# THE EOCENE THROUGH EARLY MIOCENE SEDIMENTARY RECORD IN WESTERN MONTANA

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## ABSTRACT

The unconformity-bounded late early Eocene to early Miocene lower Bozeman Group (Renova Formation and equivalents) is primarily preserved in western Montana erosional and extensional terrestrial basins. Proximal volcanism and initial core complex exhumation were coeval with the late early Eocene onset of extension, and deposition of the oldest lower Bozeman Group rocks. Subsequently, distal volcanism contributed abundant ash to the basins. Fine-grained deposits dominated, with subordinate coarse-grained fluvial and basin-margin deposits. Fluvial clast composition documents exposure of Laramide uplift basement cores and specific batholiths and plutons during lower Bozeman Group deposition.

The lithologic variability across the basins led some to adopt a sequence stratigraphic approach to Bozeman Group stratigraphy. Generally, however, the Renova Formation is considered the dominant lithostratigraphic unit of the lower Bozeman Group, although its extent and lower contact have not been applied consistently. Renova Formation age equivalents occur in northwestern Montana, in bordering Alberta and Saskatchewan, and in southeastern Montana.

The initiation of Basin and Range extension produced a widespread unconformity at the top of the lower Bozeman Group that separates the Renova Formation and equivalents from the overlying Sixmile Creek Formation of the upper Bozeman Group in much of western Montana. Unconformities within the lower Bozeman Group may reflect augmented relief or the influence of climate such as the global Middle Eocene Climatic Optimum. Locally, paleodrainages may have reorganized as sediment input changed, volcanic eruptions occurred, or structural changes disrupted drainage patterns, but in widespread areas paleodrainage patterns remained consistent.

Ongoing basin analysis projects are evaluating several hypotheses regarding basin formation and development and are refining understanding of sedimentology, depositional environments, paleoclimate, paleotopography, and paleodrainage. Stratigraphic dating has evolved from primarily vertebrate fossil-based methods, supplemented with magnetostratigraphy, to emphasis on radiometric dating, primarily of volcanic ash and detrital zircons. This has led to better constraints on depositional ages of units, and more refined evaluation of provenance.

## INTRODUCTION

The lower Bozeman Group deposits discussed in this chapter represent the transition between the cessation of Laramide-Sevier contraction (late Paleocene-earliest Eocene) and the onset of Basin and Range extension in western Montana (early Miocene). Despite its importance, this part of the stratigraphic section received little attention until the late 1950s through the 1970s when most studies emphasized vertebrate paleontology. Formal stratigraphic names are sparse, whereas informal names that reflect various approaches to stratigraphy abound. Interpretations of depositional and tectonic settings have been inconsistent, but recent work on these deposits has added new sedimentologic, magnetostratigraphic, thermochronologic, detrital zircon, and radiometric data, leading to refined interpretations of stratigraphic correlation, tectonism, landscape evolution, and climate. The various approaches and interpretations for this part of the stratigraphic section in western Montana are reviewed in this chapter. Coeval deposits that occur as isolated remnants in the southeastern part of Montana and in southern Alberta and Saskatchewan are also discussed.

Most of the original age assignments for the lower Bozeman Group (fig. 1) were based on vertebrate paleontology. Revisions to Paleogene geochronology and biochronology (Prothero and Swisher, 1992; Woodburne and Swisher, 1995; Prothero and Emry, 2004; Tedford and others, 2004) changed the position of the Paleogene-Neogene and the Eocene-Oligocene boundaries from their previous placement by Wood and others (1941). This paper uses the updated chronostratigraphy even when citing literature that pre-dates the change. The paper is intended to serve as an overview of various observations and interpretations.

## STRATIGRAPHY

The lower Bozeman Group (fig. 1) discussed in this chapter refers to a part of the early Eocene to early Miocene section in western Montana that is bounded by two significant, regional unconformities, and is generally referred to as the Renova Formation and equivalents (fig. 1), or as Sequences 1, 2, and 3 (fig. 2). Robinson (1963) was the first to apply the formal stratigraphic name *Bozeman Group* to Paleogene and Neogene post-Laramide deposits of western Montana. Fields and others (1985) originally placed the oldest Bozeman Group deposits as coeval with early Eocene extensional volcanism. However, an addendum at the end of the report (Fields and others, 1985) modified the basal Bozeman Group to a younger position that excluded deposits genetically related to the initial early Eocene extensional volcanism. Hanneman and Wideman (1991) indicated that early Eocene extensional volcanic rock (e.g., Lowland Creek and Challis; see Mosolf and others, 2020) and associated sedimentary deposits should be considered part of the Bozeman Group, as originally designated. Based on Robinson's (1963) designation of the Bozeman Group as "post-Laramide," Rasmussen (2003) agreed that it should include volcanic rock from the initial early Eocene extension and noted that it should also include the Absaroka Supergroup volcanic rocks. Fritz and others (2007), on the other hand, indicated that the area where Renova Formation occurs is geographically bordered by the Eocene Challis, Lowland Creek, and Absaroka volcanic fields, and thus does not include that volcanic rock, except where it interfingers with basin sediment.

### Lithostratigraphy

Kuenzi and Fields (1971) recognized two unconformity-bounded, "lithologically and homotaxially distinct" sequences within the Bozeman Group. They applied lithostratigraphic terminology to the two sequences, which are separated by a "mid-Tertiary unconformity." They designated the lower sequence *Renova Formation* and the overlying sequence *Sixmile Creek Formation*.

