated convergence rates, from a relatively slow ~5 cm/a between ~145 and 130 Ma, to 8–12 cm/a during Sevier and Laramide orogenesis (~120–50 Ma) based on the marine magnetic record (Yonkee and Weill, 2015, and references therein). Other processes that may have contributed to flat-slab subduction and strong dynamic coupling include accretion of offshore exotic or suspect terranes, subduction of an oceanic plateau that formed astride the East Pacific Rise (conjugate to the Shatsky Rise; Saleeby, 2003), and distributed inboard transpression caused by dextral oblique convergence of the North American and Farallon plates (Yonkee and Weill, 2015). Based on a diverse dataset, Fan and Carrapa (2014) concluded that Laramide deformation of the central Rockies (Wyoming) occurred in two stages, with stage 1 (Maastrichtian–Paleocene) occurring during flat-slab subduction of the Farallon plate, and stage 2 (late Paleocene–early Eocene) occurring during rollback and/or slab removal of the Farallon plate in a progressive southwestward direction. Geophysical and geological evidence for flat-slab subduction of the Farallon Plate is extensive, supporting the model based on accelerated convergence rates. For example, a magmatic gap developed in the Sierra Nevada–Mojave region, as arc magmatism swept eastward into the foreland ("inboard sweep" of Coney and Reynolds, 1977); this inboard sweep of arc magmatism also occurred across the northern Rockies, as will be discussed later. Other evidence for flat-slab subduction is given by xenoliths of subducted oceanic crust and metasomatized mantle lithosphere, and seismic imaging of the subducted Farallon plate beneath the central and eastern U.S. (Yonkee and Weil, 2015, and references therein).

Northern Laramide Province

Many previous workers have recognized the broad, convex-northeast oroclinal curvature of Laramide uplifts and basins from Colorado to Montana (e.g., Hamilton, 1981). In order to accommodate crustal shortening across the north–south breadth of this arc, displacement occurred along several transverse (east–west) accommodation zones of sinistral transpression from southern Wyoming to central Montana, often involving *en echelon* arrays of faults and folds. From south to north, major foreland accommodation zones are the Ferris–Seminoe Mountains, Rattlesnake Hills, eastern and western Owl Creek Mountains, north end of the Pryor Mountains and the Nye–Bowler lineament, Lewis and Clark/Lake Basin Fault Zone, and a complex array of faults in the structurally inverted Central Montana Trough that includes the Cat Creek trend (fig. 9). Transverse accommodation zones also exist in the southern Rockies, but are not discussed herein. These transpressional accommodation zones are an integral component of the Laramide structural family across the entire Rocky Mountain foreland, and are every bit as important as the larger and more obvious thrust-bounded basement arches.

Oroclinal curvature of basement-involved structures from Wyoming to Montana is also associated

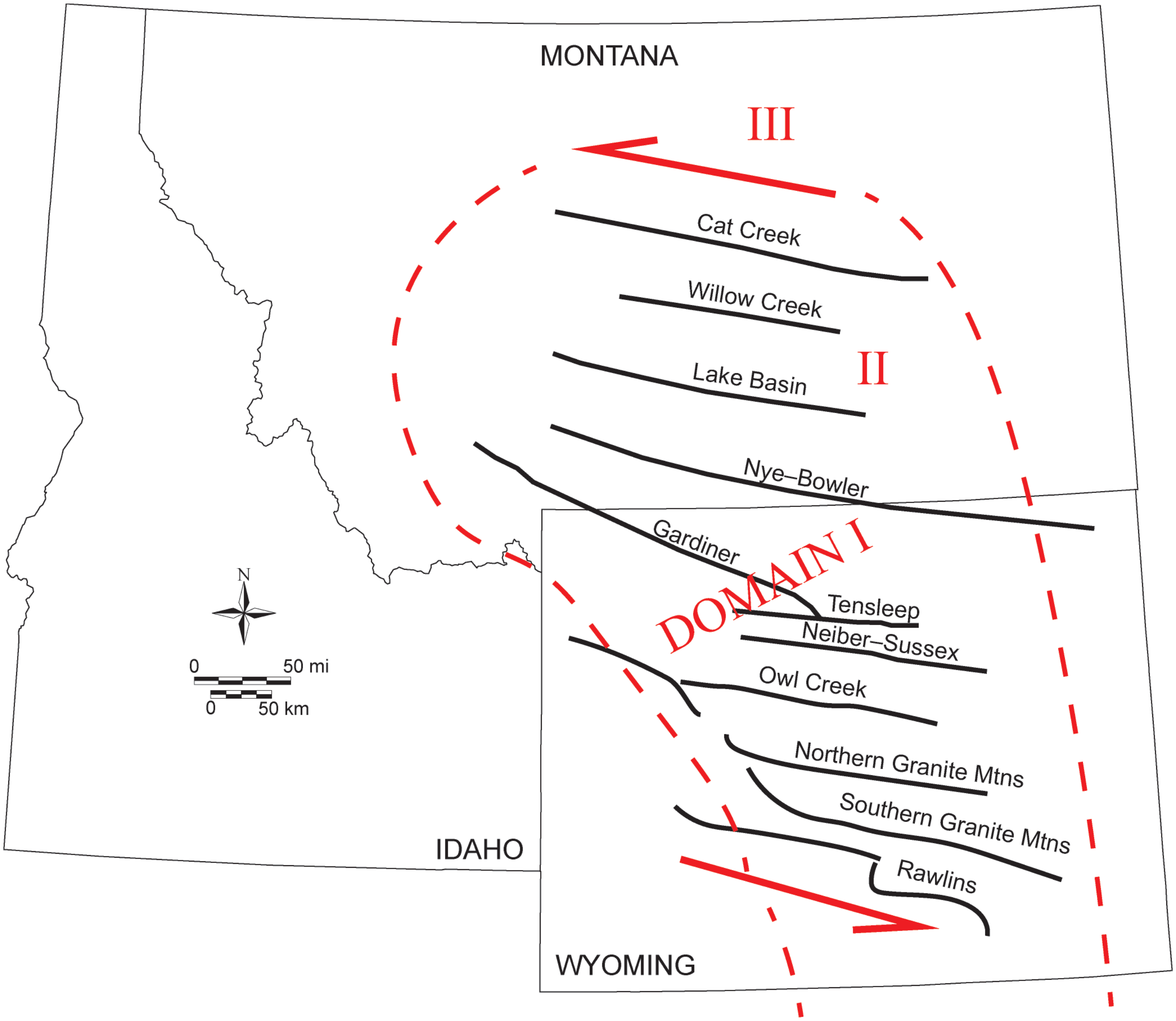

Figure 9. Map showing several WNW-trending, transverse zones that accommodate (compartmentalize) the broad, convex-NE oroclinal curvature of the Rocky Mountain foreland from Colorado to Montana. The array of *en echelon* faults and folds that characterize these zones often indicates sinistral transpression.

with northward dip (surface elevation) of the entire Laramide foreland deep into central Montana. However, most published tectonic maps abruptly terminate the Laramide province in southwest Montana (e.g., McMannis, 1965; Yonkee and Weil, 2015), thus ignoring many basement-involved structures farther north in Montana. In contrast, we propose that the "true" northern termination of the Laramide Province takes place in steps across central and northern Montana, as shown by decreasing structural amplitude of basement-cored arches and basins that mirrors northward-decreasing surface elevations, coupled with an increasing influence of reactivation or inversion of older Proterozoic fault systems in central Montana. We propose that Laramide deformation affected the entire northern margin of the Archean Wyoming Province, including basement rocks of the Big Sky orogen and southern Medicine Hat Block, and we therefore redefine the north end of the Laramide Province as much farther north than is traditionally shown in southwest Montana.

There is a rapid northward decrease in average surface elevation into southern and central Montana from the "high ground" of Laramide arches and deep sedimentary basins in Wyoming. The average elevation of Wyoming is ~2,000 m above SL (6,700 ft) and, without mountains, the average elevation is still above 1,800 m (>6,000 ft; University of Wyoming, State Climate Office data). In contrast, the mean elevation of Montana is slightly greater than 1,000 m (~3,400 ft), with the lowest elevations in eastern and northwest Montana. Potential field geophysical data reflect these elevation changes, as well as changes in crustal architecture as previously discussed. Despite decreasing surface elevations, Deep Probe seismic imaging data show that the Wyoming Province and Medicine Hat Block of central and northern Montana are characterized by uniformly thick continental crust (~50–60 km) that includes a thick (10–30 km) lower crustal layer (LCL) of high-velocity, mafic/ultramafic rock (Gorman and others, 2002). The LCL is interpreted to have resulted from Proterozoic underplating during collisional orogenesis, possibly contemporaneous with the Trans-Hudson orogeny, or during a later Proterozoic rifting event at the cratonic margin (Gu and others, 2018; Gorman and others, 2002; Ross, 2000 and references therein). Much remains unknown about the timing and origin of this mafic layer, but the important point for this paper is that it appears to become irregular and thin beneath the Great Falls Tectonic Zone and northern Montana, and is not present in the lower crust of the Hearne Province farther north (fig. 5). Therefore, we propose that the northern limit of the LCL near the U.S./Canadian border was perhaps a major factor in determining the northern extent of Laramide-style deformation. Yonkee and Weil (2015, p. 579) suggested that a strong lower crust composed of “mafic granulite” would facilitate lithospheric buckling and dynamic coupling during flat-slab subduction, as opposed to a weak lower crust composed of “felsic granulite.” We believe that the LCL beneath Wyoming and Montana served a strong “structural-lithic unit” in the transmission of layer-parallel compression to the Laramide foreland, and also that the northern limit of the LCL defines the approximate northern limits of Laramide deformation. Of course, other factors also controlled the northern limit of Laramide deformation, such as the northern extent of flat-slab subduction of the Farallon plate beneath western North America, as will be discussed later. It should also be mentioned that the LCL does not extend into the southern U.S. Rocky Mountains where a collage of accreted Proterozoic terranes constitute the lithosphere, there was a strong overprint of Paleozoic orogenesis (Ancestral Rockies), and the rheological structure of the upper mantle is quite different (Karlstrom and others, 2012).

Given this context, we recognize the “dip” of the Laramide foreland from Wyoming into Montana as occurring in three steps of northward-lowering structural relief on Laramide structures, separated by transverse accommodation zones (fig. 10). Identified herein as structural domains I–II–III, these steps involve north-

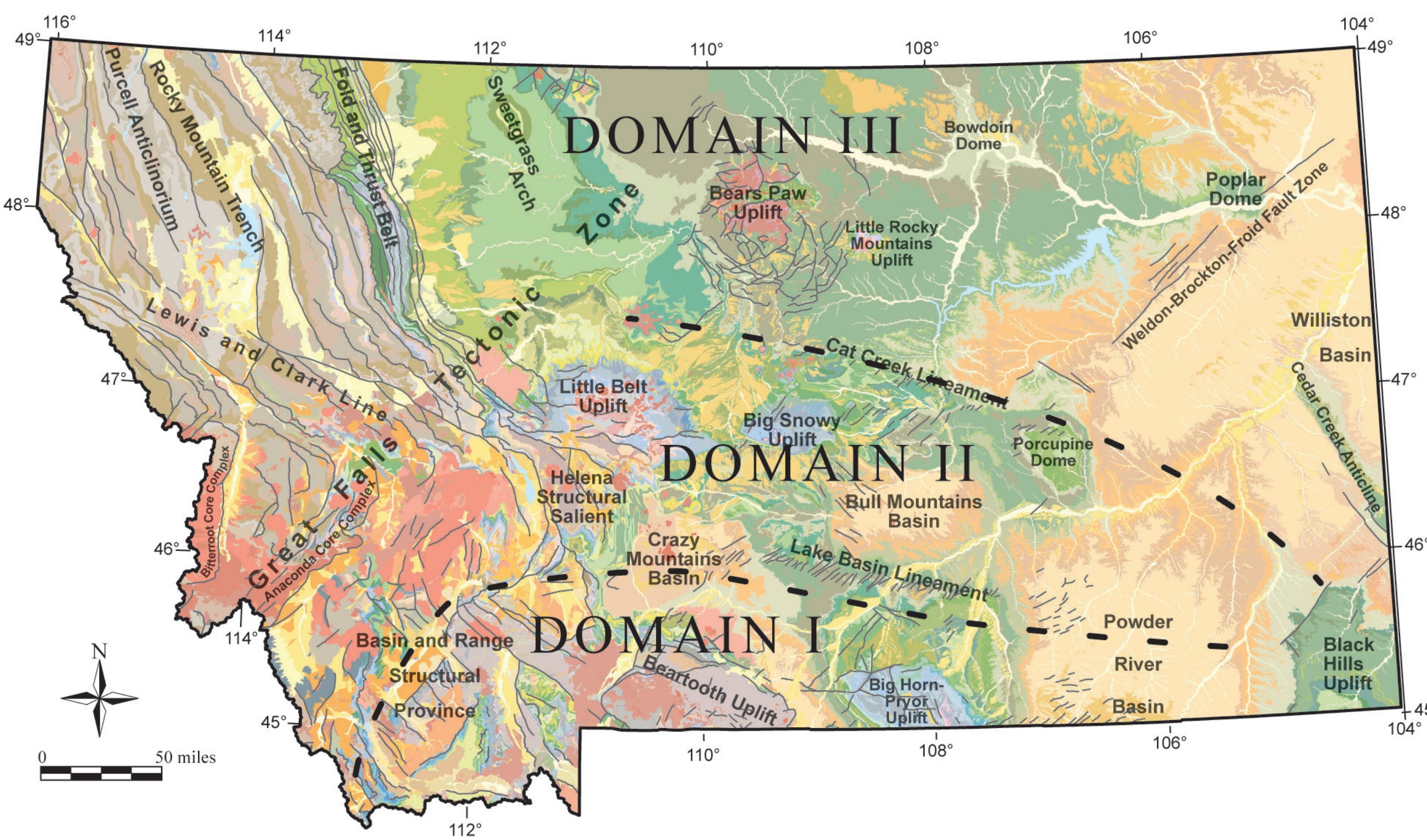

Figure 10. Map showing domains of regional plunge of the Laramide foreland from Wyoming into Montana, as occurring in three stages or steps of northward-lowering structural relief on Laramide structures (Domains I, II, and III), separated by transverse accommodation zones. See text for detailed explanation.

ward-diminishing basement shortening that extends all the way to north-central Montana from the high topography and dramatic surface exposures of Archean basement seen in northern Wyoming and southwest Montana.

Laramide Structural Domains in Montana

Laramide Domain I comprises the traditionally recognized basement-cored uplifts and basins that straddle the Wyoming–Montana border (Beartooth Mountains, Pryor/Big Horn Mountains, and Black Hills, with the intervening Big Horn and Powder River Basins), as well as those much farther west (Madison–Gravelly Arch, Spanish Peaks, Blacktail–Snowcrest Arch, Ruby–Tobacco Root–Highland Arch, and the Bridger Range; figs. 10, 11). These uplifts have received extensive study over many decades of geologic mapping, as well as resource exploration and

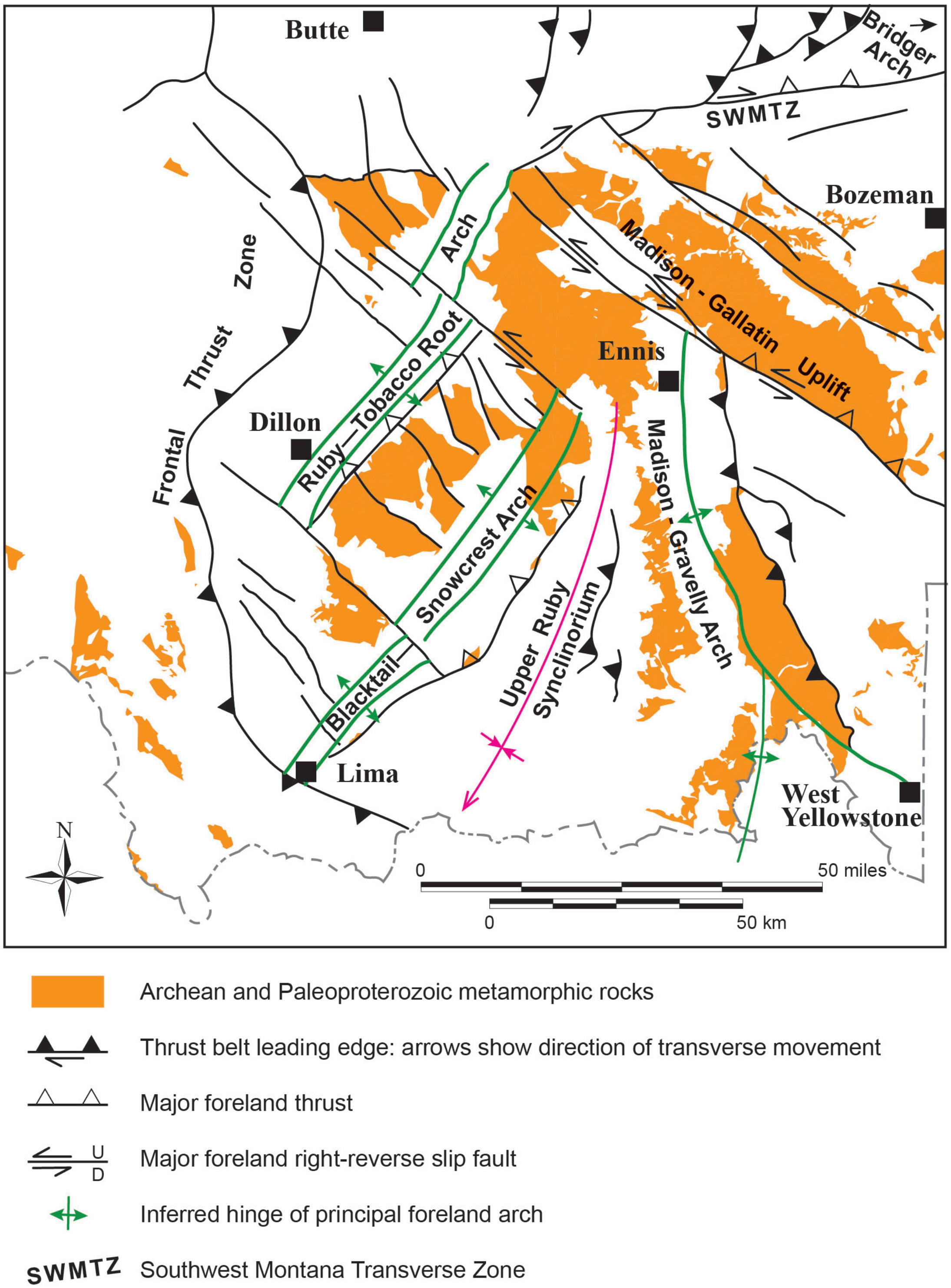

Figure 11. Laramide “Domain I” of southwestern Montana, as defined herein. Map modified from Schmidt and Garihan (1983, p. 282) and Schmidt and others (1988, p. 177).

development, and a complete structural description of each is beyond the scope of this paper. Therefore, the following serves as a brief overview, along with key references selected for those interested in more details.

The Bighorn Mountains are a classic Laramide arch in north-central Wyoming, with an early history of geologic mapping and structural analysis (Darton, 1906). The northwest end of the Bighorn Mountains abruptly plunges into southern Montana where it partitions into four basement blocks collectively called the Pryor Mountains (Lopez, 2000). Blackstone (1940) presaged modern thinking on fault-propagation folding and trishear geometry of Laramide uplifts in his mapping and structural cross-sections of the Pryor Mountains (fig. 12; as per Snoke, 1993, p. 23). An array of high-angle faults splays off the northwest corner of the Pryor Mountains into the northernmost Big Horn Basin forming the Nye–Bowler lineament, which continues WNW along the Beartooth Mountain front as a zone of sinistral shear and folding. This lineament accommodates oblique-shear in Phanerozoic cover rocks in the overlap zone between the Bighorn/Pryor and Beartooth Mountains (fig. 9). The Beartooth Mountains are a bivergent uplift, bound on the northeast by the Beartooth thrust system and Nye–Bowler lineament (Bevan, 1923; Wilson, 1936; Foose and others, 1961; Ames and Grauman, 1991; du Bray and Harlan, 1998; Wise, 2000), and on the southwest by the Gardiner Thrust Fault (Wilson, 1934; Locke and others, 1995). The highest peak in Montana lies in the lofty Archean core of the central Beartooth Mountains, Granite Peak at 3,904 m elevation (12,807 ft; fig. 13). Spectacular exposures of Archean rocks occur on the high-level (sub-summit)

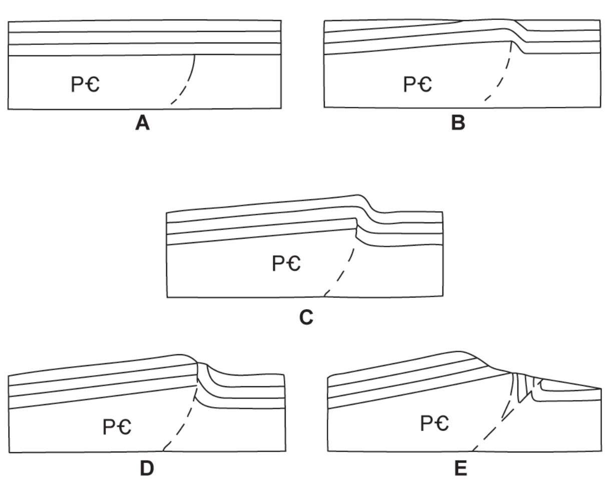

Figure 12. Fault-propagation folding (“trishear uplift”) of the Pryor Mountains as envisioned by Blackstone (1940), as per Snoke (1993).