Although many workers make a fine-grained vs. coarse-grained distinction between the Renova and Sixmile Creek Formations, the original definitions of these units were more detailed. Kuenzi and Fields (1971) defined the Renova Formation as rock containing greater than 70 percent terrigenous, very fine-grained sand, and finer sediment, and/or carbonate rock; and less than 30% coarse-grained sediment with conglomerate generally as a relatively minor component. They defined the overlying Sixmile Creek Formation as typically containing fine-grained sand and coarser sediment, characteristically including conglomerate. The names *Renova* and *Sixmile Creek Formations* have been widely used, but are not universally accepted as the best approach for inter- and intra-valley correlation (Hanneman and Wideman, 2016).

In northwestern Montana, the Kishenehn Formation (Daly, 1912) correlates stratigraphically with the Renova Formation (figs. 1, 3). Informal names (informal unit designations start with lowercase letter) were applied to other strata of this interval in parts of western Montana such as *Medicine Lodge beds*, *Sage Creek formation* (Scholten and others, 1955), *Fort Logan formation* (Douglass, 1903; Koerner, 1940), and *Blacktail Deer Creek formation* (Douglass, 1901; Hibbard and Keenmon, 1950). Fields and others (1985) suggested that the designation *Renova Formation* should apply to such informal units. The Renova Formation was not recognized in an interpreted synsedimentary rift zone in southwestern-most Montana (Janecke, 1994; Janecke and Blankenau, 2003), and in the Deer Lodge, Flint Creek, and Divide Basins (Stroup and others, 2008). However, others have applied the name *Renova Formation* in these areas (e.g., Dunlap, 1982; Rasmussen, 1989; Barnosky and others, 2007; Retallack, 2009; Elliott, 2017; Harris and others, 2017). *Renova Formation* has been applied by some workers as far west as the Lemhi Basin in southeastern Idaho (Harris and others, 2017) and the Bitterroot Valley of western Montana (DesOrmeau and others, 2009), and as far northwest as the Ninemile Valley (Hendrix and others, 2014; fig. 3).

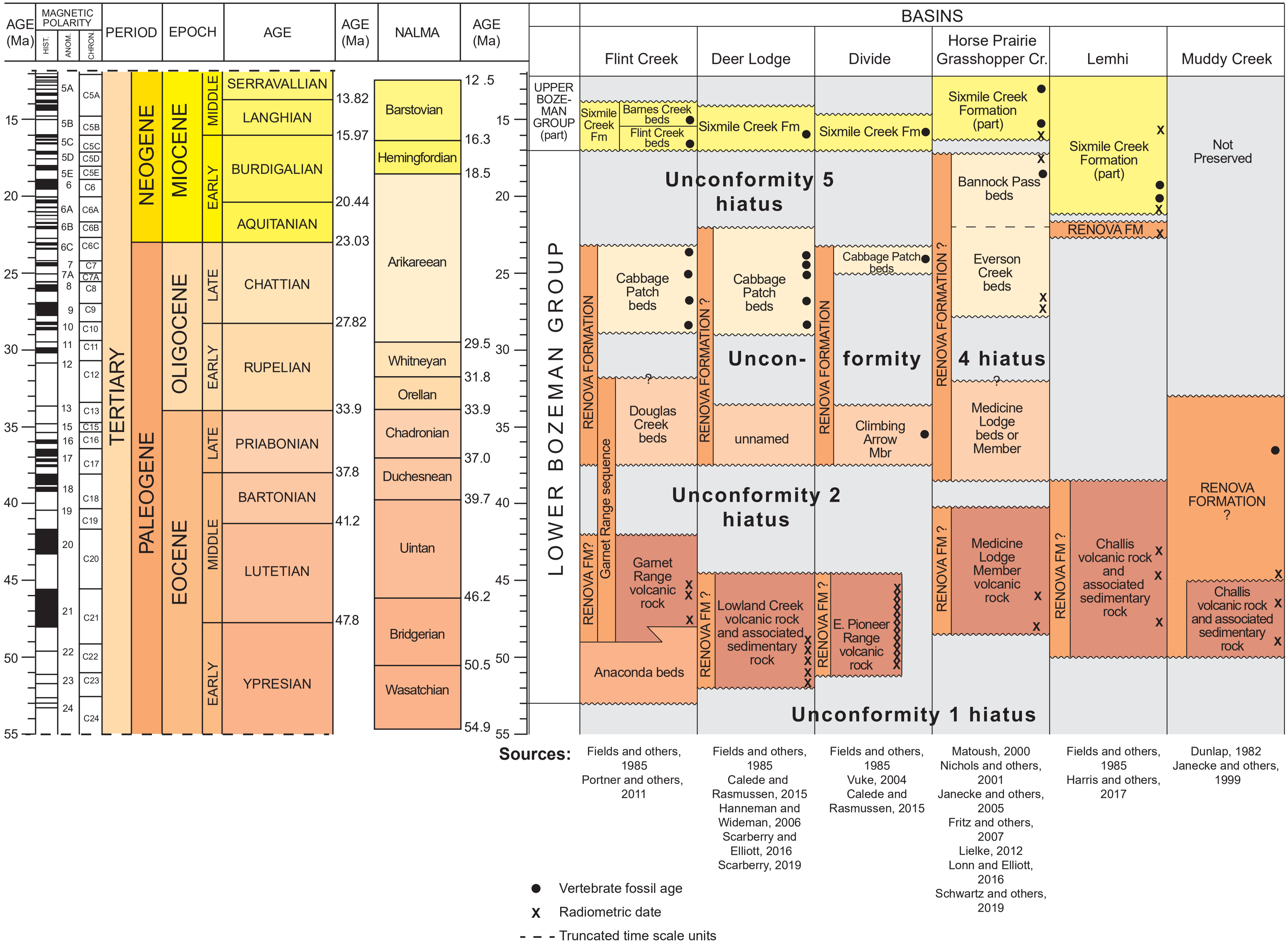



Figure 1. Correlation chart showing lower Bozeman Group units in western Montana valleys; the Cypress Hills Formation of Alberta and Saskatchewan; and the Arikaree, Brule, and Chadron Formations of southeastern Montana. Unconformities discussed in text by number. Time scale from Walker and others (2018). North American Land Mammal Ages (NALMAs) from Barnosky and others (2014).

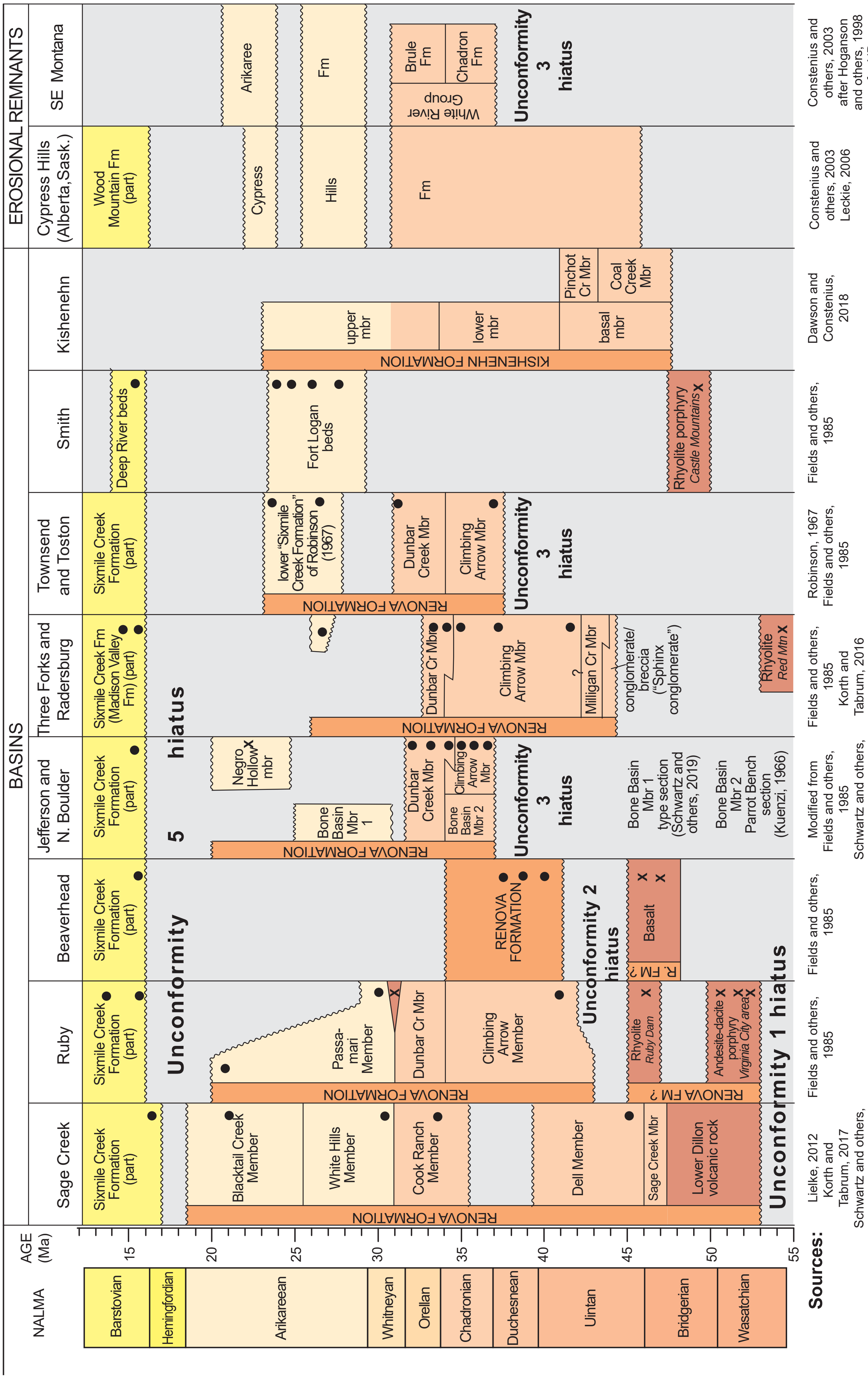



Figure 1. Continued.