Figure 13. Archean rocks displayed on the spectacular east face of Granite Peak in the Beartooth Mountains. Photo by D. Lageson.

erosion surfaces or “plateaus” of the eastern Beartooth Mountains (e.g., Lake, Fishtail, Froze-to-Death, Rosebud, Hellroaring Plateaus), whereas the Eocene Absaroka Volcanic Supergroup covers vast areas of the western Beartooths (Chadwick, 1970; Smedes and Prostka, 1972; Hiza, 1999; Feeley, 2003). Absaroka volcanic rocks overlie the Gardiner Thrust just northwest of Gardiner, but the fault emerges farther northwest along the southwest flank of the Spanish Peaks as a major, oblique-slip reverse fault. Even farther northwest, the same fault becomes the Bismark Fault in the core of the Tobacco Root Mountains. Collectively, the Bismark–Spanish Peaks–Gardiner (BSPG) fault system bounds the “Madison–Gallatin Uplift” of southwest Montana (Garihan and others, 1983), and is a northwest extension of the greater Beartooth Uplift. Laramide displacement on the BSPG was reverse-sinistral, but diabase rocks intruded within, and parallel to, the Spanish Peaks segment suggest Proterozoic inheritance (Garihan and others, 1983; Harlan and others, 1990). The BSPG fault is one of several northwest-striking faults across southwest Montana with inheritance from the Mesoproterozoic Belt Basin

(Wooden and others, 1978; O'Neill and others, 1986; Schmidt and Garihan, 1986). Three north-plunging basement arches lie southwest of the Madison–Gallatin Uplift, the Madison–Gravelly (Kellogg and others, 1995), Blacktail–Snowcrest (Perry and others, 1988), and Ruby–Tobacco Root Arches (fig. 11; Scholten, 1967; Schmidt and others, 1988). An orthogonal pattern of northeast- and northwest-striking faults dominates the present-day geology over these arches, as seen in the Dillon 1° x 2° quadrangle (Ruppel and others, 1993). Many of these are post-Laramide normal faults, or are reactivated Laramide faults with normal displacement, that have created a complex network of extensional basins. Several northwest-striking faults have sinistral components of displacement, although the magnitude of lateral displacement is not well constrained (Ruppel, 1993) and is probably minimal. The former Laramide structural landscape of southwest Montana is further concealed by extensive outcrops of volcanic and volcaniclastic rocks of Eocene and younger age. Farther west, basement rocks have been locally incorporated within thrust sheets of the Sevier orogen (Skipp, 1988), but these "overlap" occurrences are not included in the Laramide domain of southwest Montana. The Bridger Range occupies a unique position at the northern margin of Domain I, in that it is a hybrid Laramide, basement-cored uplift (McMannis, 1955) with overlapping thin-skinned thrust sheets of the Helena Salient from Ross Pass northward (Lageson, 1989). Ross Pass also marks the south margin of the Mesoproterozoic Belt Basin in this part of Montana (McMannis, 1963), reactivated during the Paleogene as a transverse lateral ramp for thrust faults arrayed along the Perry Line, as described below (Lageson, 1989). Like many Laramide uplifts in southwest Montana, the range-bounding thrust system of the Bridger Range was reactivated at depth as a normal fault during post-Laramide extension, creating a "perched basement wedge" (PBW) subtended on the east by the sub-Bridger thrust zone and on the west by the Bridger Normal Fault (figs. 14A, 14B, 14C; Lageson and Zim, 1985; Lageson, 1989; Skipp and others, 1999). The Madison Range is another excellent example of a PBW (Kellogg and others, 1995), and many other examples are found throughout the intermountain west where Basin and Range extension overlaps contractional structures of the Laramide and/or Sevier Provinces (e.g., Teton Range in western Wyoming; Lageson, 1992).

The north end of Domain I lies just north of the Beartooth–Madison–Gallatin uplifts as an east-striking fault zone, variously called the Willow Creek Fault, Perry Line, or Southwest Montana Transverse Fault Zone (Thom, 1957; Harris, 1957; McMannis, 1963; Schmidt and Garihan, 1986). This is a major fault zone with well-documented Mesoproterozoic inheritance (defining the south margin of the Helena embayment of the Belt Basin), also forming a transverse lateral ramp for thrust sheets in the Helena Salient of the fold–thrust belt to the north (Lageson, 1989), and extending from the Highland Mountains to the Bridger Range. East of the Bridgers, the north end of Domain I corresponds to the Lewis and Clark/Lake Basin lineament north of the Pryor Mountains and Black Hills. As an aside, it is perhaps no coincidence that the Yellowstone River follows an almost straight course of 060° for 100 mi (160 km) east of Columbus, parallel to the Great Falls Tectonic Zone, as well as *en echelon*, northeast-striking normal faults along the Lake Basin lineament. The Yellowstone then abruptly "dog-legs" almost due east for 50 mi (80 km) along the south plunge of Porcupine Dome, and then again turns to a northeasterly course towards Glendive and beyond. The remarkably linear, yet segmented path of the Yellowstone north of the Beartooth and Pryor Mountains is very likely controlled by deep-seated faulting following Paleoproterozoic and Mesoproterozoic weaknesses, expressed by the outcrop patterns and geomorphology at the surface at the north end of Laramide Domain I in southern Montana.

Laramide Domain II occupies the central part of Montana and is an equally complex structural region. From west to east, major uplifts in Domain II include the Little Belt Mountains, Big Snowy Arch, the complex Ivanhoe–Sumatra–Ingomar Arch and related structures, Porcupine Dome, and Cedar Creek Anticline in far eastern Montana (fig. 15). The Little Belt Mountains are a broad, basement-cored dome that exposes rocks of the Paleoproterozoic Little Belt arc, and is segmented by several high-angle, east-striking faults and intruded by several small Eocene plutons of granite, quartz monzonite, dacite, shonkinite, and related rocks (Vuke and others, 2002, 2007; Reynolds and Brandt, 2007). The leading edge of the Helena Salient of the fold–thrust belt overlaps the southwest flank of the Little Belts, marked by an array of imbricate thrust faults in the hanging wall of the Volcano Valley Fault (Reynolds and Brandt, 2005, 2007). The Volcano Valley Fault (Weed and Pirsson, 1900) had

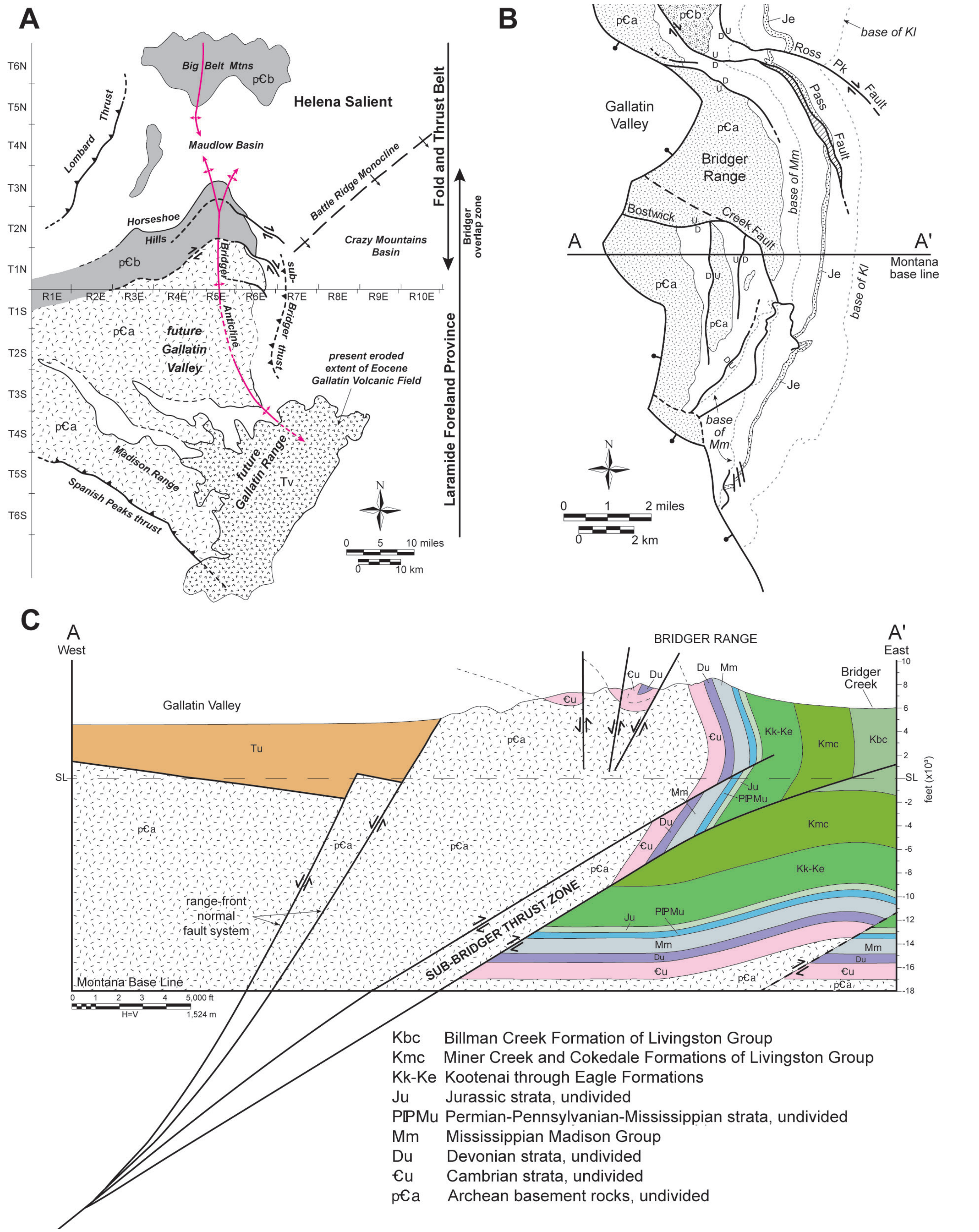

Figure 14. (A) Restored structure map of the Ancestral Bridger Range uplift in Eocene time, prior to extension and downdropping of the Gallatin Valley. p€a, Archean basement rocks; p€b, Middle Proterozoic Belt Supergroup; Tv, Eocene rocks of the Hyalite/Absaroka Volcanic Field. (B) Simplified geologic map of the southern Bridger Range showing key structural features such as the Ross Peak Fault, Pass Fault, Bostwick Creek Fault, and the post-Laramide range front normal fault along the western base of the range. Mm, Mississippian Madison Group; Je, Jurassic Ellis Group; Kl, Livingston Group. (C) Cross-section over the southern Bridger Range along the Montana Baseline, showing the sub-Bridger thrust zone; footwall anticline was seismically imaged and drilled by Sohio Petroleum.

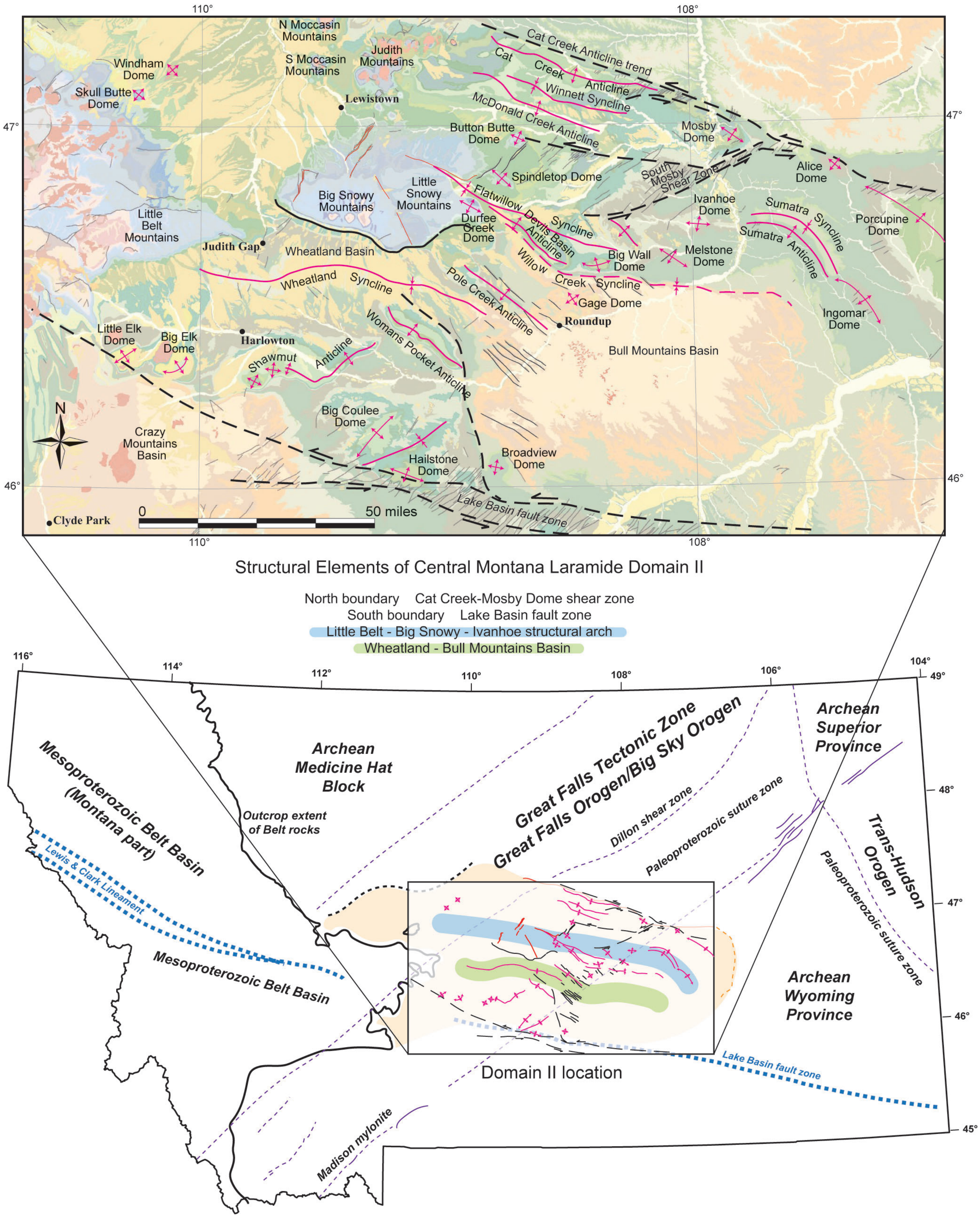

Figure 15. Tectonic map of Montana showing "Laramide Domain II" in central Montana (box), as defined herein. Laramide Domain II overlaps the Paleoproterozoic suture zone known as the Great Falls/Big Sky Orogen, the Helena Embayment of the Mesoproterozoic Belt Basin (represented in part by the tan shaded area beneath the Domain II location box), and at its western end, the Helena Salient of the Sevier fold-thrust belt.

normal movement (down to the south) during the Mesoproterozoic, subsequently reactivated as a reverse fault (up to the south) during Late Cretaceous to Paleocene time (Reynolds and Brandt, 2005). The Volcano Valley Fault forms the bounding fault on the north side of the Flagstaff Anticline that plunges southeast into the northern Crazy Mountains Basin near Checkerboard (McDonald and others, 2005); this overall structural trend marks the eastern limits of the Helena Salient of the fold–thrust belt, overlapping uplifted basement rocks of the southwestern Little Belt Mountains. Just west of the Little Belts, the Big Snowy Arch is a classic Laramide-style uplift that trends WNW–ESE. The Big Snowy Uplift is subtended by a northeast-dipping thrust fault that forms a trishear zone along the southern flank of the range. The western end of the arch is cut by several high-angle, north–south transverse faults that have served as conduits for hydrothermal alteration (Jeffrey, 2014). The Big Snowy Arch is a composite structure, the western half forming the main block of the uplift and the eastern half plunging eastward into a structurally lower saddle that forms the Ivanhoe–Sumatra–Ingomar Arch. The Bull Mountains and Wheatland Basins lie south of these uplifts and north of the Lake Basin lineament. The Bull Mountains Basin is a semi-rhombic depression distinguished by a pervasive northwest-trending drainage pattern, with several parallel, northwest-striking, high-angle normal faults in the western part of the basin. This pattern of faulting is similar to that found in southwest Montana and, similarly, may be related to Mesoproterozoic rifting along the south margin of the Helena Embayment of the Belt Basin (with Phanerozoic fault reactivation). This pattern of parallel, northwest-striking faults is also structurally compatible with shear between the sinistral Lake Basin lineament and the subsurface fault system that bounds the south margin of the Ivanhoe–Sumatra–Ingomar Arch. The Cat Creek trend defines the north margin of Domain II, a zone of sinistral transpressional with *en echelon* faults and smaller, oil-producing domes with a well-documented history of reactivation since the Mesoproterozoic based on subsurface data (Nelson, 1993). Porcupine Dome lies at the east end of the Little Belt–Big Snowy–Sumatra corridor of reactivated basement faults and uplifts; it is a large, doubly plunging, east-vergent anticline, bound to the north by the Cat Creek trend and to the south by the Lake Basin Fault Zone. Many tectonic maps show the eastern end of the Mesoproterozoic Belt Basin coinciding with Porcupine Dome (e.g., MBMG, 2007, fig. 3), although the basin may have extended farther east.

Overall, Domain II represents the structurally uplifted/inverted Central Montana Trough (CMT) of the Mesoproterozoic Belt Basin, underlain by Paleoproterozoic crustal rocks of the Big Sky orogenic belt (Little Belt magmatic arc mentioned previously). This part of central Montana is included in the Laramide foreland because Precambrian basement rocks were clearly uplifted and shortened during Laramide orogenesis and the style of deformation is similar to other Laramide uplifts and basins farther south in zones where transpressional accommodation of regional northeast–southwest shortening occurred.

Laramide Domain III lies in north-central Montana, north of the Cat Creek trend and the Helena Embayment of the Belt Basin, and south of the U.S./Canadian border (fig. 16). We propose that this area represents the far-northern extent of Laramide de-

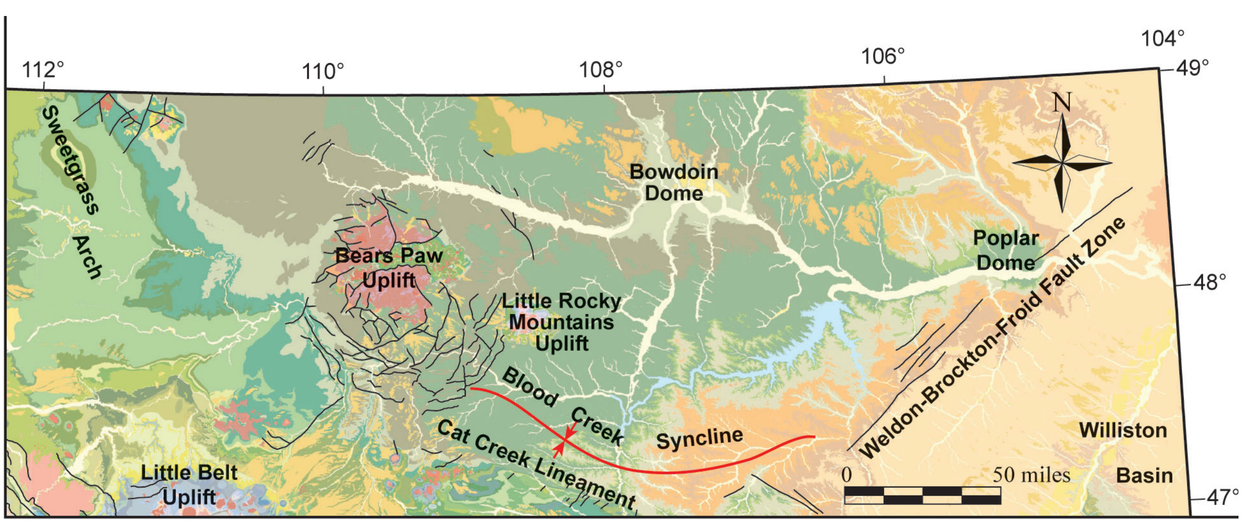

Figure 16. Laramide "Domain III" in north-central Montana, as defined herein. This is the area of lowest structural relief on basement-involved Laramide structures (domes, arches, and basins).

formation in Montana, inasmuch as the Bears Paw Mountains are constructed on a basement arch that has several thousand feet of structural relief compared to the adjacent plains. During the Eocene, the arch was the site of intrusive and extrusive alkaline igneous activity as well as concurrent, low-angle, gravity-slide detachments of shallow Phanerozoic sedimentary and volcanic units. These young igneous rocks and structures conceal the fact that the Bears Paw Mountains overlie a significant basement arch. Data from deep drilling demonstrate that the Precambrian basement is uplifted as much as 5,000 ft (>1,500 m) above the regional level of 7,000 ft (~2,135 m) beneath the plains (Hearn, 1976). Therefore, it is our contention that the Bears Paw Mountains are not solely the product of Eocene laccolithic doming and volcanism, as has been the traditional interpretation. We interpret the arch to be the result of far-field Laramide shorting and doming, possibly involving deep-seated, reactivated faults along the Great Falls Tectonic Zone. The Bears Paw Arch is approximately equal in size to the Little Belt and Big Snowy Mountains of central Montana, but the latter uplifts expose deeper structural levels (down to the basement) because of greater amplitudes of uplift in central Montana. Basement "highs" that are satellite to the Bears Paw Arch include the Little Rocky Mountains Arch to the southeast, also the site of Eocene igneous activity, and the Bowdoin Dome farther east–northeast. To the west, the Kevin–Sunburst Dome (KSD), part of the larger Sweetgrass Arch (SA), is questionable in terms of inclusion in our assessment of far-field Laramide structures. The KSD/SA parallels the eastern front of the fold–thrust belt in a similar structural position to the Moxa Arch in western Wyoming, thus being transitional into Laramide-style deformation east of the Sevier orogen, but the KSD/SA also has a complicated Phanerozoic history of recurrent uplift (Lorenz, 1982). However, Upper Cretaceous strata preserved on both flanks of the KSD show little or no thinning over the crest of the present-day dome, so basement-involved amplification (~250-m closure) of the arch probably occurred in Paleocene or early Eocene time—i.e., towards the end of regional Laramide deformation (Lorenz, 1982). Therefore, KSD remains an enigma, having a long pre-Laramide history of instability and recurrent uplift, yet also with characteristics of a basement-cored forebulge just east of the fold–thrust belt (like the Moxa Arch) and having been amplified at the same time as nearby Laramide uplifts in northern Montana.