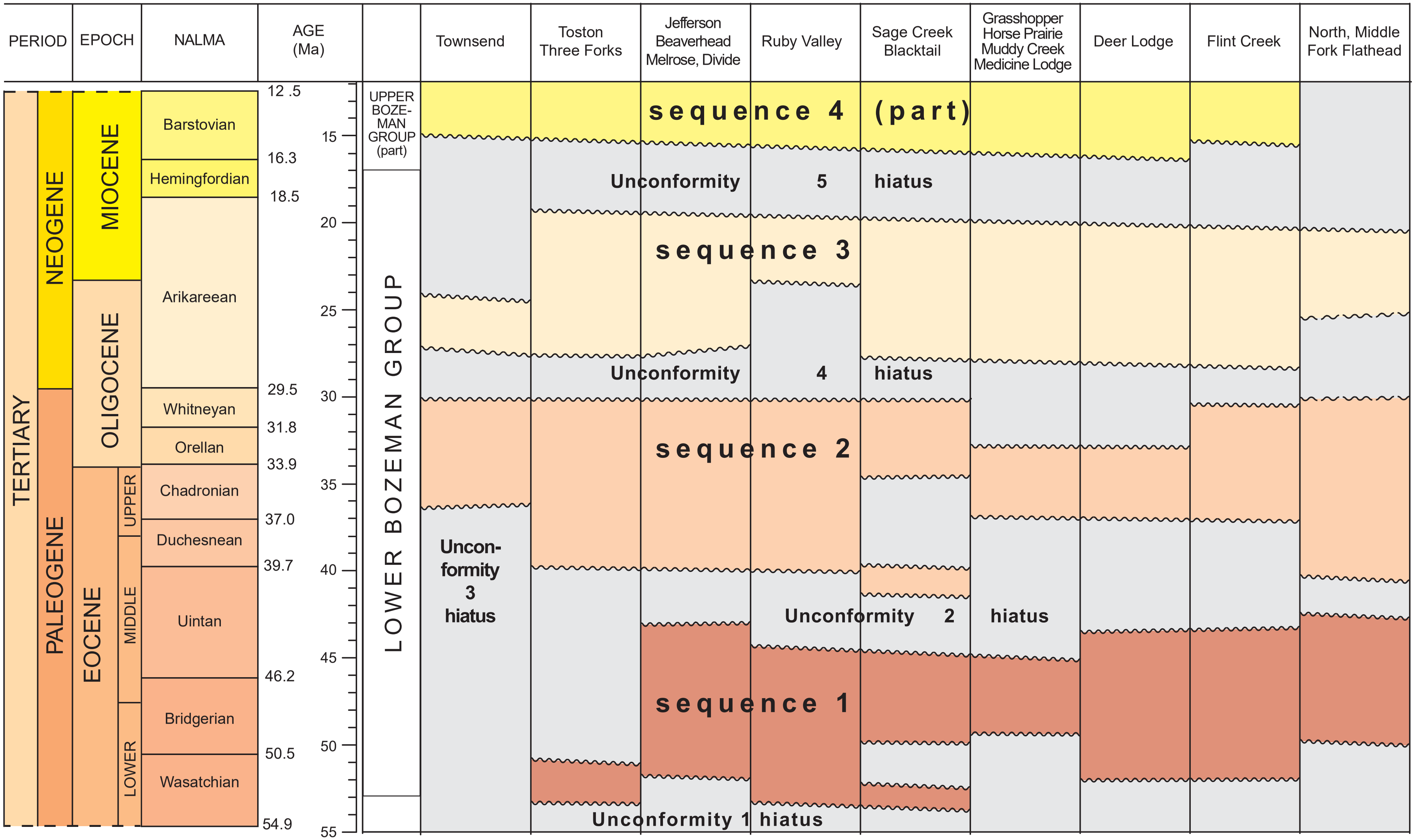



Figure 2. Sequence stratigraphy of lower Bozeman Group (modified from Hanneman and Wideman, 2016). Unconformities discussed in text by number. Time scale from Walker and others (2018). North American Land Mammal Ages (NALMAs) from Barnosky and others (2014).

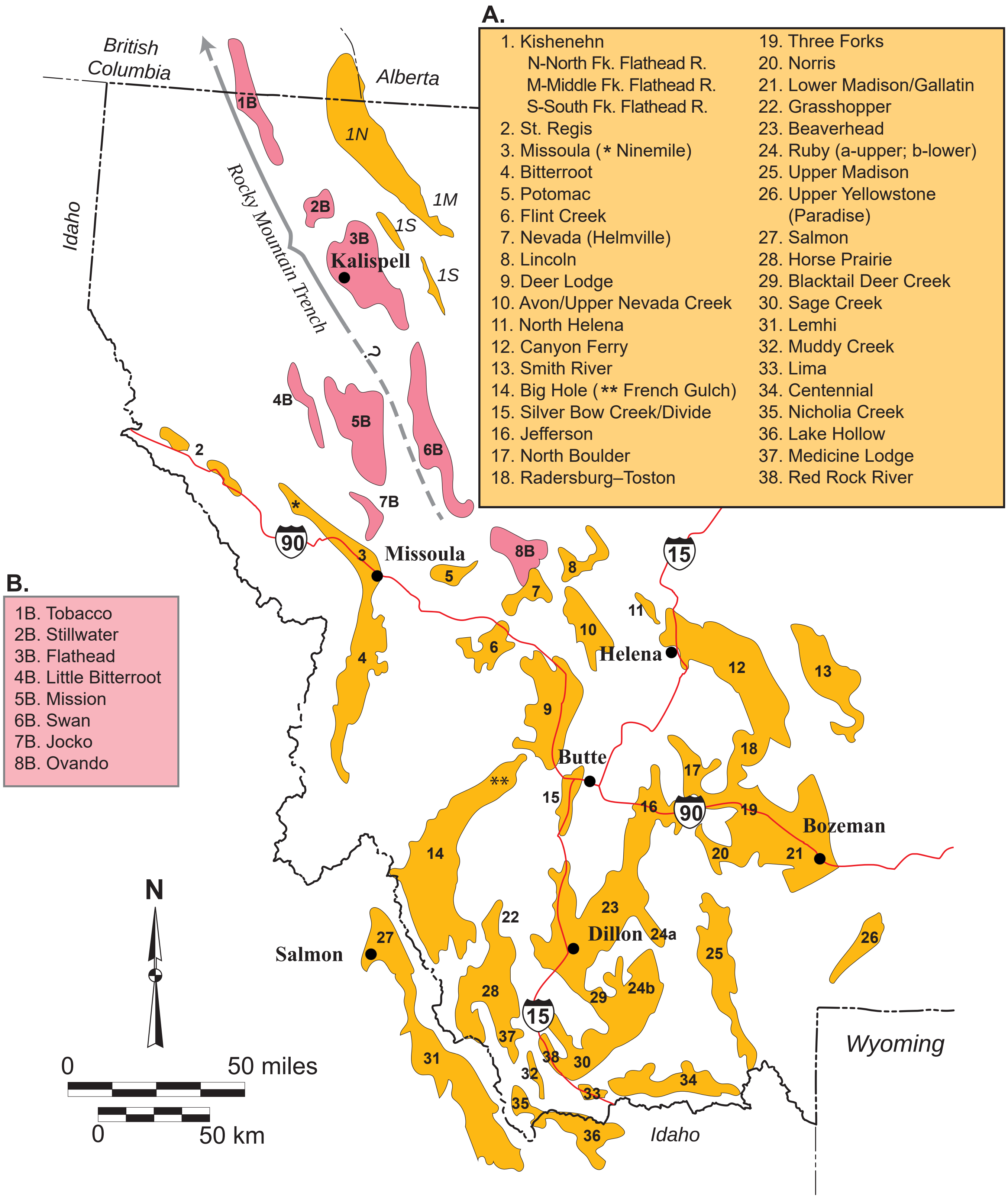



Figure 3. Western Montana valleys: (A) known to contain lower Bozeman Group (early Eocene to early Miocene) deposits, including in Madison Valley subsurface (Rasmussen and Fields, 1985); (B) likely contain subsurface early Eocene to early Miocene deposits.

Kuenzi and Fields (1971) formally designated three members of the Renova Formation in the Jefferson Valley: Dunbar Creek, Bone Basin, and Climbing Arrow Members (figs. 1, 3, 4). The Dunbar Creek and Climbing Arrow Members had previously been designated as formations in the Three Forks area (Robinson, 1963) and were later extended into the Toston area (Robinson, 1967). Fields and others (1985) further confirmed that the lower Renova Formation includes locally derived coarse-grained arkose, conglomerate, and gravel, as well as local interbedded volcanic flows and ash. Monroe (1981) designated the Passamari Member of the Renova Formation in the Ruby River Basin where it overlies the Dunbar Creek Member. Elsewhere, the informal names Cabbage Patch beds (Konizeski and Donohoe, 1958), Negro Hollow beds (Lofgren, 1985), and part of the Medicine Lodge beds (Scholten and others, 1955) were applied to rocks of similar age (late Oligocene to early Miocene) as the Passamari Member based primarily on vertebrate fossils. Enough information was provided on the Cabbage Patch beds for formal designation as a new formation (Rasmussen, 1977), but subsequently, the unit was treated as part of the Renova Formation (Rasmussen, 1989) or "lithologically similar to the Renova Formation" (Rasmussen and Prothero, 2003). Similar to designations of Fritz and others (2007; i.e. Medicine Lodge beds changed to the Medicine Lodge Member of the Renova Formation) in the Sage Creek Basin, the Cabbage Patch beds were mapped as the Cabbage Patch member of the Renova Formation in the Avon and Nevada (Helmville) Valleys (Mosolf and Vuke, 2017; McDonald and Vuke, 2017; fig. 3). The previously designated Medicine Lodge beds and the Cabbage Patch beds are each over 1,000 m thick (Scholten and others, 1955; Loen, 1986).

Certain lithologic characteristics represented in the Renova Formation and equivalents, but not the Sixmile Creek Formation, help distinguish between these units. For example, mollusk-bearing marlstone and siliceous facies, considered diagnostic of the Cabbage Patch beds in the Flint Creek Basin (Portner and others, 2011), are also recognized in the same part of the section in the Avon area (Mosolf and Vuke, 2017). Paper shale, including oil shale, or otherwise thinly laminated silt, mud, and clay—especially with rich plant, insect and/or mollusk remains (Dorr and Wheeler, 1964; Becker, 1973; Miller, 1980; Dunlap, 1982; Constenius and Dyni, 1983; Monroe, 1981; Rasmussen, 1977, 1989; Pierce, 1993; Ripley, 1995; Pierce and Constenius, 2001; CoBabe and others 2002; Rasmussen and Prothero, 2003)—are Renova or Renova-equivalent lithologies, not those of Sixmile Creek Formation. Insects are remarkably preserved in some areas such as the Kishenehn Basin, where many insect fossils, including an Eocene blood-engorged mosquito, were found (Briggs, 2013; Greenwalt and Labandeira, 2013; Greenwalt and others, 2013). Insects have not been found in the Sixmile Creek Formation. Diatomite and diatomaceous beds have been described in Renova deposits (Monroe, 1981; Ripley, 1987, 1995; Vuke, 2003; Rasmussen and Prothero, 2003; Vuke, 2004; Pierson and Schwartz, 2005), but also not in Sixmile Creek Formation deposits. Coal and lignitic beds in many valleys such as Bitterroot, Missoula, Flint Creek, Deer Lodge, Avon (Pardee, 1911), Toston (Robinson, 1967), Medicine Lodge (Dyni and Schell, 1982; Fritz and others, 2007), Kishenehn (Constenius and Dyni, 1983), and Ninemile (Hendrix and others, 2014) are Renova, Renova-equivalent deposits (fig. 1), or deposits beneath Eocene volcanic rock.