SEVIER FOLD–THRUST BELT

The Cordilleran fold–thrust belt, or Sevier orogenic belt, geographically spans the eastern Cordillera from the Canadian Rockies southward to the Sierra Madre Occidental Ranges of Mexico. The history of geologic research and mapping in the Sevier orogen is long and rich, involving literally thousands of publications spanning many decades. However, several key publications and events had an enormous impact on our understanding of thrust belt structure in the Wyoming–Idaho–Utah Salient and in western Montana. Armstrong and Oriel (1965) published a historic paper on the tectonic development of the Idaho–Wyoming thrust belt, followed by Armstrong (1968), who named the "Sevier orogenic belt" after the "Sevier arch." The Sevier arch (Harris, 1959) was a name used for many years as the source area for Cretaceous clastic deposits, named after the Sevier River and Sevier Desert in southwest Utah. During this time to the north, Bally and others (1966) published on the orogenic evolution of the southern Canadian Cordillera. Then in 1970, Clint Dahlstrom presented a masterful, well-illustrated synthesis of the structural geology along the eastern margin of the Canadian Rocky Mountains, and Ray Price and Eric Mountjoy published their classic study of thrust belt structure between the Bow and Athabasca Rivers, Alberta/BC. All of these publications had a major impact on our understanding of thin-skinned (décollement) tectonics, particularly with respect to fold–thrust geometry and kinematics of deformation. Subsequently, a team of Chevron geologists (Royse and others, 1975) applied the lessons learned from the Canadian Rockies and elsewhere to western Wyoming, Idaho, and Utah in their classic paper on "thrust belt structural geometry." Prior to the 1970s, however, drilling activity in westernmost Wyoming was sporadic and unsuccessful, and the region was known as a "driller's graveyard" largely because the thin-skinned, "fold-and-thrust family of structures" was not well understood at the time by the few oil companies who dared to explore there (Lageson and Schmitt, 1994). However, all that changed in 1975 with the discovery of huge oil reserves in Jurassic rocks at Pineview field in southwest Wyoming, kicking off an unprecedented "boom" in oil exploration throughout the length of the Sevier orogen that lasted for many years, resulting in many more large discoveries in southwest Wyoming. Although Montana did not benefit from large oil discoveries in the thrust belt for a variety of reasons, the work done by industry, government, and academic geologists during the 1970s, 80s, and 90s led to huge refinements in our understanding of fold–thrust structures in Wyoming, Utah, Idaho, and Montana. Several field conference guidebooks published during this era contain important, classic papers that should not be forgotten (e.g., Joint Wyoming–Montana–Utah Geological Associations Guidebook, 1977; Rocky Mountain Association of Geologists, 1975, 1982; Montana Geological Society, 1981, 1984). Before abandoning this brief historical overview, it is important to make special note of several field geologists who were true pioneers in establishing the structural and stratigraphic framework of the "Disturbed Belt" in northwest Montana. Perhaps most notable among these is Melville R. Mudge, who mapped many 7.5-minute quadrangles across the width and length of the Sawtooth Range—a classic thin-skinned, fold–thrust salient. Mudge, Earhart, Whipple, and Harrison (1982) published the Choteau 1° x 2° quadrangle, covering a vast part of the Rocky Mountain Front, followed by Mudge and Earhart's (1983) remarkably detailed bedrock geologic map of the entire "northern Disturbed belt." Many other individuals could be cited for their important work in unravelling the thrust belt in western Montana, and some will be cited in specific context below.

The Sevier fold–thrust belt can be defined as a swath of regional-scale, thin-skinned thrust faults and accompanying folds that extends from the southern Canadian Rocky Mountains to southeastern California (Monger and Price, 1979; Allmendinger, 1992; DeCelles, 2004). In this section, the focus is on main elements of thin-skinned, or Sevier-style, contractional deformation that took place from Late Cretaceous to Paleogene time in Montana. Thin-skinned deformation is typically defined as thrust systems that only involve the sedimentary cover rocks and not deeper crystalline (Precambrian) basement rocks. Thin-skinned systems contrast with the larger-scale Laramide-style basement-involved arches, discussed elsewhere in this chapter. We wish to note, however, that many of the thin-skinned thrusts in western Montana also transported relatively thin slices of basement rock (Skipp, 1988; Schmitt and others, 1995; Kipf and others, 1997). These slices are especially evident within ramps and lateral ramps that formed along the previously rifted margin of the Belt Basin. Because of their significance, we extend the use of "thin-skinned thrust system" to those that include basement in western Montana, recognizing that basement involvement is also common in most hinterland settings of continental fold–thrust belts. It should also be noted that in westernmost Montana, brittle thrusts of the Sevier belt dip westward and eventually combine with medium- to high-grade metamorphic rocks in the hinterland via plastically deformed shear zones (Hyndman and others, 1988; Sears, 1988, 2001; Fillipone and Yin, 1994; Kalakay and others, 2001; McClelland and Oldow, 2004). Thus, the Sevier thrust belt in Montana varies in width from ~250 km in the northwestern part to >300 km in the central section to ~50 km in the southwestern part of the State.

Described herein are the main structural elements of the Late Cretaceous–Paleocene Sevier orogenic belt of Montana, which include: (1) regions that are dominantly thin-skinned folds and thrusts, (2) areas where Laramide-style, basement-cored uplifts overlap with thin-skinned structures, and (3) sections where silicic intrusive and extrusive igneous rocks were emplaced within contractile structures. With these elements in mind, the Sevier orogenic belt of Montana can be divided into three distinct domains: a northern domain, characterized by the northwest Montana fold–thrust belt; a central domain, characterized by the Helena fold–thrust/magmatic salient; and a southwest Montana domain that exhibits a complex interaction among thin-skinned thrusting, basement-involved thrusting, and silicic magmatism (including what has been called the "southwest Montana recess" of the fold–thrust belt). Timing was roughly coeval throughout the three domains from ca. 80 Ma to 52 Ma (Harlan and others, 1988; Sears and Hendrix, 2004; Foster and others, 2007b; Fuentes and others, 2012).

Northern Domain: The Northwest Montana Fold–Thrust Belt

The fold–thrust belt of northwest Montana can be considered the southern extension of the retroarc fold–thrust belt of the Canadian Rocky Mountains. Like its counterpart in Idaho, Wyoming, and Utah, the Canadian fold–thrust belt has been host to some vitally important studies of the Cordilleran orogenic system. Much of the current understanding about thrust belt structure, kinematics, and foreland basin development comes from these now-classic locations (e.g., Bally and others, 1966; Armstrong, 1968; Dahlstrom, 1970; Price and Mountjoy, 1970; Price, 1973, 1981; Gordy and others, 1977; Royse and others, 1975; Burchfiel and Davis, 1972, 1975; Jordan, 1981; Lamerson, 1982; Wiltschko and Dorr, 1983). In contrast, the northwest

Montana fold–thrust belt has not enjoyed as much scientific attention (Mudge and Earhart, 1980; Mudge, 1982; DeCelles, 2004; Constenius 1996; Fuentes and others, 2012). During the 1960s and 1970s, a large effort put forth by the U.S. Geological Survey resulted in mapping and later publication of 1:24,000-scale quadrangle maps for the frontal part of the northwestern Montana thrust belt and compilation maps at 1:250,000 scale for the hinterland and northernmost part of the thrust belt (Mudge and others, 1982; Mudge and Earhart, 1983; Harrison and others, 1986, 1992, 1998). More localized studies were conducted by Mitra (1986) and Holl and Anastasio (1992). Other, less detailed work focused primarily on the frontal part of the thrust belt (Fritts and Klipping, 1987; Sears, 2001, 2007). Until recent work by Fuentes and others (2011, 2012) there had been no effort to comprehensively document the development of this thrust system and its associated foreland basin. With permission, we adopt the excellent, balanced structural cross-section from Fuentes and others (2012) in this review paper (figs. 17A, 17B). For more complete and data-intensive coverage, readers are referred to the original work of Fuentes and others (2012, and references therein).

Thick sequences of the Belt Supergroup dominate the thrust belt of northwestern Montana. The Belt Supergroup (see Lonn and others, 2020, this volume) originally formed an eastward-tapering sedimentary wedge (Winston, 1986a,b), which was subsequently overlain by Phanerozoic strata that also thin eastward. The leading edge of the thrust belt tends to imitate the original geometries of the Proterozoic and Paleozoic basin/shelf structure. The Purcell Anticlinorium dominates the westernmost part of this Sevier belt segment. It is considered a regional antiformal culmination that developed as a mega-fault-bend fold over a footwall ramp separating autochthonous from allochthonous Belt Supergroup rocks (Price, 1981; Constenius, 1996; Sears, 2001; Fuentes and others, 2012). West of the Purcell Anticlinorium, there are two major hinterland thrust systems, the Moyie Thrust and the Libby Thrust System, in addition to several Late Cretaceous plutons (Fillipone and Yin, 1994). The Libby thrust belt is the easternmost of the two systems. It is composed of a series of thrust faults that sole into a basal décollement in Belt strata at a depth of ~15 km (Harrison and Cressman, 1993; Fillipone and Yin, 1994). West of the Libby thrust belt, a second major thrust, the Moyie Thrust, places lower Belt strata on middle and upper Belt strata. The Moyie Thrust is interpreted to merge at depth with the same décollement as the Libby thrust system (Harrison and others, 1992; Fillipone and Yin, 1994). According to Fillipone and Yin (1994), episodes of thrusting and magmatism in the hinterland occurred synchronously with thrusting in the foreland. They argue that the décollement linking these two regions lies beneath the Purcell Anticlinorium and suggest that hinterland magmatism and thrusting were linked with thin-skinned thrusting farther to the east.

The Pinkham, Whitefish, and Lewis–Eldorado–Steinbach–Hoadley Thrusts, as well as the frontal imbricate belt of the Sawtooth Range or "Montana Disturbed Belt," lie east of the Purcell Anticlinorium (Price, 1981; Mudge, 1982; Bally, 1984; Sears, 2001). Geometries of the Pinkham and Whitefish thrust systems are poorly understood because of overprinting by post-orogenic extensional faulting and an extensive Cenozoic sedimentary cover (Constenius, 1996). The leading edge of Belt-carrying structures is defined by the Lewis Thrust and the related Eldorado, Hoadley, and Steinbach Thrusts to the south. For clarity, we adopt the approach of Fuentes and others (2012) and denote the frontal thrust as the Lewis thrust system, instead of referring to the individual names of Lewis, Eldorado, Hoadley, and Steinbach given by the U.S. Geological Survey (e.g., Mudge and Earhart, 1980). This part of the thrust belt is dominated by an allochthonous sheet of Proterozoic rocks >7 km thick that was transported in the hanging wall of the Lewis thrust system (Fuentes and others, 2012). Estimates of total shortening across the northwest Montana segment of the thrust belt range from 100 to 165 km (DeCelles, 2004; Fuentes and others, 2012). The Lewis thrust system is estimated to have accommodated at least ~50 km of shortening along a cross-section drawn from the South Fork Flathead River Valley to Augusta, Montana (Fuentes and others, 2012). This does not represent the total shortening across the entire northwest Montana thrust belt, since internal strain and shortening in the hinterland part have not been included.

In contrast to the immense Lewis thrust system, the Sawtooth Range, originally termed the "Montana Disturbed Belt" (Mudge, 1982), consists of closely spaced imbricate thrusts and tight folds in Paleozoic–Mesozoic rocks, including Jurassic–Paleocene foreland basin deposits. This overall structural pattern continues into the Alberta foothills, front ranges, and main ranges of southern Canada (Bally and others, 1966; Price and Mountjoy, 1970; Price, 1981; McMechan

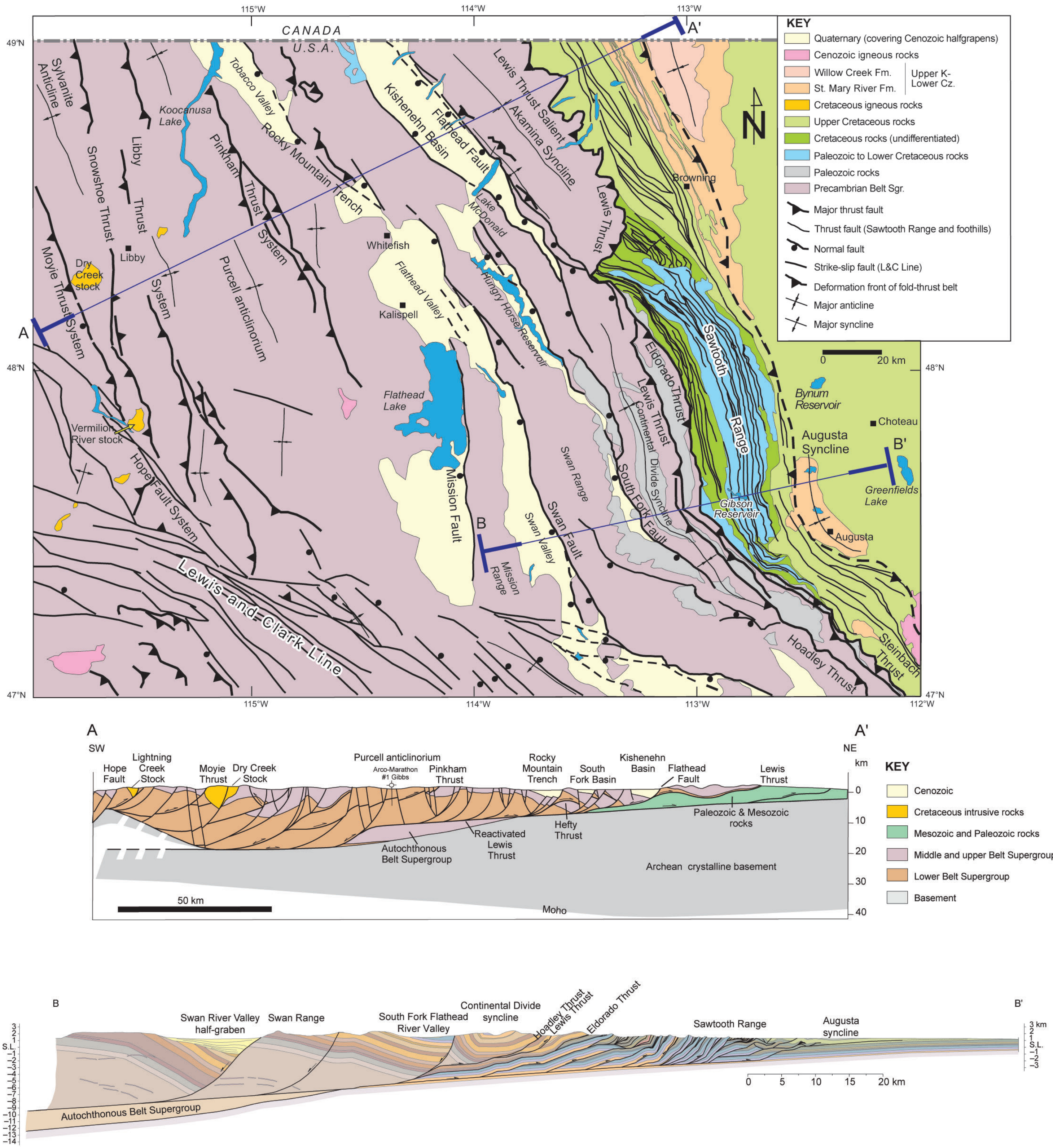

Figure 17. Simplified geologic map and structural cross-sections over northwest Montana from Glacier National Park to the southwest. From Fuentes and others (2012, p. 1107, 1110, and 1112).

and Thompson, 1993; Fermor, 1999). The USGS geological maps of Mudge (1965, 1966a,b, 1968) for the Sawtooth Range and the foothills are excellent. Fuentes and others (2012) combined the surface data of Mudge with high-quality industry seismic lines and well data to produce the first structural interpretations with subsurface control for the area. Their interpretation shows a series of stacked thrust sheets with a basal décollement horizon near the base of the Devonian section, beneath the Jefferson Formation. Where the thrust system cuts upsection to the east, detachments are located in fine-grained strata of the Cretaceous Kootenai Formation, Blackleaf Formation, and Marias River Shale.

In the southern part of the northwest Montana thrust belt, near the latitude of Helena, thrust belt structures begin to overlap with structures related to the Lewis and Clark fault system (fig. 18).

Lewis and Clark Tectonic Zone

The Helena Salient is bound to the north by a complex array of faults, historically known as the Lewis and Clark line, a wide, poorly understood, northwest-striking zone of faults and folds that transects the structural grain of western Montana and extends into Idaho. The Lewis and Clark fault system cannot be drawn as a singular linear feature across the geology of western Montana or Idaho; instead, it is a broad zone of tectonic features that developed periodically from the Precambrian to present (see references below). Given its breadth and complexity, we adopt the term Lewis and Clark Tectonic Zone as used by Smith (2016). Billingsley and Locke's (1941) original definition of the line was based on geography controlled by Cenozoic strike-slip and normal faults. Based on discrepancies in Proterozoic, Paleozoic, Mesozoic, and Cenozoic stratigraphy across the Lewis and Clark line, many have proposed a long history of recurrent movement for the Lewis and Clark line (Hobbs and others, 1965; Harrison and others, 1974; Reynolds, 1979; Leach and others, 1988; Winston, 1986a,b; Sears, 1988; Wallace and others, 1990). Many workers have concluded that contractional structures form an important component of the Lewis and Clark Tectonic Zone (Lewis, 1998; Lonn and McFaddan, 1999; Sears and Hendrix, 2004; Lonn and Smith, 2005, 2006; Lonn and others, 2007; Sears, 2016). McClelland and Oldow (2004) interpreted the Lewis and Clark Tectonic Zone as an oblique ramp connecting basement-detached hinterland structures of the Shuswap Complex in southern British Columbia and Washington with the frontal Laramide uplifts in Montana. Sears (2007) argues that the Lewis and Clark line was rotated during thrusting, from 79 to 59 Ma, into its current west–northwest orientation. Foster and others (2007b) suggested that the Lewis and Clark Tectonic Zone acted as a continental transform by connecting Eocene age, east–northeast-directed extension in the Priest River Complex with east–northeast-directed extension in the Bitterroot and Anaconda Core Complexes. According to Smith (2016), normal faults and, in some places, giant kink folds ("megakinks"), overprint all prior structures, including Late Cretaceous to early Paleogene thrust faults. Reactivation of a Precambrian structure has often been proposed to explain the location of the zone, yet all recognized structures that define it are Cretaceous or younger. Much is still unknown about the underlying basement structure and kinematics associated with the Lewis and Clark Zone. Current mapping along the Lewis and Clark Tectonic Zone by the Montana Bureau of Mines and Geology will help resolve these major problems.

Helena Structural Salient

Southward across the Lewis and Clark Tectonic Zone, the leading edge of the northwest Montana thrust belt curves to form a pronounced east-protruding fold–thrust salient. The Helena Structural Salient roughly corresponds with the geometry of the Helena Embayment that may have originally formed as a failed rift within the Belt Basin (Harrison and others, 1974; Winston, 1986; Price and Sears, 2000; Sears and Hendrix, 2004). During Late Cretaceous to Paleogene shortening, the embayment underwent tectonic inversion with major dip-slip thrusts forming in its center and oblique-slip lateral ramps forming along the northern and southern margins. The 90-km-long and 50-km-wide Boulder Batholith occupies the western end of the Helena Salient. Like the Purcell Anticlinorium to the north, the Boulder Batholith separates a distinct hinterland domain to the west from foreland structures to the east.