The Eocene Climbing Arrow Member throughout its extent in southwestern and west-central Montana is perhaps the most recognizable stratigraphic unit in the Renova Formation based on lithologic characteristics such as its degree of "popcorn weathering" (owing to swelling clay content), local, thin, organic-rich shale, coarse channel sandstone and conglomerate with rounded pebbles, local distinct olive-green or gray-brown color, and distinct topographic expression (e.g., Robinson, 1963, 1967; Kuenzi and Fields, 1971; Petkewich, 1972; Fritz and others, 2007). The mostly age-equivalent Chadron Formation of northwestern South Dakota, thin remnants of which occur in southeastern Montana (fig. 1), is described as bentonitic claystones that weather into characteristic "haystack hill" topography with a "popcorn" surface weathering texture (Lillegraven, 1970). This description was noted as "identical" to that of the Chadron Formation of the Big Badlands of central South Dakota (Lillegraven, 1970), and is also an apt brief description for distinct characteristics of parts of the Climbing Arrow Member of western Montana (figs. 4, 5).

Although the lithologies described above are characteristic of the Renova Formation and equivalents, in some areas where they are lacking it can be difficult to distinguish Renova Formation from Sixmile Creek Formation on the basis of lithologic characteristics without the benefit of age control, especially along basin margins or in fluvial deposits where exposures are limited. Notably, the original type section of the Sixmile Creek Formation in the Toston area (Robinson, 1967) was later shown to contain late Oligocene or earliest Miocene fossils in its lower part that are older than the defining early Miocene unconformity that separates the Renova from the Sixmile Creek Formations. No other dating methods have been applied to determine if the fossils were reworked into younger basin-margin debris flow deposits. Regardless, Kuenzi