There are three major thrust systems in the foreland region east of the Boulder Batholith. From west to east, they are the Lombard, Moors Mountain–Willow Creek, and Volcano Valley–Battle Ridge Thrusts (figs. 19, 20). The dominant thrust sheet, in terms of magnitude of east-directed transport and thickness, is the Lombard Thrust sheet. In map view, the geometry of the Lombard Thrust sheet and associated

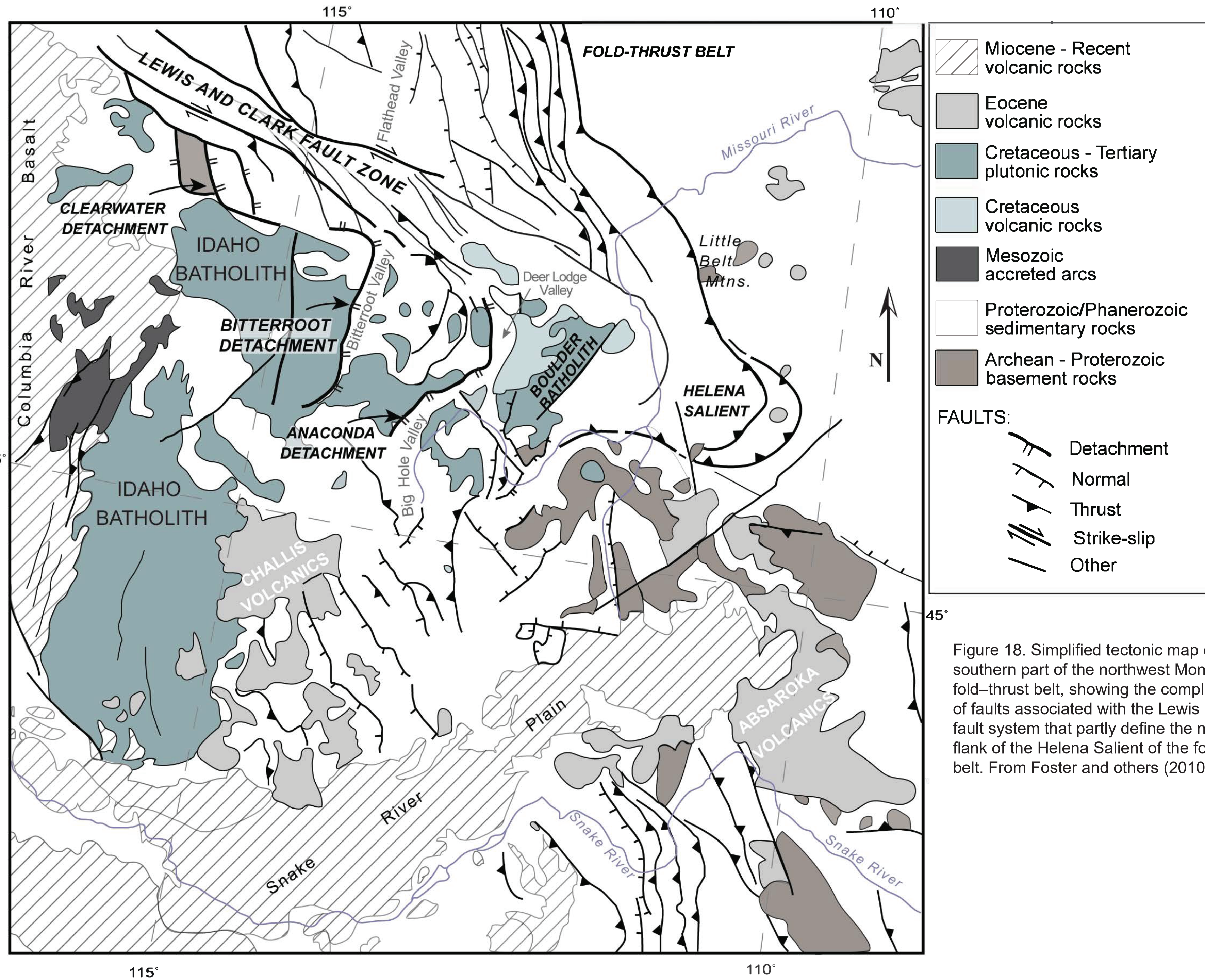

Figure 18. Simplified tectonic map of the southern part of the northwest Montana fold–thrust belt, showing the complex array of faults associated with the Lewis and Clark fault system that partly define the northern flank of the Helena Salient of the fold–thrust belt. From Foster and others (2010, p. 233).

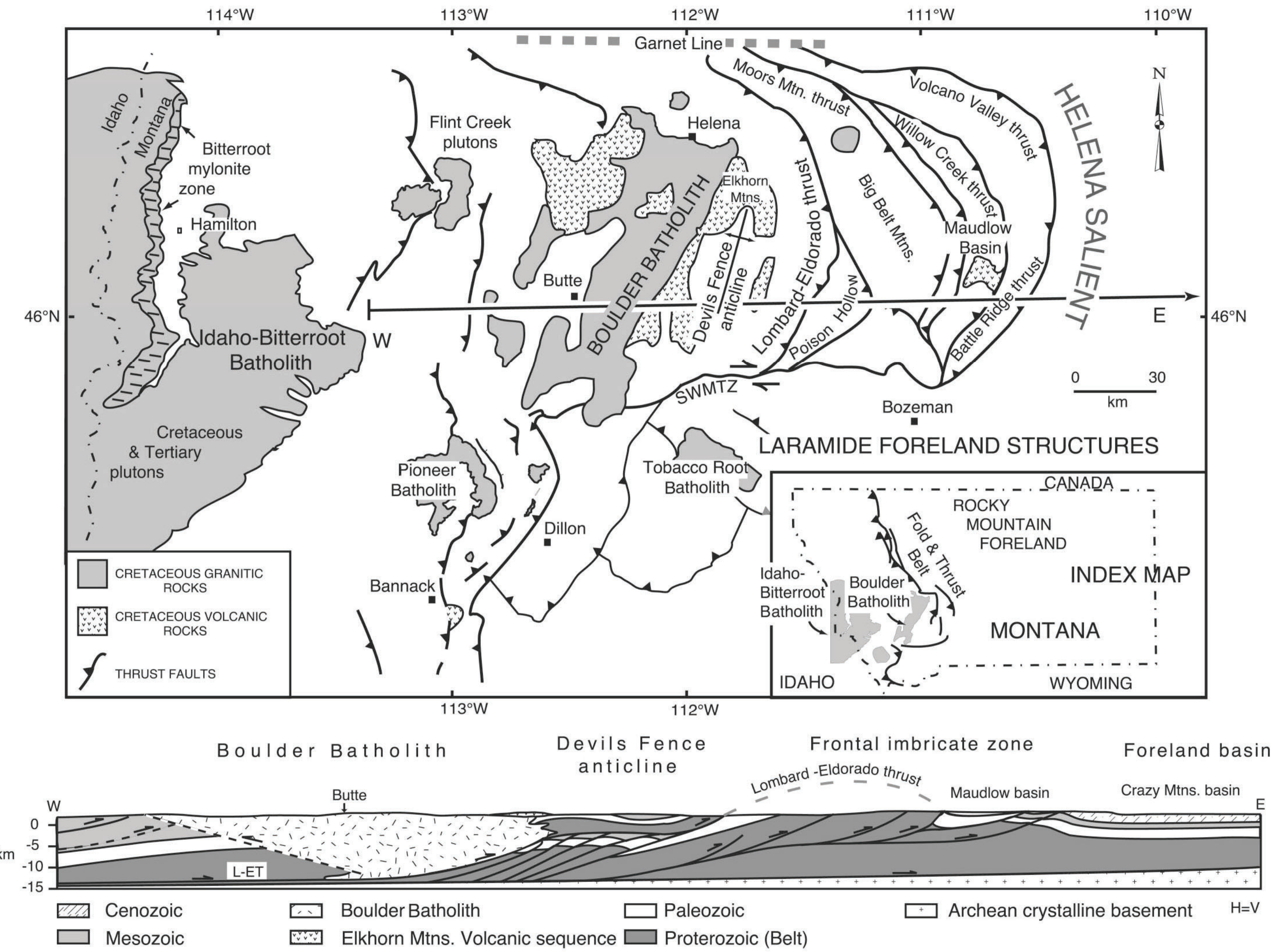

Figure 19. Simplified tectonic map showing major thrust faults of the Helena Salient of the fold-thrust belt east of the Boulder Batholith (Lombard, Moors Mountain–Willow Creek, and Volcano Valley–Battle Ridge thrust systems). The core of Devils Fence Anticline, just east of the Boulder Batholith, is a complex duplex fault zone that has folded the Lombard thrust. The regional basal décollement dips gently westward to great depths from the western Crazy Mountains Basin ("tip" of the orogenic wedge) to beneath the Boulder Batholith and beyond. From Lageson and others (2001, p. 724).

fold hinge lines imitate the geometry of the salient. Early structural interpretations of the Lombard Thrust showed it as a relatively thin sheet (4–5 km) beneath the Devils Fence Anticline, where it formed the basal décollement between Archean basement and the Belt Supergroup (Woodward, 1981; Schmidt and O'Neill, 1982). Based on this interpretation, the magnitude of eastward translation was limited to ~15 km. Petroleum geologists Jack Warne and Irvin Kranzler used exploration seismic data across the Devils Fence Anticline to show the anticline as a large duplex structure in the footwall of a <2-km-thick Lombard Thrust sheet. In their interpretation, the footwall is composed of imbricated Cretaceous rocks, with a basal décollement above basement at a depth of ~15 km. An important exploration well (Norcen Balcron UTP # 1-11 Kimpton Ranch) spudded in Belt rocks near the crest of Devils Fence Anticline (fig. 19) and confirmed the Lombard Thrust at 1,707 m (5,600 ft; Ballard and others, 1993; Burton and others, 1998). A comprehensive micropaleontological study of well-cuttings (and drilling mud constituents) showed that the footwall rocks are Cretaceous in age. The well was eventually abandoned in 1991 at a total depth of 14,846 ft (4568 m). Since then, cuttings and data from the same well were analyzed by the U.S. Geological Survey; they concluded that there is no evidence to substantiate the existence of rocks younger than Proterozoic in the well bore (Schalla, 2000). This resulted in two diametrically opposed interpretations, one developed by petroleum industry personnel and the other by the USGS, based on different conclusions about the micropale-

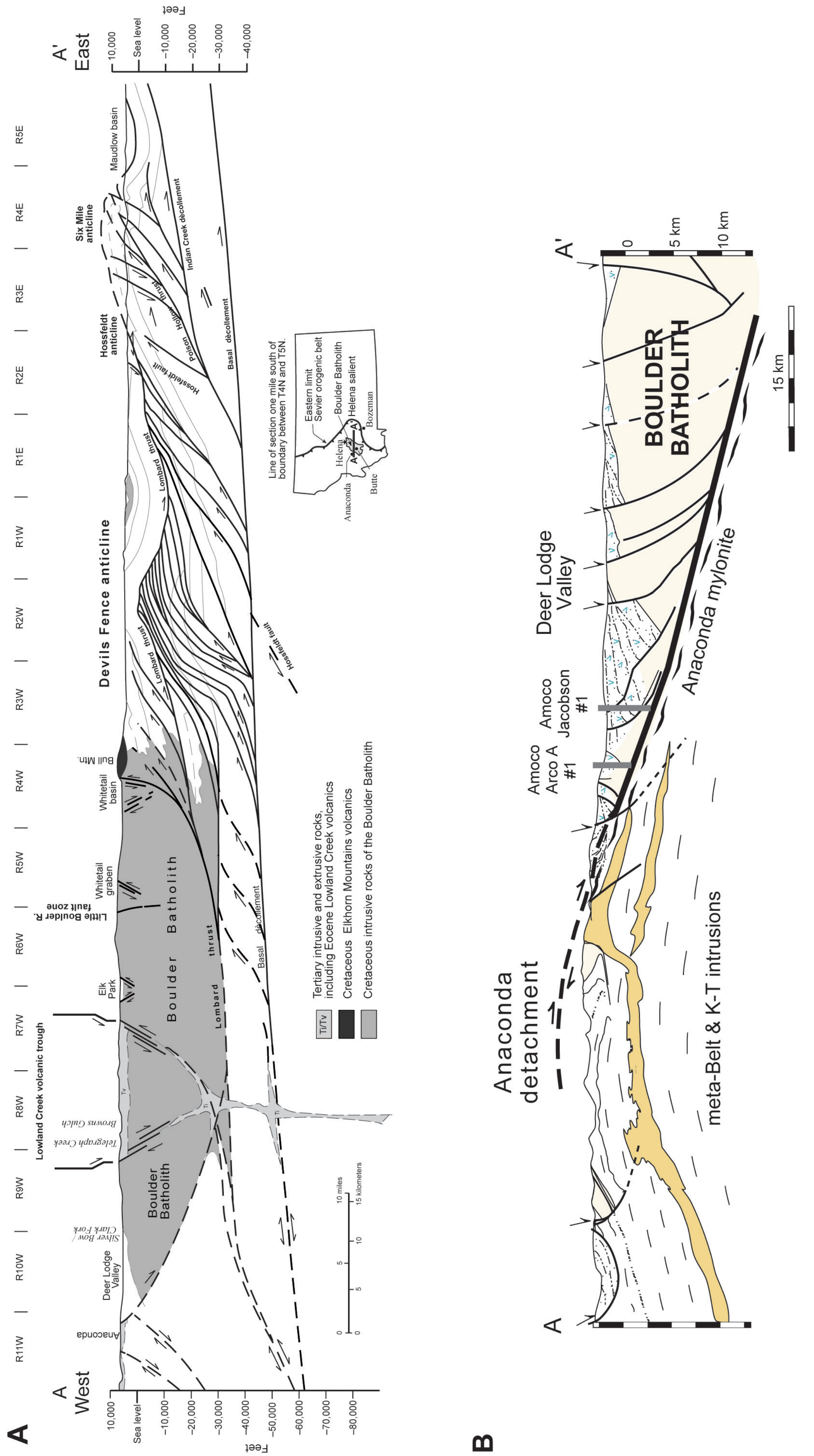

Figure 20. (A) Regional cross-section over the Boulder Batholith from the Maudlow Basin (east) to the eastern margin of the Anaconda Metamorphic Core Complex and detachment fault (west). Modified from Burton and others, 1998. (B) Detailed and updated cross-section over the Anaconda detachment fault and the western flank of the Boulder Batholith. Modified from Foster and others (2010).

ontological content of the drill cuttings and drilling mud. Resolving this problem is important, since it bears directly on determining the magnitude of west to east transport along the Lombard Thrust. If industry interpretations are correct and Cretaceous rocks exist below the Lombard Thrust, minimum displacement is ~40 km. If footwall rocks are instead Proterozoic, as suggested by the USGS, minimum displacement is ~15 km. Despite ongoing structural studies in the Helena Salient, including those that have specifically targeted the Lombard Thrust (e.g., Harlan and others, 2005a, 2008; Whisner and others, 2014; Vuke and others, 2014), the controversy is unsolved. However, based on along-strike correlation with large-displacement structures to the north and given the fact that the Lombard carries Belt strata in its hanging wall (and thus has significant stratigraphic separation, as a low-angle thrust), the larger estimate of ~40 km makes more sense (fig. 20). In addition, it should also be noted that the Lombard Thrust is an out-of-sequence thrust, with two episodes of displacement documented by footwall cutoff relationships along the fault's surface trace (fig. 21); this is not at all uncommon for a major thrust in this structural position within a thrust

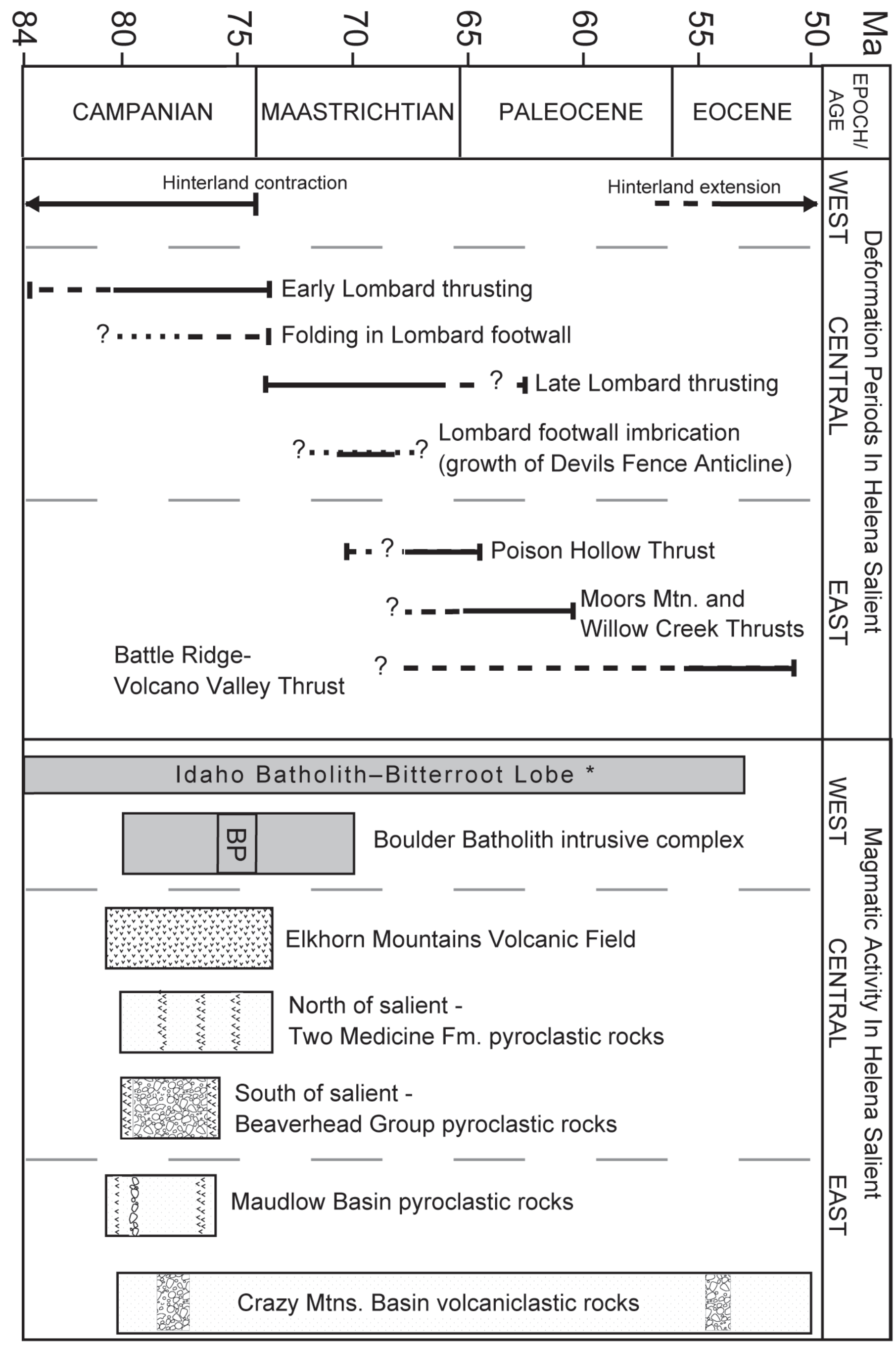

Figure 21. Chart showing timing of deformation in the Helena Salient compared to temporally overlapping magmatic activity. From Kalakay (2001).

belt and supports the interpretation of greater tectonic transport.

Structures exposed to the west of the Boulder Batholith are of vital importance in understanding the development of the Sevier fold–thrust belt in Montana. In contrast to foreland structures and rocks in the Helena Salient, this region has characteristics more like those of an orogenic hinterland. Major features include stacked thrust sheets, thrust ramps, tight east-vergent and west-vergent folds, and closely spaced faults (Lonn and others, 2010; Naibert and others, 2010; Kalakay and others, 2014; Elliott and others, 2013). In addition, the region was extensively intruded by Late Cretaceous to early Tertiary granitic to dioritic plutons (Hyndman, 1980; Desmarais, 1983; Marvin and others, 1989; Wallace and others, 1992; Grice and others, 2005; Grice, 2006; Foster and others, 2010; Naibert and others, 2010). Despite a significant overprint by Eocene extension and magmatism, structures that are coeval with foreland structures are intact and well-exposed. For clarity, we adopt the strategy of Lonn and others (2010), who divided this region into two major structural domains, whereby the NNE-striking Georgetown–Philipsburg thrust system separates an eastern domain from a western domain. The eastern structural domain encloses the Flint Creek and northeastern Anaconda Ranges, characterized by upper greenschist to upper amphibolite facies metamorphism, tight folds, closely spaced faults, and a very complex structural history. The western domain, previously termed the Sapphire tectonic block (Hyndman and others, 1975) or Skalkaho slab (Doughty and Sheriff, 1992), is allochthonous and mostly composed of low-grade metasedimentary rocks deformed into upright, open folds and cut by numerous reverse and normal faults.

The east-directed Georgetown–Philipsburg thrust system divides the western and eastern domains. This thrust system places Mesoproterozoic Piegan Group of the Belt Supergroup over upper Paleozoic and Mesozoic sedimentary rocks (Lonn and others, 2010). Total stratigraphic separation is estimated to be ~7,400 m (24,000 ft). The estimated magnitude of east-directed tectonic transport is ~35 km (Lonn and others, 2010). Based on cross-cutting plutons, a minimum age for last movement on the fault is ~78 Ma (Hyndman and others, 1982; Desmarais, 1983; Marvin and others, 1989; Wallace and others, 1992). The Georgetown–Philipsburg Thrust is folded by structures that formed in its footwall and is offset by normal faults along its trace.

East of the Georgetown–Philipsburg thrust, in the Flint Creek and northeastern Anaconda Ranges, footwall rocks of the Anaconda Metamorphic Core Complex are exposed. This structural situation provides a unique window into deep-level tectonic processes that operated within Montana's Sevier orogenic belt (Kalakay and others, 2014). Numerous workers conducted previous geologic mapping in the Anaconda and Flint Creek Ranges, which consists primarily of metamorphosed Belt quartzite, argillite, and pelite of the Missoula Group and Helena Formation (Emmons and Calkins, 1913; Desmarais, 1983; Heise, 1983; Wallace and others, 1992; Lewis, 1998). In places, metamorphosed Paleozoic units consisting of Middle Cambrian to Cretaceous rocks are also exposed. All units have been intruded by three distinct generations of plutons, dikes, and sills. Most are Late Cretaceous, Paleocene, or early middle Eocene in age (Grice, 2006; Foster and others, 2010; Howlett and others, 2021).

In this eastern domain, the structural geometry and structural history are extremely complex. During Late Cretaceous time, much of this region was presumably overlain by the thick Georgetown–Philipsburg thrust system. If interpretations for the original structural position of the Boulder Batholith are correct, then the 10-km-thick batholith would restore to a position on top of the Anaconda Core Complex footwall rocks during Late Cretaceous time (Foster and others, 2007b, 2010; Kalakay and others, 2014). Regardless of the interpretation, rocks in the eastern domain show a Late Cretaceous history of metamorphism and deformation associated with mid-crustal depths (Kalakay and others, 2003; Grice, 2006; Grice and others, 2004, 2005; Haney, 2008; Kalakay and others, 2014). The most striking structural element throughout the eastern domain is tectonic attenuation seen in the Mesoproterozoic through Mesozoic metasedimentary sequences (Lonn and others, 2010; Lonn and McDonald, 2004; Kalakay and others, 2014). In some places, attenuation was accommodated by bedding-parallel shear zones that cut out parts of the stratigraphic section (Lonn and McDonald, 2004). In other areas, the stratigraphy is intact yet reduced in overall thickness by large amounts. Rock units that show the greatest magnitude of thinning are the once-thick pelitic and carbonate (argillite) formations in the Missoula Group of the Belt Supergroup (e.g., Shepard, Snowslip, Helena, and Greyson Formations). One excellent location to view this attenuation is at Mill Creek Canyon on the southern flank of Mount Haggin, where a ~3,300-m sequence of Belt through Cambrian sedimentary rocks has been tectonically reduced to an estimated thickness of ~200 m (Heise, 1983; Kalakay and others, 2003; Lonn and others, 2010). There are many other locations within the eastern domain where similar phenomena are observed (Lonn and McDonald, 2004). The processes associated with such extreme flattening observed in these rocks are not well understood. However, it must be noted that this magnitude of vertical shortening can only be accommodated by large amounts of lateral extension or flow. High-strain, solid-state fabrics are present in only the oldest (>75 Ma) Late Cretaceous plutons that are mostly sheet-like and roughly concordant to bedding where they intruded metasedimentary rocks (Hawley, 1974; Desmarais, 1983; Grice and others, 2005; Grice, 2006; Kalakay and others, 2014). Younger plutons show surprisingly little evidence of either magmatic or sub-solidus deformation (Kalakay and others, 2014). Thus, the high-strain attenuation fabrics apparently formed during the 75–80 Ma high-temperature metamorphic event (Grice and others, 2004, 2005; Grice, 2006). This significant period of hinterland deformation was therefore coeval with ongoing shortening in adjacent areas of the foreland fold–thrust belt (Harlan and others, 1988; Sears and Hendrix, 2004; Fuentes, and others, 2012; Kalakay, 2001). How the hinterland and foreland regions might have been tectonically coupled is covered in the discussion part of this paper.

Southwest Montana "Overlap Domain"

The southwest Montana domain of the Sevier fold–thrust belt, also known as the "southwest Montana recess," exhibits complex geometric and kinematic interactions among thin-skinned thrusting, basement-involved thrusting, and silicic magmatism. This "overlap domain" of structural styles is not unique in the Rocky Mountain region, where thin-skinned thrust belt structures and thick-skinned Laramide structures have spatially and often temporally overlapped along the eastern margins of the Sevier orogen (Hamilton, 1988). The challenge of unraveling the geometric complexities and timing of overlap structures becomes ever more complicated in areas where faults associated with the Mesoproterozoic Belt Basin have been reactivated or exploited in the Sevier–Laramide overlap zone, all of which may be superimposed by Paleogene and Neogene extensional faults. The resulting structural complexities inherent to western Montana were summarized in the introduction to this paper, as well as in the section on Laramide structural domains (e.g., Bridger Range), underscoring the superimposed tectonic history of Montana that spans more than 3 billion years. Also, Parker and Pearson (2021) provide an excellent overview of well-studied sites of structural overlap in southwest Montana.

A particularly vexing area of Laramide–Sevier overlap occurs in far southwest Montana in the Tendoy and Beaverhead Mountains, where Precambrian basement rocks have been incorporated into the Cabin–Medicine Lodge thrust sheet. Here, Skipp (1988) suggested that the Cabin–Medicine Lodge thrust sheet overrode a previously faulted foreland of probable Mesoproterozoic tectonic ancestry; as the Cabin–Medicine Lodge thrust system ramped upsection to the east across these older ENE- and WNW-trending fault blocks, basement rocks were locally incorporated into the allochthon at ramp interfaces (see fig. 10 in Skipp, 1988). Skipp's (1988) kinematic model for the Cabin–Medicine Lodge thrust system also involved a complex interplay of lateral ramps and out-of-sequence thrusting, resulting in the present-day distribution of basement rocks within the "thin-skinned" thrust belt of southwest Montana.

West of the Cabin–Medicine Lodge thrust system, mapping by Parker and Pearson (2021) in the westernmost Beaverhead Mountains resulted in a new model for the incorporation of basement rocks in this part of the Sevier orogen. Their model, called the "double-decker" (fig. 22), is based on a detailed stratigraphic–structural analysis of a small area in the northern part of the Leadore quadrangle, Lemhi County, Idaho (Parker and Pearson, 2020), with a focus on understanding the mechanical stratigraphy of the rock succession. The double-decker model involves: (1) an eastward-propagating, thin-skinned thrust belt above a regional décollement overlying autochthonous silica-cemented and recrystallized Mesoproterozoic quartzite to the west, and Paleoproterozoic/Archean basement rocks to the east; and (2) subsequent shortening that lowered the regional décollement to the brittle-plastic transition zone in the basement, thus incorporating Mesoproterozoic quartzite and Paleoproterozoic/Archean basement rocks into the allochthon. Then, as thrust sheets cut upsection relatively to the east, basement rocks were eventually incorporated into

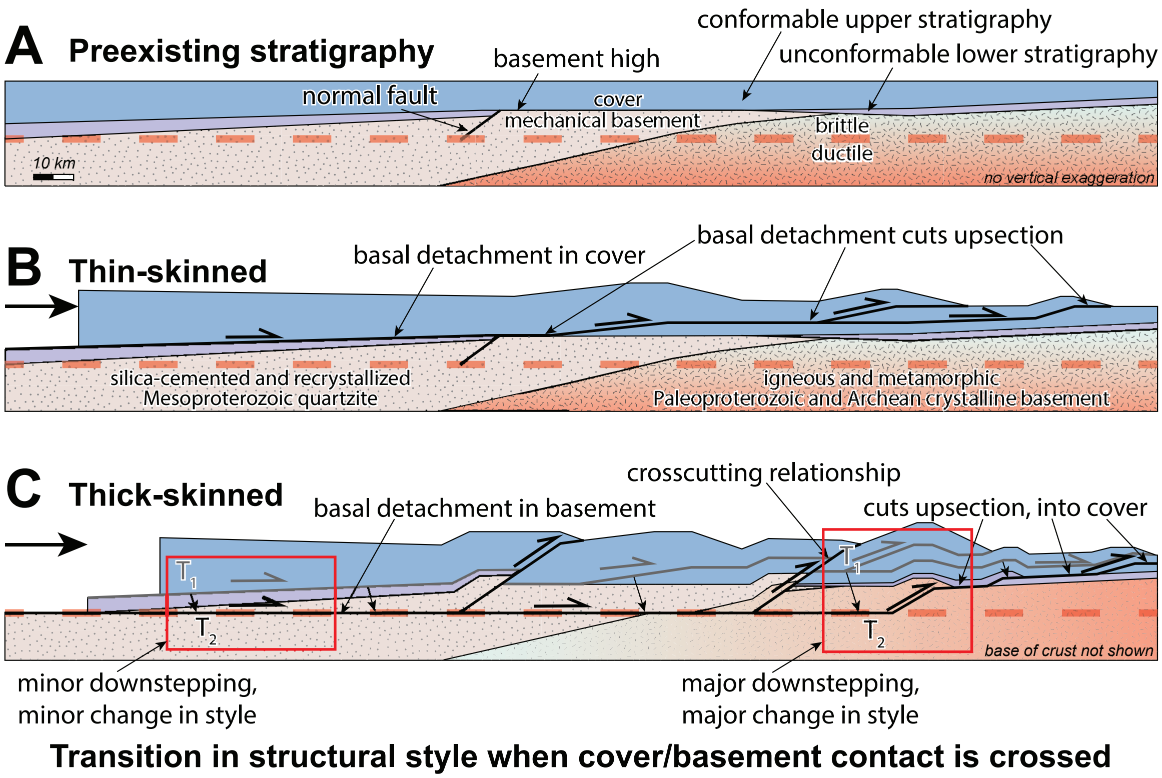

Figure 22. Schematic cross-sections illustrating the double-decker model: (A) initial undeformed state, (B) early thin-skinned thrusting, and (C) later thick-skinned thrusting. From Parker and Pearson, 2021, with permission (their fig.11).

the cores of fault-bend folds in the thrust belt; these folds were often later bisected by Neogene extensional faults to form “perched basement wedges” (Lageson, 1989). Although the Sevier–Laramide structural interactions in the overlap domain of southwest Montana are extremely complicated, made even more so by Precambrian and Neogene tectonic elements, the double-decker model based on mechanical stratigraphy promises to be a testable hypothesis that can be applied to other areas of structural overlap in southwest Montana and elsewhere.

TECTONICS OF PLUTON EMPLACEMENT

Structural Position of Late Cretaceous Plutons

In western Montana, the Mesozoic magmatic arc spatially overlapped with the thin-skinned Sevier orogenic system (Hyndman and others, 1988; Constenius, 1996; Foster and others, 2001, 2007a, 2012; Kalakay and others, 2001; Naibert and others, 2010; see Scarberry and others, 2020, this volume). This is in contrast with areas to the north (northwest Montana and Canada) and south (Idaho, Utah) where the Sevier shortening occurred in a distinctly back-arc foreland setting (e.g., Price, 1981; Fuentes and others, 2011). In general, western Montana plutonism was synchronous with a period of crustal shortening and thickening between 85 and 55 Ma based on K-Ar geochronology of crosscutting felsic dikes (Robinson and others, 1968; Hoffman and others, 1976), paleomagnetic and K-Ar isotopic data (Harlan and others, 1988), $^{40}Ar/^{39}Ar$ geochronology and thermochronometry (Snee, 1982; Zen, 1988; Fillipone and Yin, 1994; Foster and others, 2001), and U-Pb zircon geochronology (Foster and others, 2007a, 2012). Major composite plutonic centers include the Idaho, Boulder, and Pioneer Batholiths, emplaced between 80 and 53 Ma (Foster and Fanning, 1997). The Boulder Batholith and associated Elkhorn Mountains Volcanic Field, the Pioneer igneous complex, the Flint Creek plutons, and numerous smaller bodies form an expansive belt of Late Cretaceous magmatic rocks that lie 80 to 100 km east of plutonic centers in the Idaho Batholith. Unlike mid-crustal magmatic systems exposed in the Idaho Batholith, plutons within the eastern magmatic belt were emplaced within the evolving fold–thrust belt and foreland basin at relatively shallow depths (1–10 km), mostly as thin (meter to kilometer scale) tabular sheets or laccoliths (Hyndman and others, 1988; Sears and others, 1989; Kalakay and others, 2001). Many intrusive bodies spatially overlap with major contractional structures (Kalakay and others, 2001). Regional cross-sections have depicted the granitoid sheets as occupying major thrust zones (e.g., Hyndman and others, 1988; Kalakay and others, 2001), or superjacent to major thrust surfaces (Burton and others, 1998).

Numerous field studies indicate that many Late Cretaceous batholiths of western Montana were emplaced as tabular bodies, specifically at the top of frontal thrust ramps (fig. 23) within the Sevier orogen (Burton and others, 1998; Lageson and others, 1994; Kalakay and others, 2001). There are several examples in which pluton emplacement occurred during deformation. However, some plutonism may have occurred after thrust motion had ceased. In most cases, magma exploited either developing fault zones (syn-kinematic) or preexisting fault zones (post-kinematic) during some stage of emplacement. The McCartney Mountain thrust salient of southwest Montana could be considered the type locale for exhibiting ramp-top emplacement of plutons, since there are several locations where the relationship between thrust ramps and plutons are well exposed. These locations include Bannack, McCartney Mountain, and the eastern margin of the Pioneer Batholith.

In the vicinity of Bannack, several granodiorite stocks and sills intrude deformed Paleozoic and Mesozoic strata (Kalakay and others, 2001; Mack and others, 1999). Near Badger Pass, granodiorite bodies occur as thin (3–50 m) sheets that intruded the nearly flat-lying, eastern Ermont thrust system. South of Badger Pass, the granodioritic Bannack and Anniversary Plutons exposed along Grasshopper Creek display a slightly deeper level of the intrusive system. The Bannack and Anniversary Plutons range from 200 to 600 m in thickness and were emplaced within a ramp system that involves the Ermont Thrust and imbricated basement rocks at depth (Kalakay and others, 2001; Mack and others, 1999; Coryell and Spang, 1988).

The McCartney Mountain Pluton is the easternmost intrusive body of the McCartney Mountain Salient. It is a composite body consisting of four mappable phases ranging from granodiorite to granite in composition (Kalakay and others, 2001). Friberg and Vitaliano (1981) originally described the pluton as a sub-vertical body comprising three plutons, fed from a common pipe-like source directly beneath the pluton. More recent mapping (Gunckel, 1990; Kalakay and others, 2001) has shown that both the aureole rocks and foliations within the plutonic phases dip moderately away from the pluton along its northern boundary. These orientations, together with roof pendants exposed in the area, suggest a level of exposure near the pluton's roof. In contrast, along the southern margin of the pluton, both wall rock and magmatic foliations dip gently inward, suggesting an exposure level close to the pluton's floor. These recent studies portray a sill-like geometry for the McCartney Mountain pluton with an overall thickness of ~700–800 m. Recent mapping has also demonstrated that the McCartney Mountain Pluton intruded along an east-to-west stratigraphic discontinuity, interpreted as a footwall ramp–hanging wall flat system located between the Anglers Thrust to the west and the structurally lower Sandy Hollow–Hogback Thrust to the east (Gunckel, 1990; Kalakay and others, 2001).

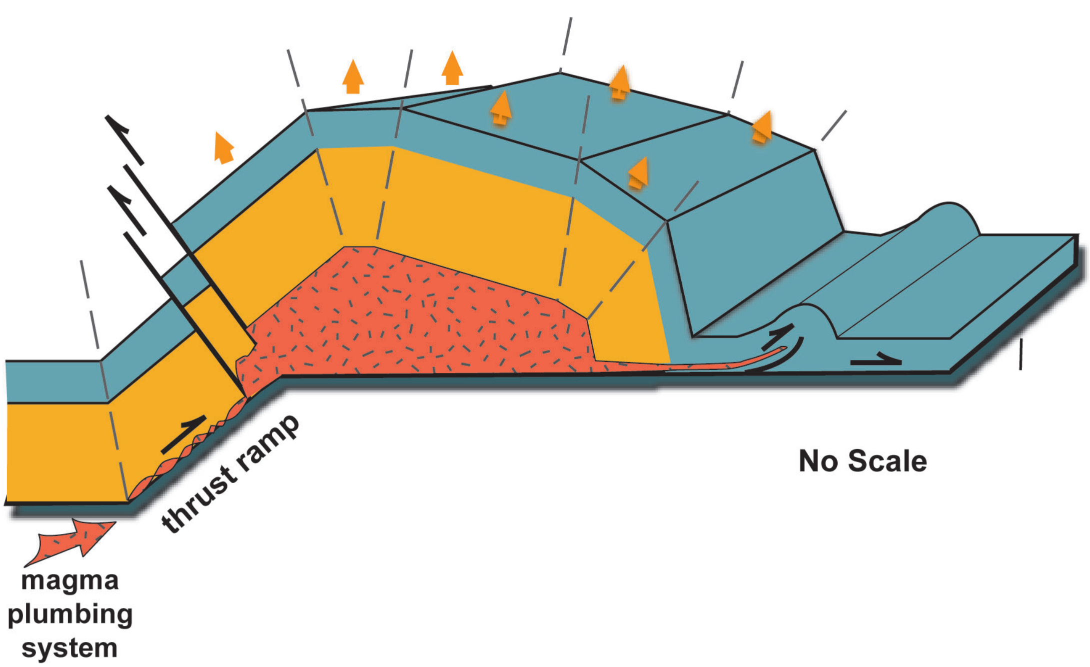

Figure 23. Simplified block diagram showing ramp-top pluton emplacement model, including fore-thrusts, antithetic back-thrusts, dilatant expansion zone at the top of the ramp (an area normally occupied by an imbricate thrust fan, in the absence of magma). From Kalakay and others (2001).

The Pioneer Batholith is exposed over an area of ~800 km^2 and forms the largest intrusive body in the McCartney Mountain thrust salient. The eastern contact of the Pioneer Batholith extends north–south for over 70 km and forms the western boundary of the McCartney Mountain thrust salient. Sedimentary rocks north, east, and south of the batholith consist of Cambrian through Mesozoic strata that exhibit east-verging, nearly isoclinal and reclined folds to the north, becoming progressively more open and upright to the south (Theodosis, 1956; Brandon, 1984; Zen, 1988). The largest pluton, the Uphill Creek granodiorite, constitutes over 75% of the exposed batholith and gives a U-Pb zircon crystallization age of 72.0 ± 0.5 Ma (Foster and others, 2012). Other plutons in the Pioneer Batholith were emplaced between 78 and 72 Ma based on U-Pb zircon data (Foster and others, 2012). Alignment of internal plutonic contacts, the general elongation of the plutons, and locally developed magmatic fabrics within the batholith led Snee (1982) and Zen (1988) to suggest a synkinematic mode for pluton emplacement. This interpretation is corroborated by the geometry and distribution of cleavage subparallel to the margin of the Pioneer Batholith, suggesting a synchronous relationship between batholith emplacement and major folding in the country rocks (Tysdal and others, 1994; Kalakay and others, 2001).

Structural data from roof and floor regions of the intrusive contact clearly illustrate the concordant and tabular geometry of the Pioneer Batholith (Zen, 1988; Kalakay and others, 2001). At the northern edge of the batholith, where the deepest parts of the plutonic system are exposed, the contact intersects a ramp in the Wise River Thrust where it places Middle Proterozoic Belt strata on Paleozoic rocks. Near this same locality, slivers of crystalline basement are found within the imbricated Belt stratigraphy (Zen, 1988). Taken in total, these data suggest that most plutons in the Pioneer Batholith were synkinematically emplaced along a major footwall ramp. This thrust ramp formed near the east-tapering margin of Belt deposition as suggested by the involvement of both Belt and basement rocks in the imbricated system.

Boulder Batholith

The Boulder Batholith is a composite body over ~100 km long in a north–south direction, spanning the entire eastern margin of the Helena Salient of the Sevier fold–thrust belt (figs. 18, 19, 21). Previous investigations have suggested strong similarities between the geometry and structural position of the Boulder Batholith and the somewhat smaller intrusive bodies described in previous sections (Lageson and others, 2001; Kalakay and others, 2001; Vejmelek and Smithson, 1995). However, unlike plutons in the McCartney Mountain Salient, the Boulder Batholith was overprinted by significant Eocene extension during development of the Anaconda Metamorphic Core Complex (Foster and others, 2010; Kalakay and others, 2014). Movement along the Anaconda detachment translated the batholith as part of the hanging wall, and placed it ~20 km east of its original location. This makes the pluton's structural position at the time of emplacement difficult to ascertain. The footwall of the Anaconda detachment exposes Late Cretaceous and Eocene plutons that intruded a high-grade sequence of deformed Belt and Paleozoic sedimentary units (Foster and others, 2010; Kalakay and others, 2014). Deformation in the footwall is characterized by extreme attenuation of the Belt section associated with a collapsed thrust ramp system that formed structurally beneath the Georgetown Thrust. This collapsed ramp coincides, along strike, with ramps in the Pioneer Batholith complex and those farther south, near Bannack (Kalakay and others, 2001, 2014; Lonn and others, 2003; Ruppel and others, 1993; Fraser and Waldrop, 1972). By restoring the Boulder Batholith westward along the Anaconda detachment back to its original position, it ends up on top of the collapsed ramp system just described. Thus, it remains plausible that the Boulder Batholith, like plutons to the south, was emplaced near the top of a major footwall ramp in the Sevier orogenic system as previously proposed (figs. 21, 23).

Emplacement Model

A model for emplacement of Late Cretaceous silicic plutons in the Sevier fold–thrust belt of western Montana is based on several investigations of structural relations between plutons and their wall rocks. In many cases, field data show a clear spatial correlation between the plutons and the top of major frontal thrust ramps that cut upsection across footwall rocks. Frontal thrust ramps demonstrate many key elements that may facilitate pluton emplacement: (1) extensional strains along the ramp interface produced by incremental plane-strain simple shear; (2) a dilatant space or "releasing-step" at the top of the ramp; and (3) antithetic back-thrusts that may assist in pluton emplacement (fig. 23). Regardless of whether the pluton is synkinematic (*sensu stricto*), post-kinematic, or some combination thereof, there is evidence that frontal ramp tops create a dilatant environment where plutons are initially emplaced and grow. Bannack, McCartney Mountain, Pioneer Batholith, and the Boulder Batholith are examples of intrusive centers located at ramp-top structural positions in southwestern Montana.

COLLAPSE AND EXTENSION OF THE OROGENIC PLATEAU

Shortening and thrusting ended in the foreland of the Montana Disturbed belt and the Helena Salient, and in the basement-cored uplifts at about 53–52 Ma. By this time, the core of the Cretaceous–early Paleogene orogenic belt had begun to extend either by gravitational collapse or as a result of change in plate dynamics that caused extension, exhumation of mid-crustal rocks in metamorphic core complexes, and voluminous magmatism. Significant extension of the Sevier–Laramide orogenic belt started at about 53–52 Ma (Foster and others, 2001, 2007b, 2010; Constenius, 1996), which was within 1–3 million years after the end of thrusting in the Cordilleran foreland fold–thrust belt at 55–52 Ma (Harlan and others, 1988; Sears and Hendrix, 2004) and continued to after 40 Ma (Foster and Raza, 2002; Foster and others, 2007b, 2010). Timing constraints from stratigraphy, paleomagnetism, and geochronology indicate that initial Eocene extension in the hinterland postdates most Cretaceous–Paleogene contraction, but may have been coincident with the last phase of shortening in the foreland (Constenius, 1996; Foster and others, 2001; Harlan and others, 1988). The early Eocene extension was coincident with the onset of the widespread Challis–Absaroka–Kamloops magmatism in what was previously the back-arc position of the orogenic belt (e.g., Breitsprecher and others, 2003; see Mosolf and others, 2023, this volume). This voluminous magmatism has been attributed to several different settings, including: regional extension (Morris and others, 2000), subduction (Armstrong and others, 1977), a slab window between the Farallon and Kula (or Resurrection) plates (Breitsprecher and others, 2003; Haeussler and others, 2003; Foster and others, 2010), or a combination of these related to the accretion of the Siletzia terrane and slab removal (Schmandt and Humphreys, 2011; Gao and others, 2011). It is, therefore, important to note that extension, core complex formation, and magmatism all started at the same time and were presumably related on a regional scale.