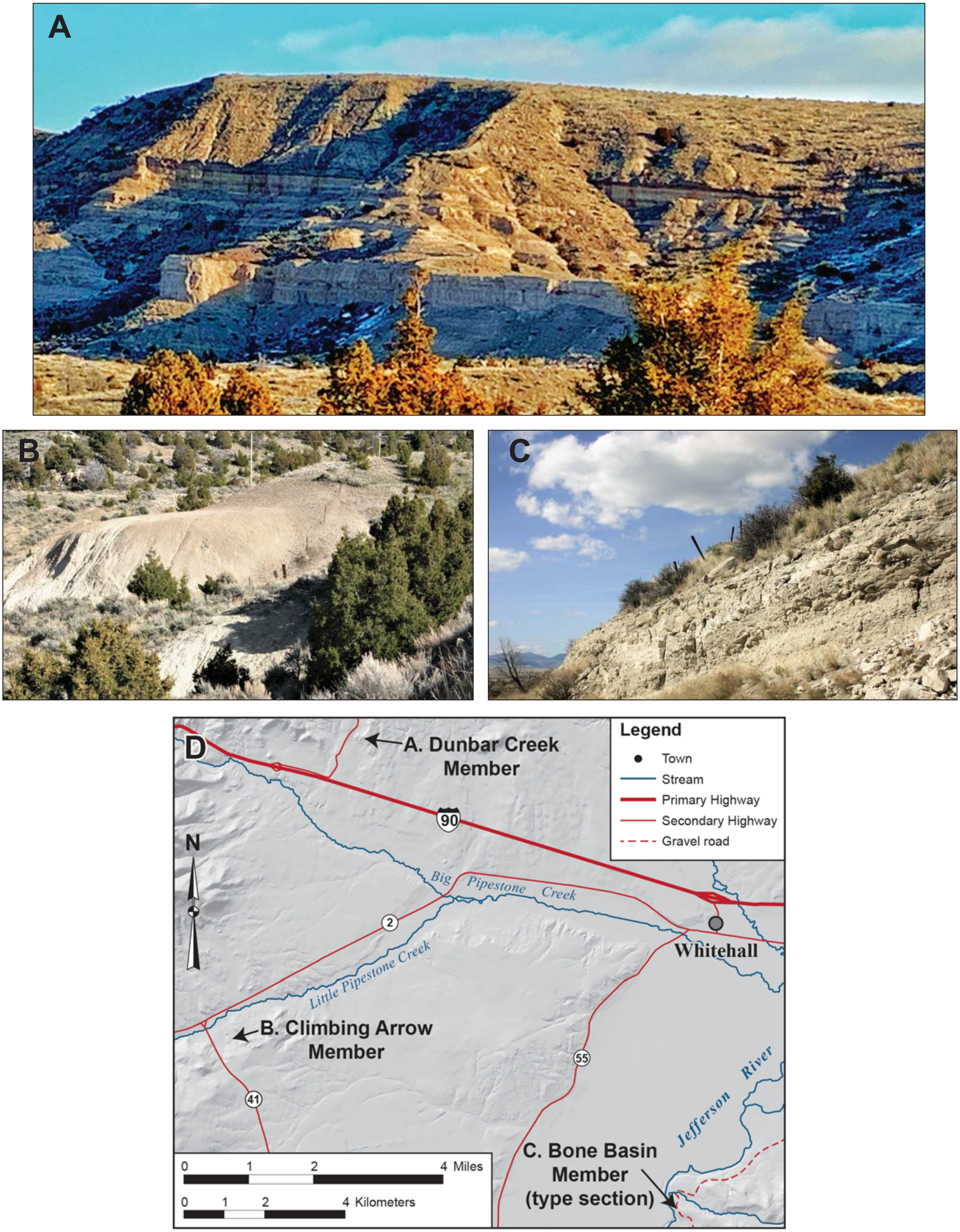



Figure 4. Members of Renova Formation designated by Kuenzi and Fields (1971) in the Jefferson Valley. (A) Dunbar Creek Member; (B) Climbing Arrow Member; (C) Bone Basin Member; (D) photo locations.

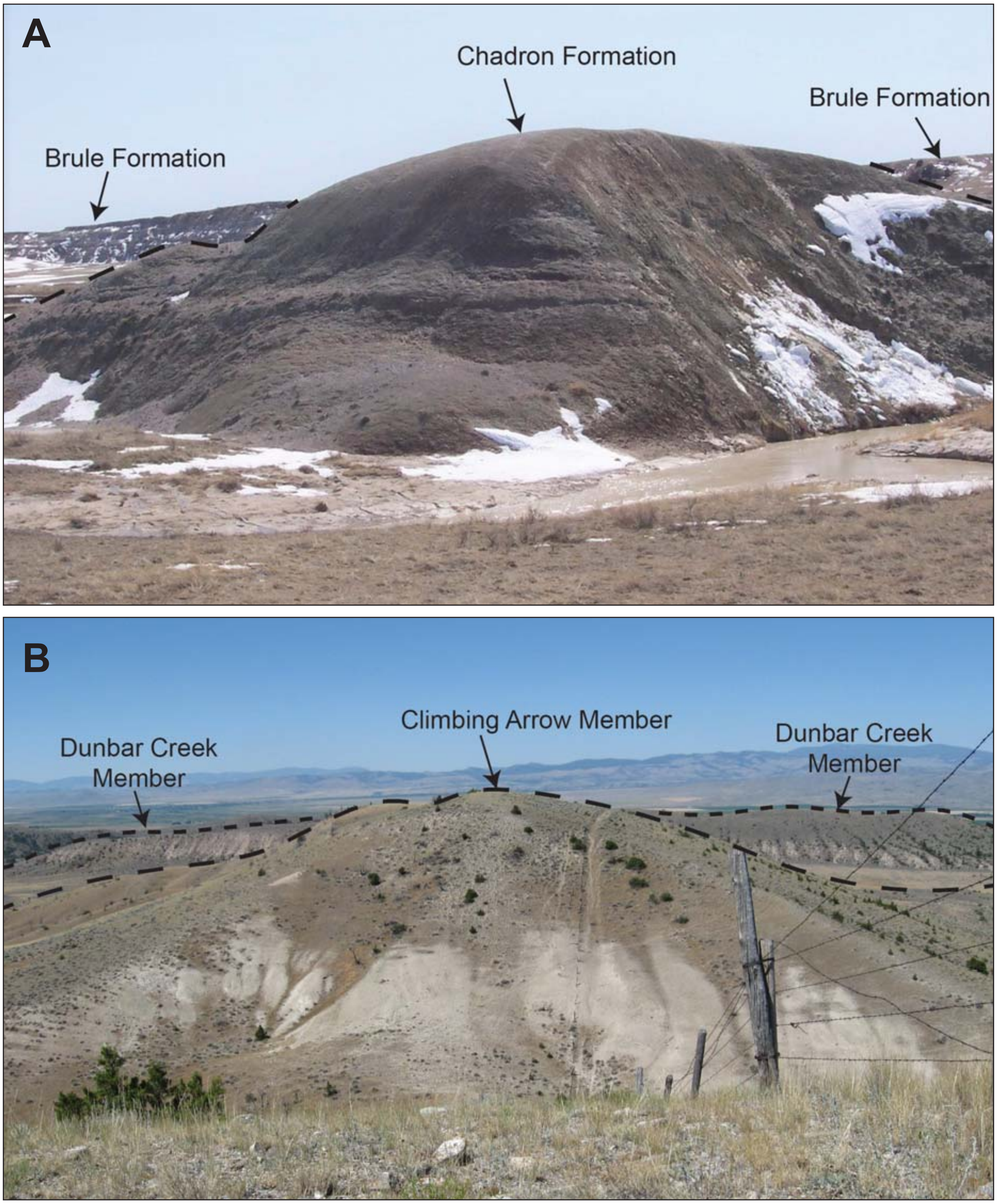



Figure 5. (A) Chadron Formation (Chadronian) in foreground, Brule Formation (Orellan) in background at Badlands National Park in South Dakota (National Park Service photo). (B) Climbing Arrow Member of Renova Formation (Chadronian) in foreground, Dunbar Creek Member of Renova Formation (Orellan) in background near Toston, Montana.

and Fields (1971) redefined the Sixmile Creek Formation as restricted to above the "mid-Tertiary unconformity," although according to The Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1961) they should have formally abandoned and replaced the name Sixmile Creek (Tabrum, oral commun., 2002). However, the redefined name Sixmile Creek is now ingrained in the literature and widely used.