End of Laramide reorganization of the regional stress field in western Montana during the early–mid Eocene is reflected in the distribution and length of radial dike swarms that surround the Big Timber Stock and its satellite plutons in the central and northern Crazy Mountains Basin (CMB; fig. 24). The igneous bodies intrude the Paleocene Fort Union Formation throughout the central CMB and Cretaceous rocks in the northern part of the basin. $^{40}Ar/^{39}Ar$ ages of alkaline dikes and sills in the northern CMB are reported between 50.61 Ma and 50.03 Ma, defining a very narrow window of intrusion (Harlan, 2006). Subalkaline rocks in the southern CMB yield ages between 50.6 and 49.2 Ma, overlapping with but slightly younger than ages to the north (du Bray and Harlan, 1996). Collectively, the CMB radial dike swarm is highly asymmetrical, with the longest, most continuous dikes oriented NNW (~330°), whereas much shorter, less continuous dikes are distributed orthogonally to this trend (Roberts, 1972, plate 3; Berg and others, 2000; McDonald and others, 2005). Non-rotated dikes and related dilational fractures define the least compressive stress orientation (σ3) at the time of their intrusion, forming perpendicular to σ3 and parallel to the maximum compressive stress orientation (σ1; Fossen, 2016; Gudmundsson, 2011). Therefore, the radial dike swarm in the Crazy Mountains Basin is a visual representation for the roughly 90° rotation of the principal horizontal compressive stress direction from SW–NE during Laramide/Sevier contraction, to NNW–SSE in the early to mid-Eocene (post 52 Ma), signaling the onset of orogenic collapse by 51–50 Ma. This simple stress analysis, of course, assumes that the family of radial dikes in the CMB all formed during the same tectono-magmatic event during the Eocene, and published ages give us no reason to doubt this. Harlan (2006) states that “all the igneous rocks in the Crazy Mountains were emplaced in a narrow time interval of 1–2 m.y.,” clustering at ~50 Ma (Harlan, 2006).

In Montana the most obvious tectonic features of Paleogene extension are the Bitterroot and Anaconda Metamorphic Core Complexes (fig. 25), which were exhumed on large extensional detachments that include thick mylonitic zones, because of flow in the deep crust, and overprinting brittle faults that formed in the shallow crust. In cross-section, these detachments have footwalls composed of high-grade metamorphic and igneous rocks and hanging walls composed of rocks that were in the upper crust in Eocene time, along with basins filled with sedimentary and

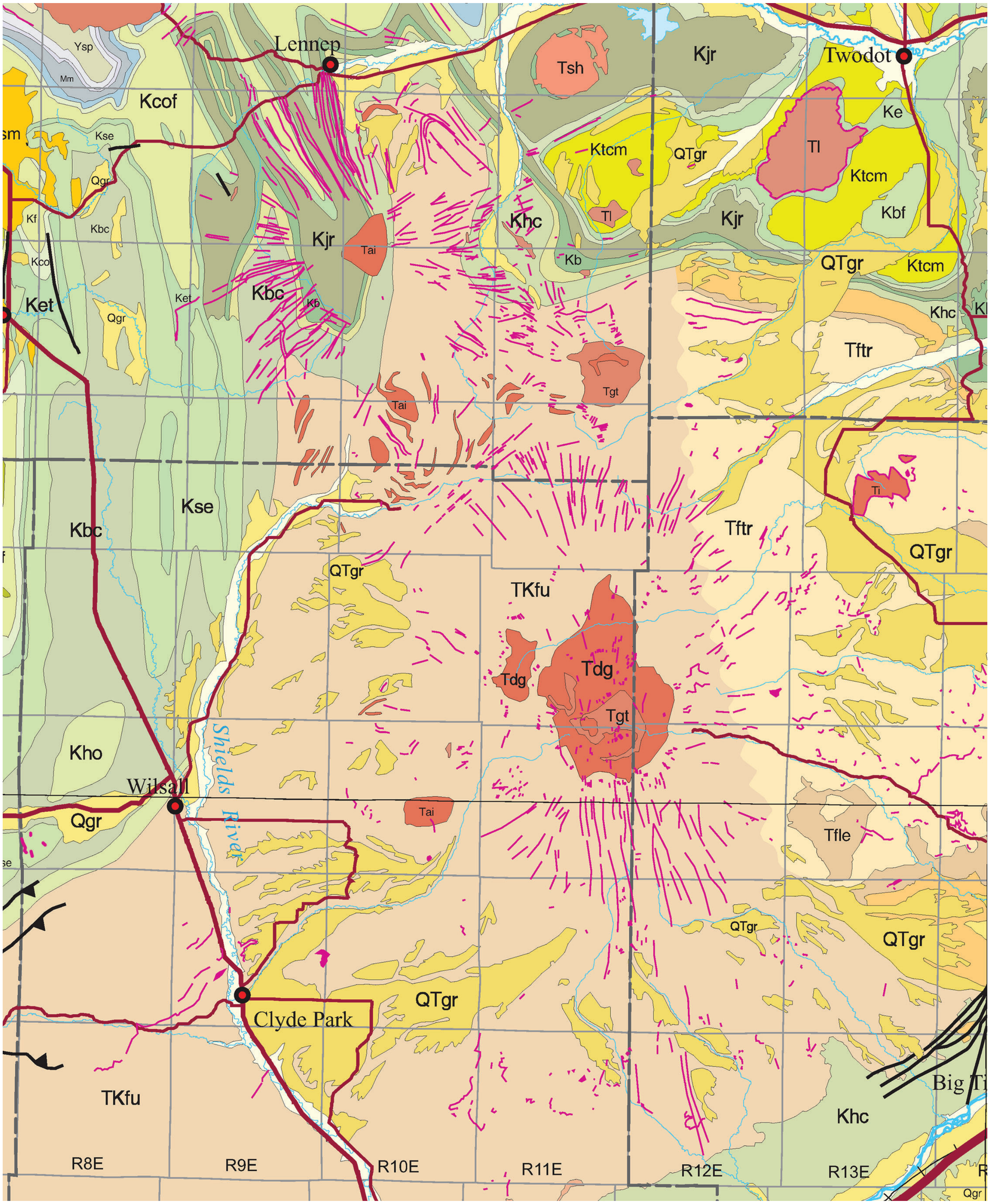

Figure 24. Eocene radial dike swarm surrounding stocks of the Crazy Mountains intrusive complex. From MBMG, 2007.

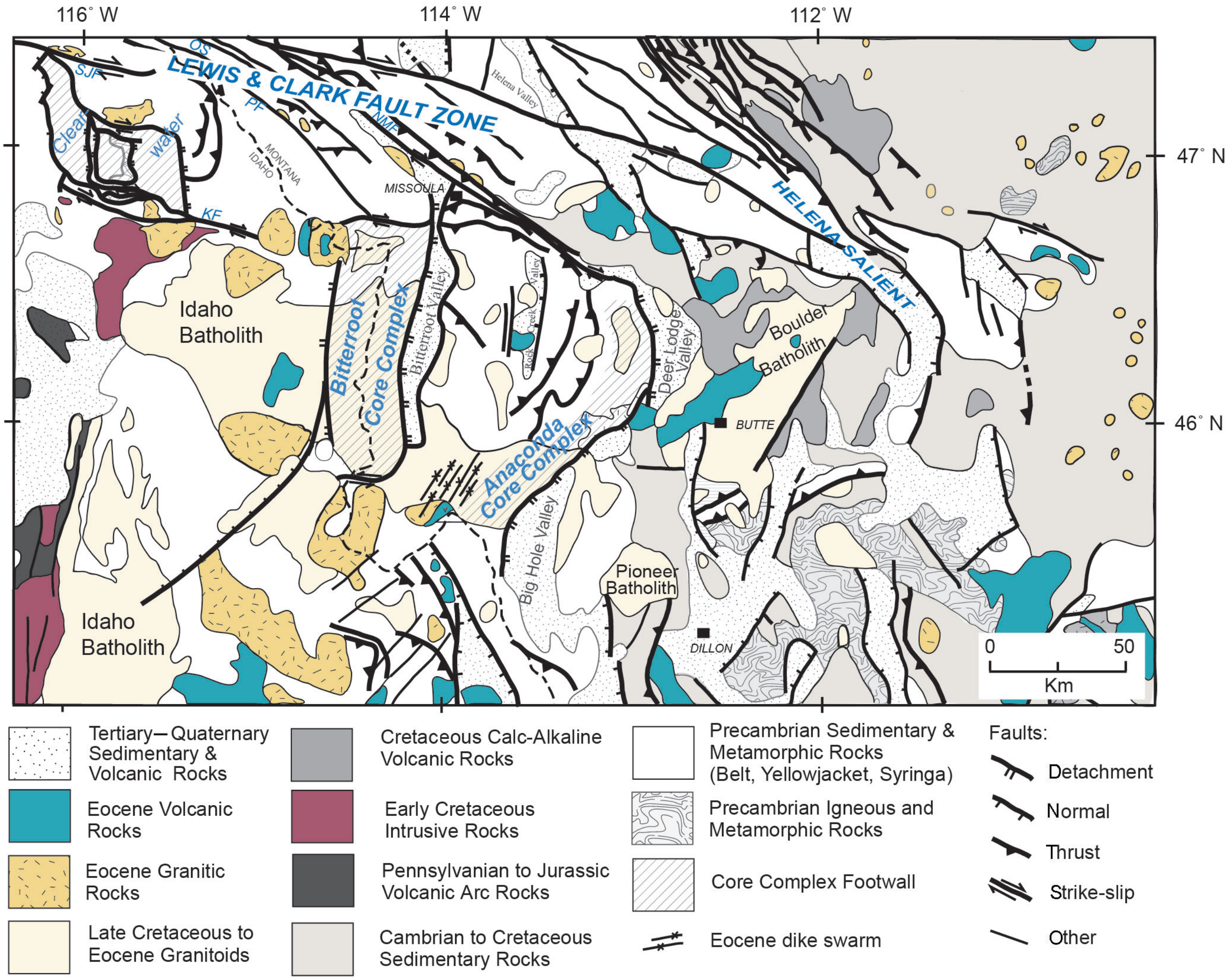

Figure 25. Tectonic map showing age distribution of rocks and key structural elements of the Bitterroot and Anaconda Metamorphic Core Complexes. From Foster and others (2007, p. 212).

volcanic rocks. The Anaconda Core Complex footwall is exposed in the Anaconda and Flint Creek Ranges with a detachment that dips beneath the Deer Lodge Valley, Cretaceous Boulder Batholith, and Elkhorn Mountains volcanic rocks (figs. 21, 26). Similarly, the Bitterroot Core Complex formed beneath the Bitterroot mylonite/detachment fault, which dips beneath upper plate rocks in the Bitterroot Valley and Sapphire Mountains. The detachments are laterally extensive east-dipping normal faults cut from the surface down to depths of 10–12 km in the case of the Anaconda Fault (Foster and others, 2010; Kalakay and others, 2014), and depths of 15–20 km in the case of the Bitterroot Fault (Foster and others, 2001; House and others, 2002). Displacement on these faults was so large—in the Bitterroot about 25 to 30 km (Foster and others, 2007b) and Anaconda about 18 to 20 km (Foster and others, 2010)—that rocks from the middle crust that were deforming plastically and producing mylonite were brought up in the footwall. The large amount of extension and eastward transport of the hanging walls unloaded the footwalls and folded the detachment surfaces back to the west as a result of isostatic rebound, exposing them as antiforms in the Bitterroot Mountains and the Anaconda Mountains, respectively. These two structures formed, in many ways, similar to how the Death Valley region is extending today and exhuming middle crustal rocks in the so called "turtle backs" of the Black and Mormon Mountains.

Extension and magmatism took place over a wide region of the northern Rockies, as much as 500–1,000 km east of the contemporaneous trench (Foster and others, 2010; Vogl and others, 2012). The extension direction for the metamorphic core complexes throughout the northern Rockies is remarkably sim-

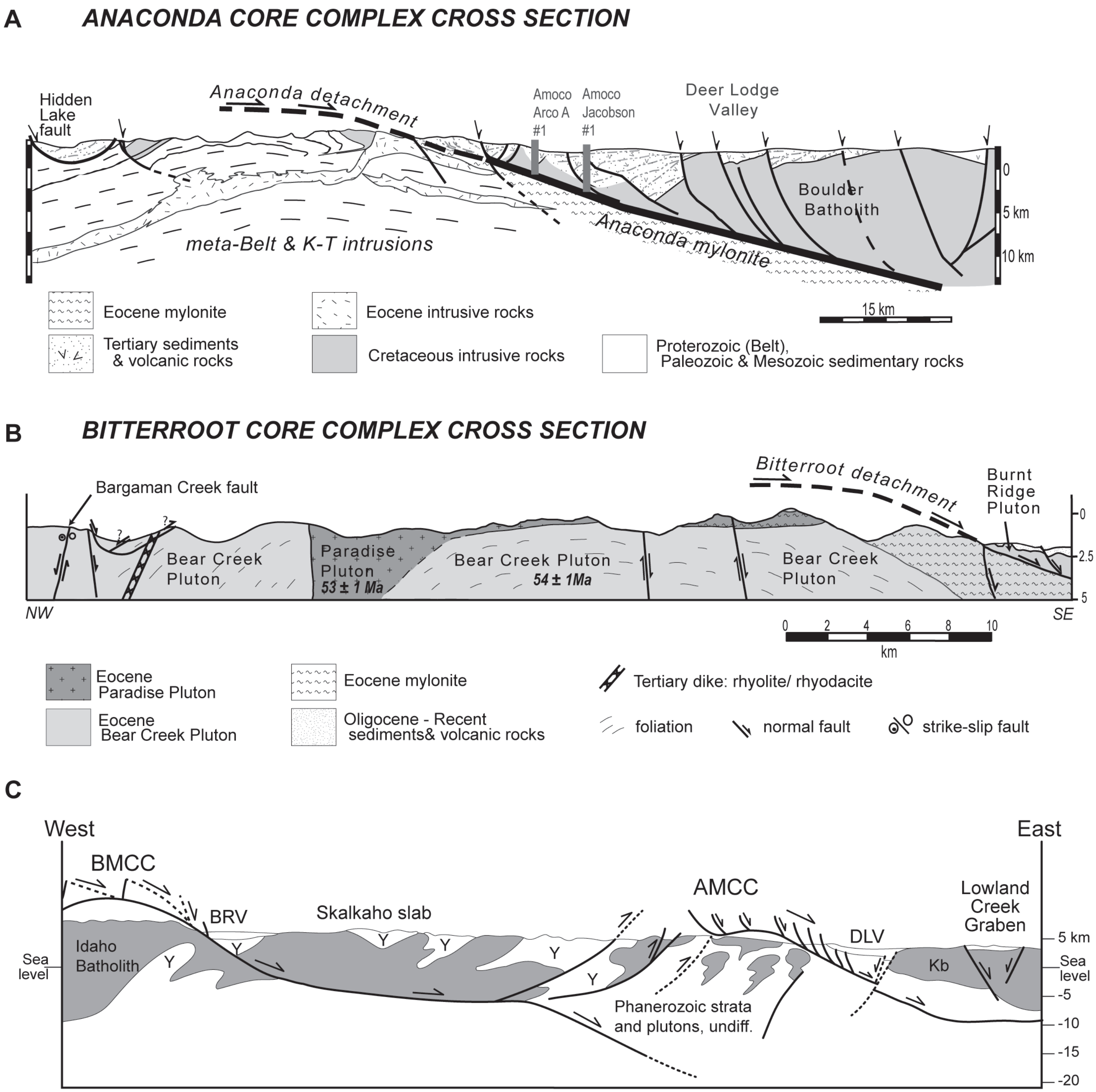

Figure 26. Cross-sections through the Bitterroot and Anaconda Metamorphic Core Complexes. (A) Detailed cross-section through the Anaconda Metamorphic Core Complex showing the arched exposure of the footwall and the Boulder Batholith in the hanging wall. From Foster and others (2007, p. 217). (B) Detailed cross-section of the Bitterroot Metamorphic Core Complex showing the domal exposure of the footwall beneath the Bitterroot detachment and hanging wall fault slivers of the Burnt Ridge Pluton. From Foster and others (2007, p. 214). (C) Regional cross-section showing the relationship between the two metamorphic core complexes and the Skalkaho “slab” in the hanging wall of the Bitterroot detachment. Modified from O’Neill and others (2004, p. 70). BMCC, Bitterroot Metamorphic Core Complex; AMCC, Anaconda Metamorphic Core Complex; DLV, Deer Lodge Valley.

ilar at between 104° and 110°, which also suggests that collapse of the orogenic plateau was caused by major plate-scale processes. The extensional detachment faults are linked to strike-slip faults including the Lewis and Clark Tectonic Zone, and on a larger scale, to northwest-striking faults like the northern Rocky Mountain Trench and Tintina faults (Price and Carmichael, 1986; van der Velden and Cook, 1996), suggesting that extension was related to a change to regional transtension along the plate boundary. The Lewis and Clark Fault Zone acted as an accommodation zone between extension in the Priest River Core Complex (Idaho) and the Flathead Fault on the north side, and extension in the Bitterroot and Anaconda Core Complexes to the south (fig. 27). Large hanging wall basins like the Bitterroot, Big Hole, Flathead, and Deer Lodge Valleys, among others, opened during late Paleogene extension. The total amount of Paleocene extension north and south of the Lewis and Clark Fault Zone is estimated at about 90–100 km (Foster and others, 2007b).

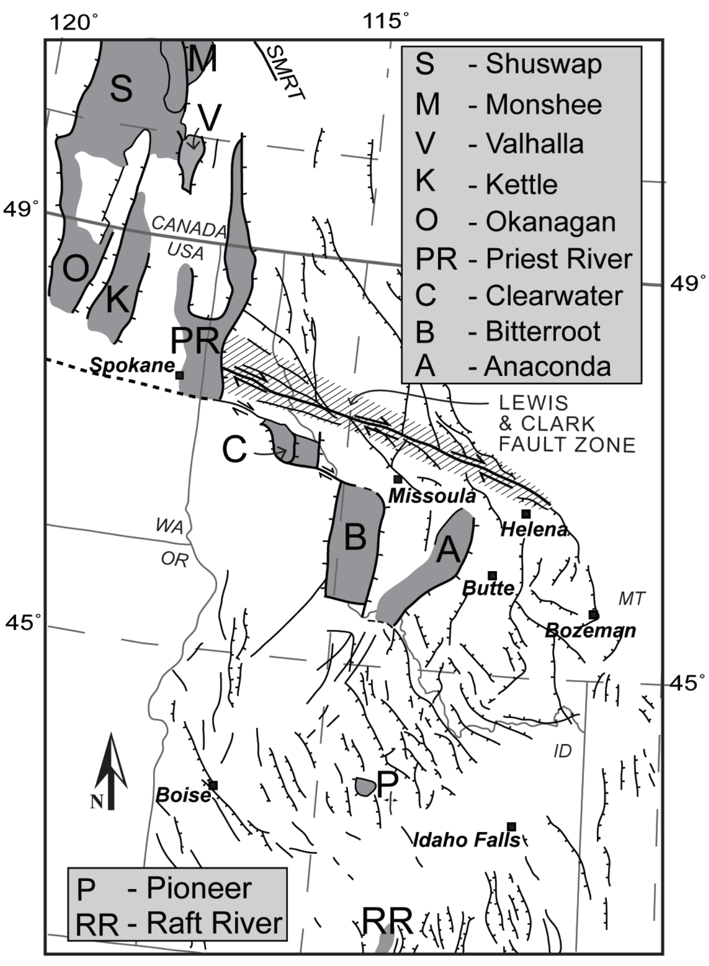

Figure 27. Map showing the distribution of metamorphic core complexes north and south of the Lewis and Clark Fault Zone. From Foster and others (2007, p. 210).

The driving force for dextral transtension within the northern Rockies was most likely generated by plate boundary processes resulting from the northward-moving Kula Plate (or the proposed Resurrection Plate) north of the triple junction between the Farallon and North American Plates (fig. 28), which allowed for collapse of the Cordilleran orogen in the northern Rockies (e.g., Haeussler and others, 2003; Brietsprecher and others, 2003). Very rapid exhumation and voluminous magmatism in a back-arc position are consistent with the region sitting over a slab window (Brietsprecher and others, 2003). The northern side of the triple junction was presumably above a slab of normal dip, whereas shallow subduction of the Farallon Plate persisted to the south through Eocene time (Humpreys, 2009; Foster and others, 2010; Vogl and others, 2012). The relatively rapid switch between shortening and extension could have resulted from accretion of Siletzia (part of the Farallon plate) at the plate margin, and perhaps beneath much of the Columbia Embayment (Humpreys, 2009; Schmandt and Humpreys, 2011; Gao and others, 2011). The accretion of Siletzia, however, did not occur until about 50 Ma (Wells and others, 2014), which was at least 3 million years after the onset of extension and magmatism. Early Eocene crustal extension, along with the Challis–Absaroka–Colville–Kamloops–northern Idaho Batholith–Montana Alkalic Province magmatism at 53–45 Ma (Carlson and others, 1991; O'Brian and others, 1991; Janecke and Snee, 1993; Foster and Fanning, 1997; Morris and others, 2000; Foster and others, 2001, 2007, 2010; House and others, 2002; Feeley and others, 2002; Feeley, 2003; Breitsprecher and others, 2003; Madsen and others, 2006), was therefore the result of asthenospheric upwelling between the subducting slabs, and partial melting of a lithosphere that had been metasomatized by a long history of Mesozoic subduction. Localization of large-scale extension in the Bitterroot, Priest River, and Anaconda Complexes was probably a consequence of these areas being the thickest parts of the orogenic wedge and the areas where significant middle crustal partial melting and pluton intrusion occurred (Foster and others, 2001; Kalakay and others, 2014).

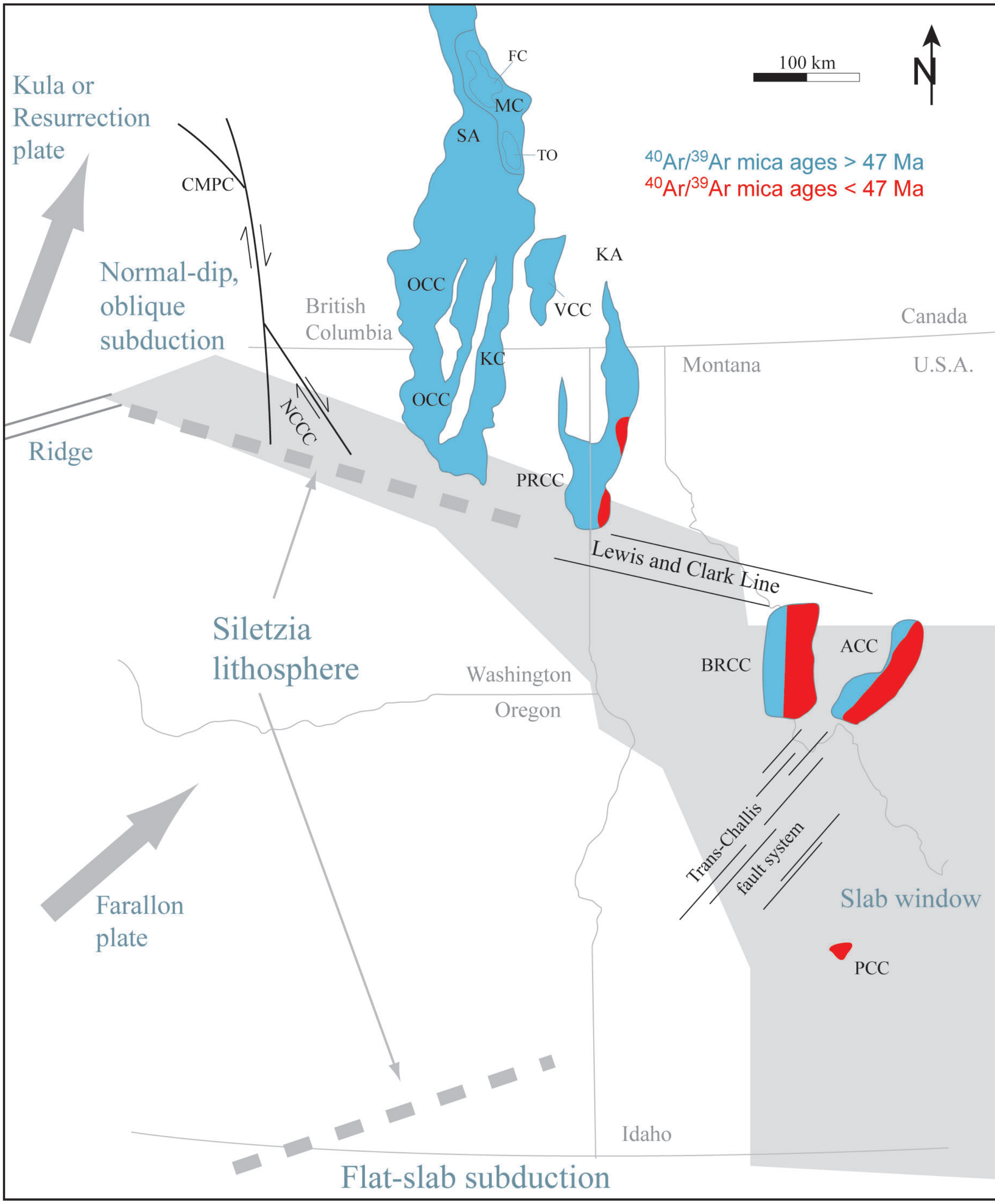

Figure 28. Eocene tectonic setting of western Montana and Idaho relative to oceanic plates and terranes to the west. From Vogl and others (2012, p. 18). ACC, Anaconda Core Complex; BCC, Bitterroot Core Complex; CMPC, Coast Plutonic Complex; FC, Frenchman Cap Dome; KA, Kootenay Arc; KC, Kettle Complex; MC, Monashee Complex; NCCC, North Cascades Crystalline Core; OCC, Okanogan Core Complex; PCC, Pioneer Core Complex; PRCC, Priest River Core Complex; SA, Selkirk Allochthon (lower); TO, Thor-Odin Dome; VCC, Valhalla Core Complex.

DISCUSSION

As emphasized throughout this paper, western Montana is unlike other segments of the eastern Cordillera to the north and south. In Montana, Laramide basement-involved structures "step-down" in structural relief northwards, up to the Canadian border. The three segments of the Sevier fold–thrust belt in northwest, west–central (Helena Embayment), and southwest Montana are quite dissimilar in structural details and reflect varying degrees of basement influence, structural inversion of fault-bound sub-basins of the Mesoproterozoic Belt Basin, and overprinting of Eocene and younger extension. Arguably, one of the biggest differences between the eastern Cordillera to the north and south of Montana is the comingling of arc-derived magmatic rocks with structures of the eastern fold–thrust belt. Throughout most of the eastern Cordillera, there is a clear spatial separation of the Cordilleran magmatic arc to the west and the retro-arc fold–thrust belt to the east. For example, in the California to Wyoming corridor of the Cordillera during Cretaceous time (ca. 160–85 Ma), the Sierran magmatic arc was over 1,000 km west of the evolving Sevier orogenic wedge, separated by two thrust belts in western and central Nevada and a hinterland metamorphic plateau (DeCelles, 2004). In the northern U.S. Rocky Mountains, arc magmatism overprinted this orderly arrangement of tectonic regimes in Idaho, southwestern Montana, west–central Montana, and in the Laramide foreland of south–central and central Montana from the Late Cretaceous to the Paleogene.

During the mid-Cretaceous, an extensive, high-elevation hinterland plateau separated thrust sheets of the Sevier orogen to the east from voluminous arc magmatism in the Sierra Nevada. This plateau has been named "Nevadaplano" by DeCelles (2004) based on tectonic and geomorphic similarities to other high-elevation, convergent orogenic plateaus around the world, such as the Andean Altiplano-Puna and the Tibetan Plateau (Yildirim and Moores, 1999). Although several workers have attempted to reconstruct the elevations across the Nevadaplano during Late Cretaceous to Paleocene time using stable isotope paleoaltimetry calculations (e.g., Chamberlain and others, 2012 and references therein), the results are inconclusive; nevertheless, most workers agree that a high hinterland plateau existed based on geologic evidence. The Nevadaplano was situated in the hinterland of the Sevier fold–thrust belt and was underlain by high-grade (>9 kbar and ~800°C) metamorphic rocks of Jurassic to Paleogene ages (DeCelles, 2004). These high-grade rocks are currently exposed in the detachment footwalls of mid-Cenozoic metamorphic core complexes and are thus strongly overprinted by cooling and mid-Cenozoic exhumation histories (e.g., Miller and Gans, 1989; McGrew and others, 2000). As credited by DeCelles (2004, p. 118), Peter Coney and Tekla Harms (1984) were among the first to interpret this metamorphic region as an "over-thickened tectonic welt" in the hinterland of the Sevier fold–thrust belt, with high-grade metamorphism occurring contemporaneously with thrust shortening farther east. Subsequently, when concepts related to "critical taper" and Coulomb wedge dynamics were applied to studies of convergent orogens (Dahlen, 1990), it became clear that thickened, metamorphic regions in the hinterland (and oft-associated high topography) are dynamically linked to the propagation of foreland fold–thrust belts.

In the northern U.S. Rocky Mountains, arc magmatism within the evolving fold–thrust belt significantly inflated the orogenic wedge during contractile orogenesis. As described earlier, the Upper Cretaceous Boulder Batholith is exposed over 6,000 km^2 and was emplaced in the mid- to upper crust (<20 km) in the hanging wall of the Lombard–Eldorado Thrust system, more than 400 km inboard from the main axis of Cordilleran magmatism (Lageson and others, 2001). Thickness estimates for the batholith vary, but geophysical data suggest a thickness range of 12–18 km (Vejmelek and Smithson, 1995; Burton and others, 1998; Berger and others, 2011). The Elkhorn Mountains Volcanic Field comprises the eruptive carapace of the Boulder Batholith, consisting of a heterogeneous assemblage of volcanic and volcaniclastic rocks that were erupted during the early stages of emplacement of the Boulder Batholith, between 81 and 74 Ma. The Boulder Batholith locally intruded this massive volcanic carapace during its "main phase" of emplacement (~76 Ma), as originally suggested by Warren Hamilton in his classic paper on the nature of batholiths (Hamilton and Myers, 1967). Despite present-day deep erosion, the Elkhorn Mountains Volcanics are thick (3.5–4.6 km), voluminous (1.3 x 105 km^3), and widespread (covering ~26,000 km^2). It has been proposed that the emplacement of >10 km of intrusive rock of the Boulder Batholith, coupled with 5–6 km of cogenetic volcanic rock, created an anomalously high-elevation region within the Sevier fold–thrust belt of western Montana during Campanian–Maastrichtian time (Lageson and others, 1994, 2001). At the same time just to the south, Laramide shortening in the northern Madison Range and adjacent areas was well underway between 79 and 69 Ma, as demonstrated by $^{40}Ar/^{39}Ar$ dating and paleomagnetic analyses of dacite porphyry sills and dikes (Kellogg and Harlan, 2007). This over-thickened, upper crustal assemblage of thrust sheets, magmatic rocks, and Laramide uplifts created a structural-magmatic culmination, similar to the Wasatch and other basement-involved culminations farther south (figs. 29, 30; DeCelles, 2004). In addition, other large intrusive bodies emplaced within the evolving stack of thrust sheets during the Late Cretaceous (e.g., Pioneer Batholith), along with their cogenetic volcanic contributions, created a high-elevation plateau similar to that envisioned for the mid-Cretaceous Nevadaplano. However, quite unlike the Nevada-plano, the Late Cretaceous plateau across the northern U.S. Rocky Mountains spatially overlapped a large part of the Sevier fold–thrust belt east of the hinterland through the introduction of voluminous magmatic rocks well into western Montana (Helena Salient), locally inflating the upper crust by as much as 15–20 km and driving the orogenic wedge into a state of super-critical Coulomb taper (Lageson and others, 2001). In western Montana and adjacent Idaho, the concept of distinct hinterland and foreland regions, with a magmatic arc to the west, falls apart because the magmatic arc invaded the foreland with magmatism essentially to the shores of the Cretaceous Western Interior Seaway. Therefore, we herein define this Late Cretaceous tectono-magmatic plateau across the hinterland and foreland of the northern U.S.Rocky Mountains as the “Montanaplano” (fig. 31), reflecting its eastward extent well into the foreland fold–thrust belt of Montana. Literally translated, Montanaplano means “mountain plain,” which seems appropriate for the tectono-magmatic highland region, or plateau, in western Montana and adjacent Idaho prior to Paleogene extensional dismemberment. Byerly and others (2016) also suggested the existence of an orogenic plateau in Idaho during the Late Cretaceous to help explain the paucity of magmatic and solid-state fabrics within the peraluminous Atlanta lobe of the Idaho Batholith. In their model, the Atlanta lobe was intruded into over-thickened crust (orogenic plateau) characterized by vertical stress gradients, in which innumerable peraluminous sills

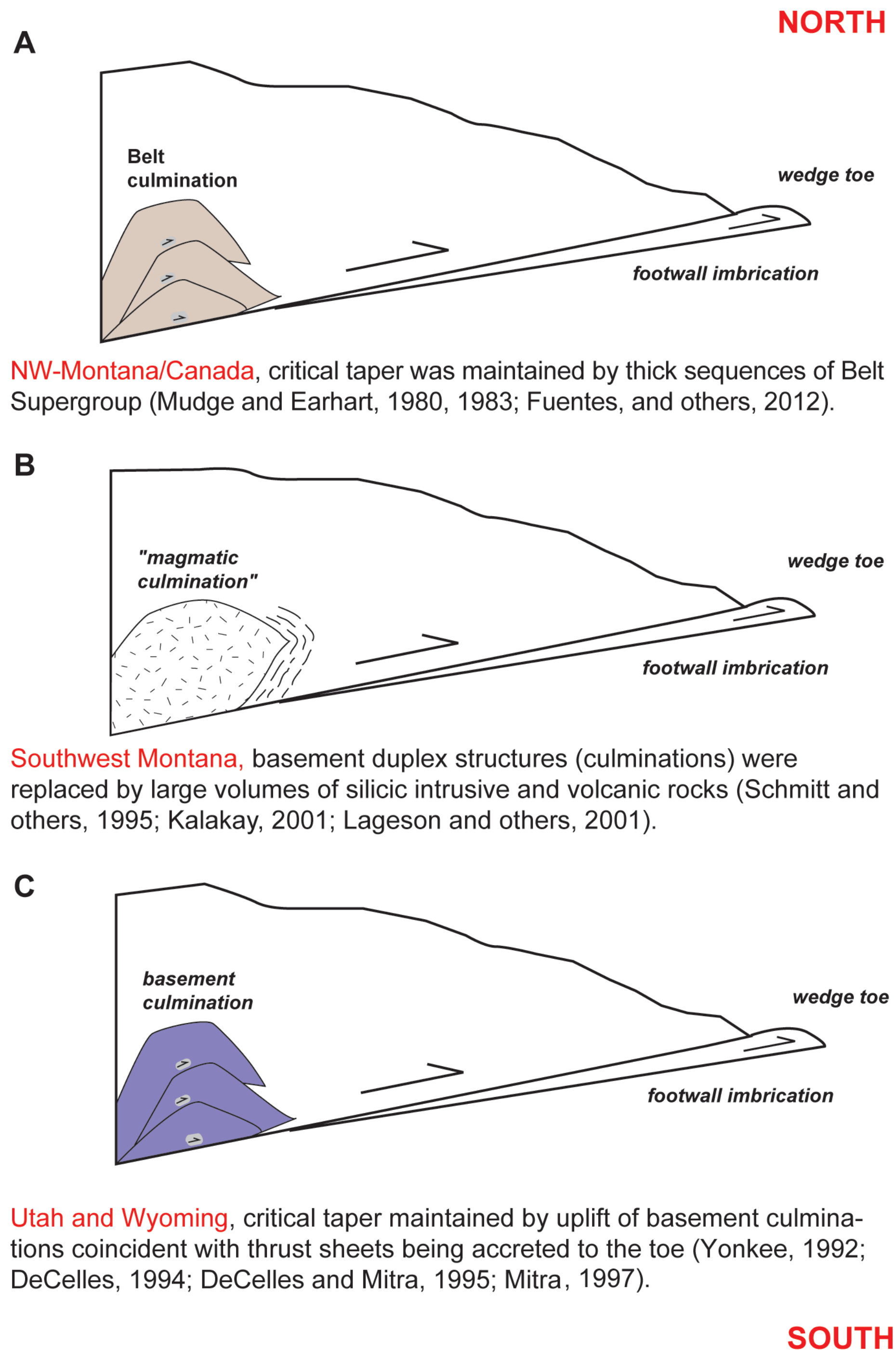

Figure 29. Three types of hinterland culminations involving (A) structural stacking of Belt Supergoup rocks, (B) magmatic inflation, and (C) basement (crustal) culminations. From Kalakay, 2001.

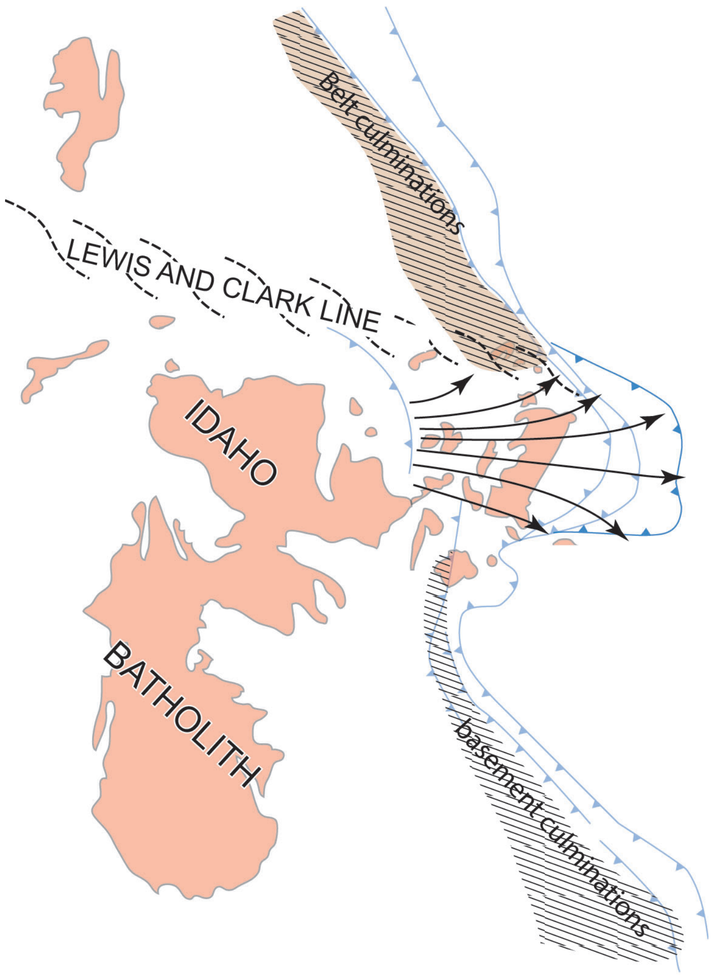

Figure 30. Simplified map showing the “eastward extruding” Bitterroot–Boulder magmatic channel. Bitterroot is the northern lobe of the Idaho Batholith. From Kalakay and others (2004).

were injected into a mid-crustal zone of stress neutrality, thus accounting for the lack of fabrics. A stress regime that promoted extension of the uppermost crust was above the neutral zone, and contraction occurred at depth within the plateau roots (Byerly and others, 2016). Therefore, we define Montanaplano to have spatially encompassed the Sevier orogenic belt across the northern U.S. Rocky Mountains, and specifically formed the tectono-magmatic carapace to the many silicic plutonic centers of western Montana and Idaho.

Just as the Nevadaplano underwent extension and collapse with the cessation of contractile orogenesis, the Montanaplano also collapsed to form several Eocene metamorphic core complexes, as previously described. We propose that the Montanaplano connected topographically to the south with the Nevadaplano, as defined by DeCelles (2004), across a broad, regional upland now partly occupied by the eastern Snake River Plain (fig. 31). The eastern Snake River Plain may have existed long before the track of the Yellowstone hotspot, serving as a cross-strike structural discontinuity during Sevier thrusting and as a transverse drainage system for Upper Cretaceous and Paleocene conglomerates transported eastward from the western hinterland (e.g., Lageson, 1998; Lageson and others, 1999; Lageson and Christiansen, 2002), although this is beyond the scope of this paper.

Pluton emplacement within convergent tectonic settings has been a fertile topic for research for many years. In the absence of *in situ* melting of the upper crust (anatexis), how do large batholiths find space in a crustal environment that is undergoing orogenic contraction/shortening? In any discussion of this topic, it is critical to establish the timing of pluton emplacement relative to thrusting, i.e., determine pre-, syn-, or post-kinematic relationships among plutons and the thrust sheets they intrude. As pointed out earlier, many felsic plutons of Late Cretaceous age are broadly synkinematic with development of the Sevier orogenic wedge in western Montana. Therefore, it has always been a question as to how the “main phase” of the Boulder Batholith found accommodation space during shortening and specifically emplacement of the Eldorado–Lombard thrust system (fig. 21; e.g., Schmidt and others, 1990; Kalakay and others, 1998, 2001). Underscoring this point is the fact that, although the Boulder Batholith includes at least 15 distinct plutons, emplacement of roughly 90% of the exposed batholith occurred at ~76 Ma, and is composed of the Butte Granite (Lund and others, 2002). Given the dimensions of the Boulder Batholith, it is difficult to reconcile a felsic plutonic mass this large being “squeezed” into an actively forming fold–thrust belt. Many investigators over the years have tried to construct models that explain the intrusion of the Boulder Batholith into the evolving fold–thrust belt based on geological and geophysical data (e.g., Tilling and others, 1968; Hamilton and Meyers, 1974; Hyndman and Chase, 1979; Lageson and others, 1994; Vejmelek and Smithson, 1995; Burton and others, 1998; Kalakay and others, 2001; Berger and others, 2011; Sears, 2016). For example, the rhombic shape of the Boulder Batholith was used to suggest a “pull-apart” model of emplacement by some workers (Schmidt and others, 1990), a model that has been championed by more recent authors, albeit with significant modification (Berger and others, 2011; Sears, 2016). However, at present, the ramp-top model of emplacement appears to be a geometrically and volumetrically viable solution for reasons explained earlier (see “emplacement model”

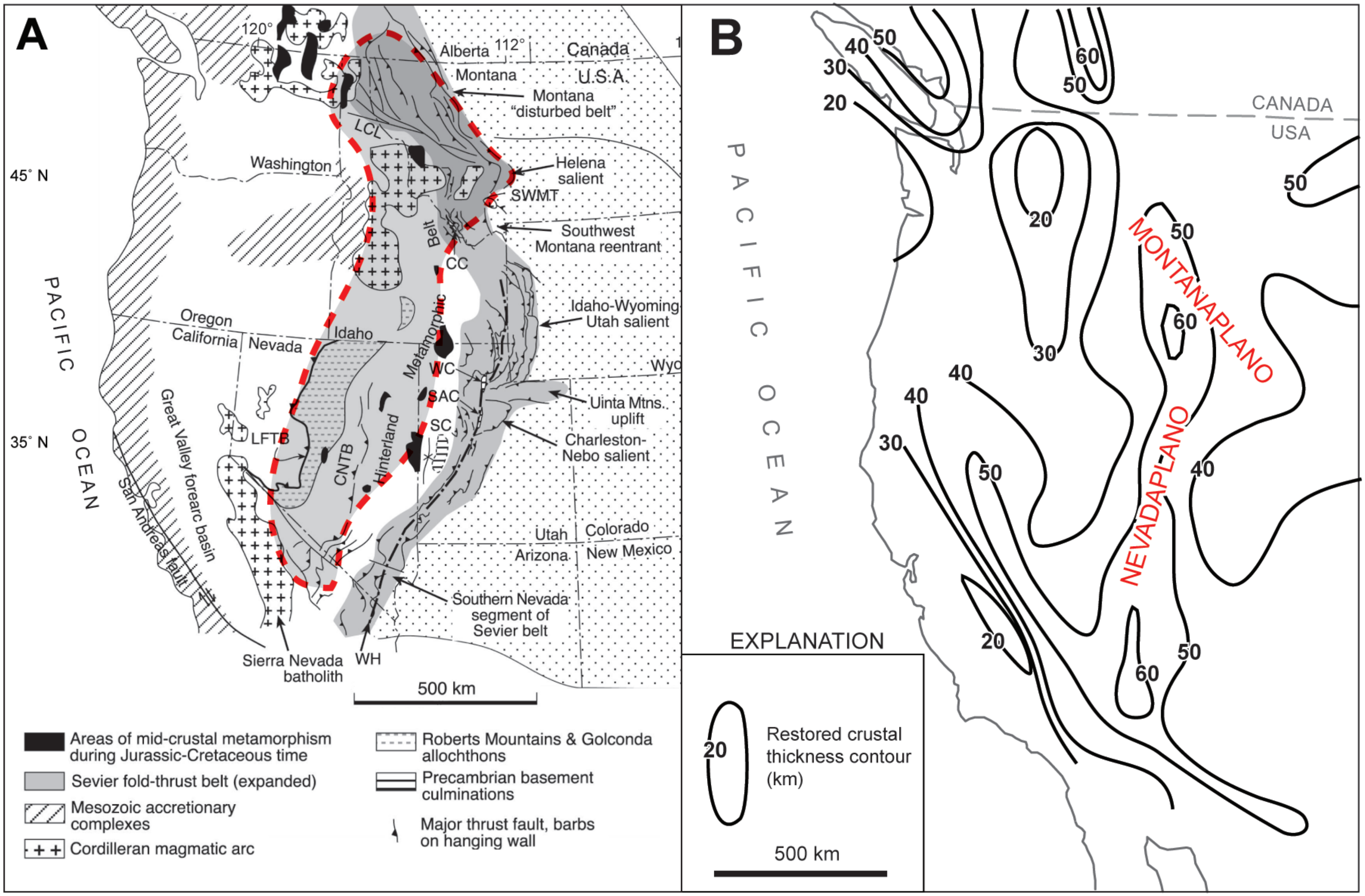

Figure 31. (A) Regional paleogeographic map of the western United States showing the general setting of the Montanaplano highland relative to Nevadaplano to the south. Bold dashed red line represents combined Montanaplano and Nevadaplano. Modified from DeCelles (2004, p. 144). (B) Map of restored crustal thickness showing the Montanaplano and Nevadaplano (From Byerly and others, 2016, p. 284; and Coney and Harms, 1984, p. 553).

in Tectonics of Pluton Emplacement section), but there is a bigger picture that may have bearing on the Montanaplano in general, and emplacement of the Idaho–Boulder Batholith and its satellite plutons in particular. Synconvergent channel flow is a tectono-magmatic model that has evolved from decades of research in the Greater Himalaya, involving the lateral extrusion or flow of mid-crustal rocks and melt towards an orogenic foreland (Godin and others, 2006). Channel flow is a time-dependent, thermo-mechanical process that dynamically couples the metamorphic hinterland to an evolving, shallow fold–thrust belt in the foreland (Godin and others, 2006). More specifically, channel flow is defined as a “viscous fluid-filled channel lying between two rigid sheets” (Godin and others, 2006, p. 2), undergoing flow induced by lateral stress gradients within the channel. Lateral stress gradients can be caused by differential lithostatic loading over broad areas, high rates of erosion along the topographic crest of the orogen (Zeitler and others, 2001), changes in thickness of the orogenic wedge as it adjusts to critical taper conditions through time (Lageson and others, 2001), or some combination of all. The kinematics and dynamics of channel flow are best understood as a hybrid of two end-member vorticity models, Couette flow and Poiseuille flow. Couette flow involves simple shear between moving plates, with uniform vorticity across the width of the channel; in contrast, Poiseuille flow (“pipe flow”) occurs between stationary plates, resulting in opposite senses of shear near the top and base of a channel, with highest flow velocities in the center (Godin and others, 2006). A wide variety of tectonic settings have been studied through geodynamic modeling of channel flow, often leading to a better understanding of orogenic processes through time, or at least opening new doors for further study. Godin and others (2006) and other papers in the volume (Law and others, 2006) provide an overview of the impact that channel flow tectonics has had on our understanding of orogenesis, particularly in convergent orogens.

We propose that emplacement of the Boulder Batholith and its satellite plutons in western Montana was facilitated by a variety of factors, one being synconvergent channel flow. The Boulder Batholith occupies a unique position in western Montana, bound to the north by the sinistral Lewis and Clark Lineament and to the south by the dextral lateral ramp of the Perry Line (southwest Montana Transverse Fault Zone), described earlier. The batholith occupies the position of the Helena Embayment of Mesoproterozoic Belt Basin and as such, its emplacement was influenced by the deep-seated crustal faults that controlled the position of the embayment. The reactivated faults provided a channel for Cretaceous magma emplacement, up-dip to the east. Furthermore, the restored position of the Boulder Batholith places it at the top of a major crustal ramp (Kalakay and others, 2001), reflecting an overall geometric and synkinematic involvement within the evolving Sevier orogen (Eldorado–Lombard thrust system), as well as structural/magmatic inversion of the Belt Embayment to form the Sevier Helena Salient of the fold–thrust belt. There were obviously several tectonic factors, both near-field and far-field, associated with the eastward, diachronous march of magmatism into western and west–central Montana during the Late Cretaceous–Paleogene. However, despite the long geologic history and inherited complexity of the region, we believe that channel flow should also be considered in tectono-magmatic models applied to western Montana. The Boulder Batholith lies within a regional, west-to-east corridor of Cretaceous–Paleogene plutons that spans west–central Montana from the Bitterroot Lobe of the Idaho Batholith on the west, to the Castle Mountains and Crazy Mountains Basin on the east (Bitterroot–Boulder tectono-magmatic channel; fig. 30). Numerous igneous bodies lie between these points, including such notable plutons as the Sapphire, Philipsburg, Mount Powell, Royal, Dodgson Creek, Big Hole Canyon, Moose Creek, Hells Canyon, Rader Creek, 10 N, and Late-K felsic plutons in the Big Belt Mountains. This plutonic corridor, or channel, intruded up-dip to the east in a diachronous manner from deep, mid-crustal structural levels in central Idaho to shallow levels in Phanerozoic rocks of central Montana, drastically altering the rheology of the continental crust in the process (fig. 32). Overall, the magmatic corridor is probably a hybrid between Couette flow (simple shear) and Poiseuille flow (pipe flow), but funneling of magmatism into the eastward-narrowing Helena Salient during thrusting suggests some degree of pipe flow vorticity. Transverse fault zones with opposite shear sense flank the central magmatic channel to the north and south, and the lower channel boundary had thrust-sense along the basal décollement of the fold–thrust belt, climbing upsection to the east along a series of ramps (Burton and others, 1998). The upper boundary of the channel is uncertain, but may be represented by later detachment faults of the Bitterroot and Anaconda Metamorphic Core Complexes (Eocene reactivation), as has

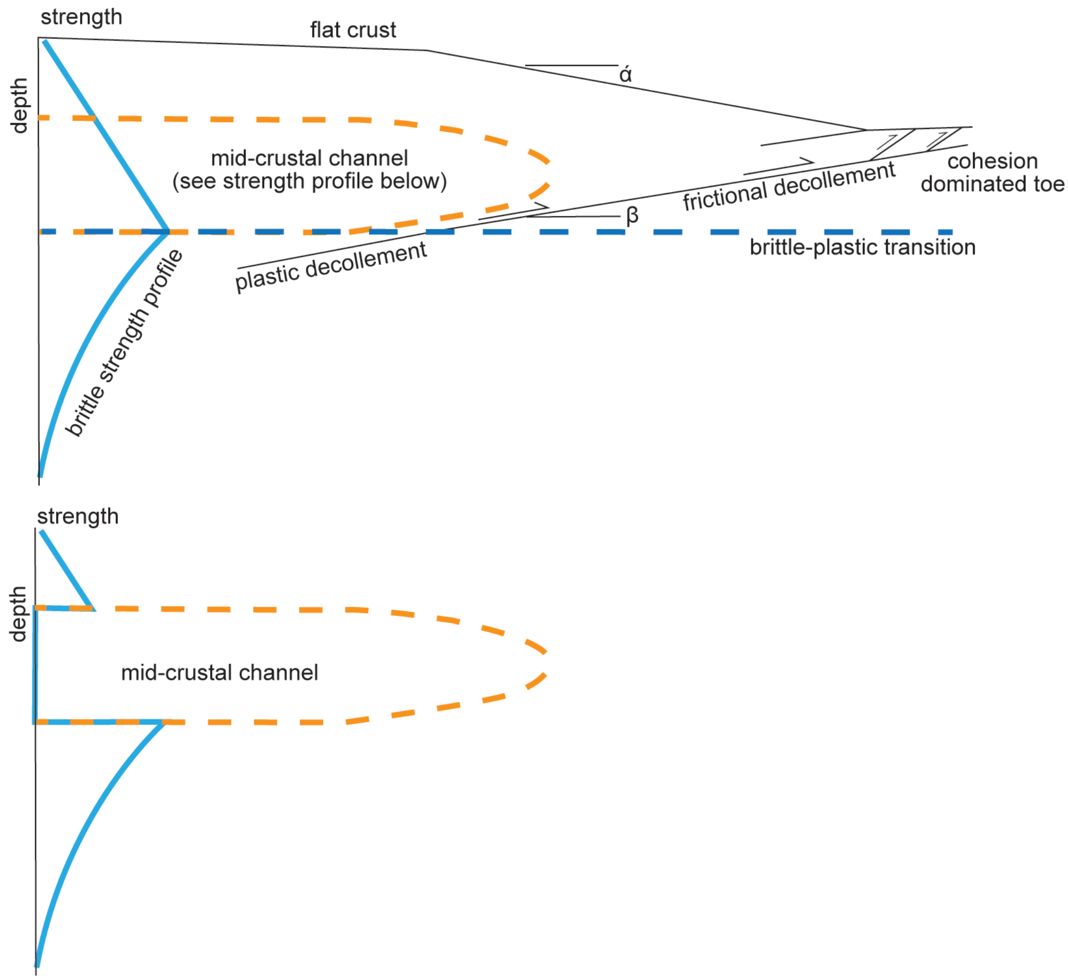

Figure 32. Rheology model of western Montana during the Late Cretaceous showing the influence of a mid-crustal magmatic channel on strength vs. depth of the crust. From Kalakay (2001).

been suggested for the Monashee Core Complex in the southeastern Canadian Cordillera (Gervais and Brown, 2011). Interestingly, channel flow has been invoked for the southeastern Canadian Cordillera by several authors (Brown and Gibson, 2006; Carr and Simony, 2006; Kuiper and others, 2006; Gervais and Brown, 2011), but until now has not been applied to the magmatically inflated thrust belt of western Montana.

The Bitterroot to Boulder tectono-magmatic channel obliquely intersects the Great Falls Tectonic Zone in central Montana, where deep-seated, northeast-trending basement structures related to the Big Sky orogen have further controlled the emplacement and location of Late Cretaceous and early Tertiary igneous rocks (O'Neill and Lopez, 1985, p. 443; Berger and others, 2011; Sears, 2016). Therefore, on a much broader scale of observation, the Bitterroot–Boulder magmatic corridor (Poiseuille channel) may only be a subset of regional channel flow processes that operated, in one form or another, from central Idaho to central Montana and involved several discrete centers of pluton emplacement at successively higher levels to the east through time (Sears, 2016).

In addition to local structural and regional tectonic controls, we propose that climate and erosion during Campanian–Maastrichtian time also influenced intrusion of the Bitterroot–Boulder magmatic channel within the Helena Salient, as proposed for the Himalaya (Zeitler and others, 2001). Global models of atmospheric circulation over the North American Cordillera during the mid- to Late Cretaceous predict a seasonal monsoonal flow path, very similar to the Asian summer monsoon that sweeps northward over the Himalaya and Tibetan Plateau (Poulsen and others, 2007; Fricke and others, 2010; Chamberlain and others, 2012). Based on the paleogeography of western North America at the time, summer moisture in the atmosphere was carried upslope to the northwest from the Cretaceous Western Interior Seaway, first hitting the front of the Sevier orogenic wedge (fig. 33; Yonkee and Weil, 2015). In Montana, this likely resulted in focused precipitation and high exhumation rates of poorly resistant pyroclastic and epiclastic rocks of

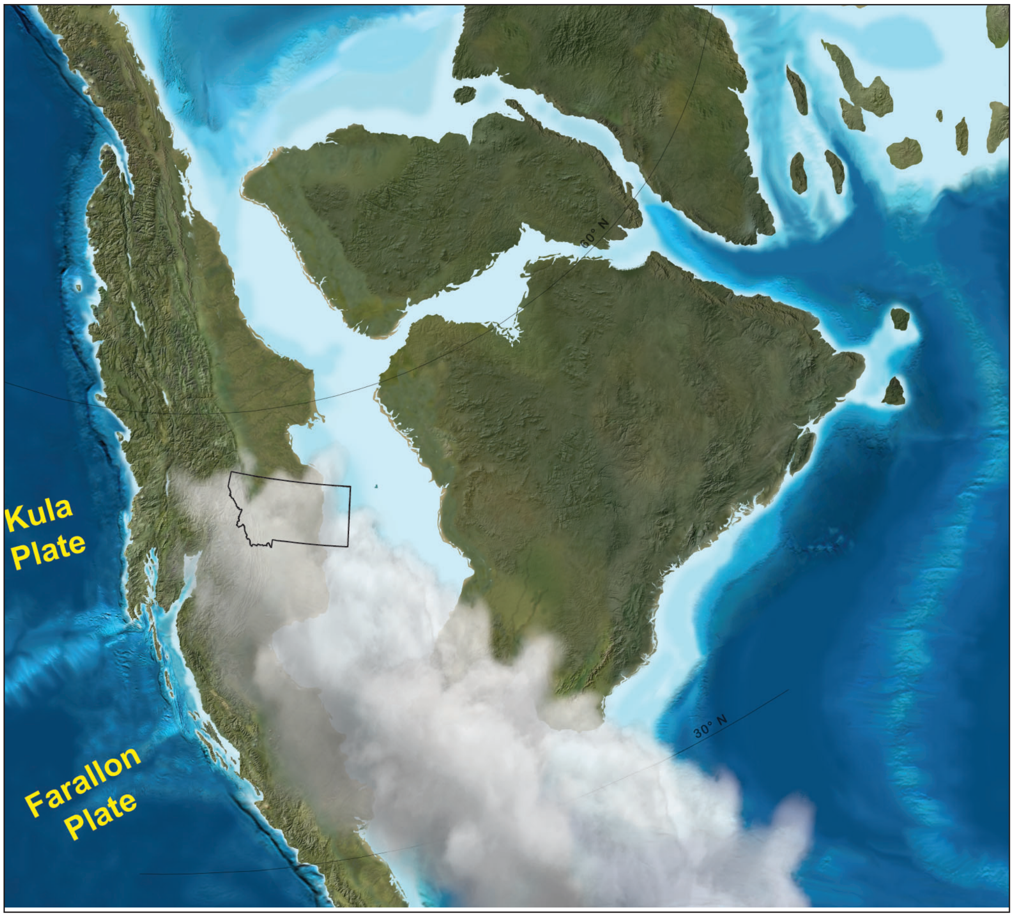

Figure 33. Late Cretaceous North American monsoonal pattern that affected the Sevier orogenic wedge during the main phase of Boulder Batholith emplacement (Mulch and others, 2007; Fricke and others, 2010; Chamberlain and others, 2012). The monsoonal pattern resulted in focused precipitation and high exhumation rates of volcanic rocks across Montanaplano. Paleogeographic map from Blakey, https://deeptimemaps.com, with permission (Blakey, 2016).

the Elkhorn Mountains Volcanic Field on top of the Boulder Batholith, and a nearly continuous delivery of sediment to the foreland basin from Campanian through early Eocene time, ca. 79–54 Ma (Lageson and others, 2001). Over 3 km of Campanian to Paleocene foreland-basin volcaniclastic strata of the Livingston Group and Fort Union Formation accumulated in the western Crazy Mountains Basin depocenter, constituting one of the thickest foreland basin-fill sequences in the western United States (Lageson and others, 2001). In contrast to these studies, Sears (2001) has suggested that regional erosion was steady-state with respect to thrust sheet emplacement in northwest Montana and the southeastern Canadian Cordillera during emplacement of the Lewis–Eldorado–Hoadley thrust slab, with minimal erosional denudation. However, the area studied by Sears (2001) lies north of the Helena Salient and Lewis and Clark Tectonic Zone, and lacks upper-crustal plutons and thick volcanic fields like those found to the south.

It has been proposed that the intrusion of >10 km of intrusive rock with 5–6 km of cogenetic, superjacent volcanic rock to form the Boulder–Elkhorn magmatic system over a relatively short period of time (ca. 79–74 Ma) effectively drove the Sevier orogenic wedge into super-critical taper conditions (Lageson and others, 2001). This pulse of voluminous magmatism, coupled with focused monsoonal exhumation, constituted nothing less than a “tectono-magmatic aneurysm” in western Montana that persisted into Paleocene (Fort Union) time. As originally conceived, the tectonic aneurysm concept was presented to explain uplift and deep erosion in the Nanga Parbat and Namche Barwa recesses at the margins of the Himalayan orogen, and is modeled on processes involving focused erosion, deep exhumation, and diversion of tectonic flow in the lithosphere towards an erosional front (Zeitler and others, 2001). We believe that linkage of the greater Boulder–Elkhorn magmatic system, with seasonal monsoonal precipitation/erosion and delivery of voluminous sediment to the Livingston/Fort Union depocenter to the east, constitutes a “tectono-magmatic aneurysm” in the Sevier orogen of western Montana. However, we do not necessarily invoke climate as the predominant driver in this system, but instead appeal to an interplay of structural/tectonic, magmatic, climatic, erosional, and paleogeographic factors that may have had varying degrees of importance through Late Cretaceous–Paleogene time.

In conclusion, there were undoubtedly several direct and indirect linkages among the various tectonic elements in western Montana throughout the ~90 Ma history of Cretaceous–Paleogene orogenic contraction and collapse. These include development of a high-elevation hinterland plateau (Montanaplano), focused magmatic channel flow into the Helena Salient, structural inversion along old faults and thrust ramps, super-critical wedge thickening and thinning, and monsoonal climate patterns coupled with deep erosion of volcanic fields; all of these combined to control the emplacement of plutons within the evolving Sevier orogen of western Montana during Late Cretaceous–Paleocene time. As suggested in recent studies of Himalayan mid- and upper crustal deformation, concepts of synkinematic channel flow and critical thrust-wedge taper are not mutually exclusive (Cottle and others, 2015). The presence of "tectonometamorphic discontinuities" in the mid-crust of the Greater Himalaya reflects boundaries of domains in which channel flow and thrust-wedge behavior have occurred simultaneously and, furthermore, the "system may migrate back and forth between these types of behavior" (Cottle and others, 2015). Perhaps the only single factor that may be considered a "constant" in the complex equation of mountain building in Montana during the Late Cretaceous–Paleogene was regional contractile deformation, driven by lithospheric compression resulting from high convergence rates and flat-slab subduction, until about 52 Ma when the regional stress field across the northern U.S. Rocky Mountains reorganized and orogenic collapse began. As summarized by Yonkee and Weil (2015), the ensuing orogenic collapse during the Eocene may have been a combination of: (1) decreased convergence rates, (2) outboard-stepping of the plate margin due to terrane accretion in the Columbia embayment, (3) rollback of the Farallon Plate, and (4) creation of a slab window and decoupling of the Farallon Plate from the base of North America lithosphere. By mid-Eocene time, when volcanism and core-complex formation dominated the geologic landscape, the regional stress field in western Montana had reorganized with $\sigma 1$ (principal compressive stress) rotating about 90° to a north–south orientation. The Rocky Mountains of Montana were now born, awaiting further modification during the Neogene!

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