## Sequence Stratigraphy

Hanneman and Wideman (1991) proposed a simplification of stratigraphic complexities and inconsistencies by using a sequence stratigraphic approach. They called attention to the difficulty of distinguishing between Renova and Sixmile Creek Formations on the basis of lithology, particularly because fine- and coarse-grained deposits occur in both formations and because of lateral and vertical variability. Their sequence-stratigraphic approach grouped relatively conformable strata into rock units bounded by significant unconformities, and it used numbered sequences in place of the numerous formal and informal formation/member names (fig. 2). They recognized calcic pedocomplexes (Hanneman and Wideman, 2006)—many of which had previously been interpreted as lacustrine deposits—at sequence boundaries in southwestern Montana valleys. They also documented that the pedocomplexes can be traced into the subsurface, providing a means of correlating outcrops with subsurface seismic data (Hanneman and others, 1994). They further noted the difficulty in making regional correlations based on lithostratigraphy, because Cenozoic deposits do not crop out extensively, making unit-by-unit correlation difficult or impossible. In addition, local variations in composition and clast size can complicate correlations based on lithostratigraphy (Hanneman and others, 2003). The sequences they defined are bounded by unconformities at basin margins, but by correlative conformities at basin centers (Hanneman and Wideman, 2010).

The designated sequences (Hanneman and Wideman, 1991, 2017; fig. 2) temporally correlate remarkably well with those identified independently in central Washington (Cheney, 1994) and are similar to those in the Great Plains (Hanneman and others, 2003), suggesting allocyclic controls on regional depositional patterns (Schwartz and Schwartz, 2013). However, not all of the sequence-bounding unconformities were recognized in the Sage Creek Basin (Kent-Corson and others, 2006; Methner and others, 2016; Schwartz and Graham, 2017), the Muddy Creek Basin (Schwartz and others, 2019a), and the Lemhi Basin (Harris and others, 2017; fig. 1).

Sequence 1, the lowest sequence of the Bozeman Group (Hanneman and Wideman, 1991), includes volcanic (figs. 2, 6) and sedimentary deposits from the initial early and middle Eocene stage of extension. It is not present in every basin. Sequences 2 and 3 are generally equivalent to all or part of the Renova Formation and equivalents depending on how low in the section the name is applied by different workers. Sequence 4 is generally equivalent to the Sixmile Creek Formation.

### Chronostratigraphy and Geochronology

Despite potential drawbacks, vertebrate paleontology correlated with North American Land Mammal Ages (NALMAs, fig. 1) has historically been the most employed method of dating the lower Bozeman Group. The NALMAs for deposits discussed in this chapter from oldest to youngest are Bridgerian, Uintan, Duchesnian, and Chadronian (Eocene); Orellan and Whitneyan (Oligocene); Arikareean (Oligocene and Miocene); and Hemingfordian (Miocene), which range from 50.5 Ma to 16.3 Ma (fig. 1).

Fossil reworking into younger units (e.g., Lofgren and others, 1990) is one possible problem with using fossil data to assign ages. Provincialism and endemism of local faunas can also make correlations with NALMAs challenging, so confirmation of biostratigraphy with paleomagnetic and geochronologic analyses has been desirable (Tabrum and others, 1996). Magnetostratigraphy has refined the ages of fossil mammal assemblages across the Eocene–Oligocene transition in the Jefferson, Beaverhead, and Sage Creek Basins of southwestern Montana (Tabrum and others, 1996). It was also employed to refine ages of fossil mammals across the Oligocene–Miocene transition in the Flint Creek and Deer Lodge Basins, although with less certainty, because many short episodes of normal and reversed polarity are present in the late Oligocene and early Miocene magnetic time scale (Rasmussen and Prothero, 2003).

Recent chronostratigraphic dating has contested, refined, or corroborated the older biostratigraphic and magnetostratigraphic data. For example, significant discrepancies were found between a radiometrically calibrated age model (Harris and others, 2017) and Miocene ages previously interpreted from magnetostratigraphy and biostratigraphy (Barnosky and others, 2007) in the Lemhi Basin (fig. 1). The newer research suggests that radiometric calibration could significantly refine the magnetostratigraphic and biostratigraphic age interpretations elsewhere (Harris and others, 2017).

Chadronian (Eocene) fossils were identified in the Bone Basin Member in one Jefferson Valley section (Kuenzi, 1966). A nearby section was designated the type section of the Chadronian Bone Basin Member, yet in two much later separate studies, detrital zircon data from the type section from which fossils were not obtained independently indicated an Arikareean (Oligocene) maximum depositional age of ca 25 Ma (Stroup and others, 2008; Schwartz and others, 2019a), as much as 12 Myr younger than originally indicated for the Bone Basin Member type section (Kuenzi and Fields, 1971; fig. 1).

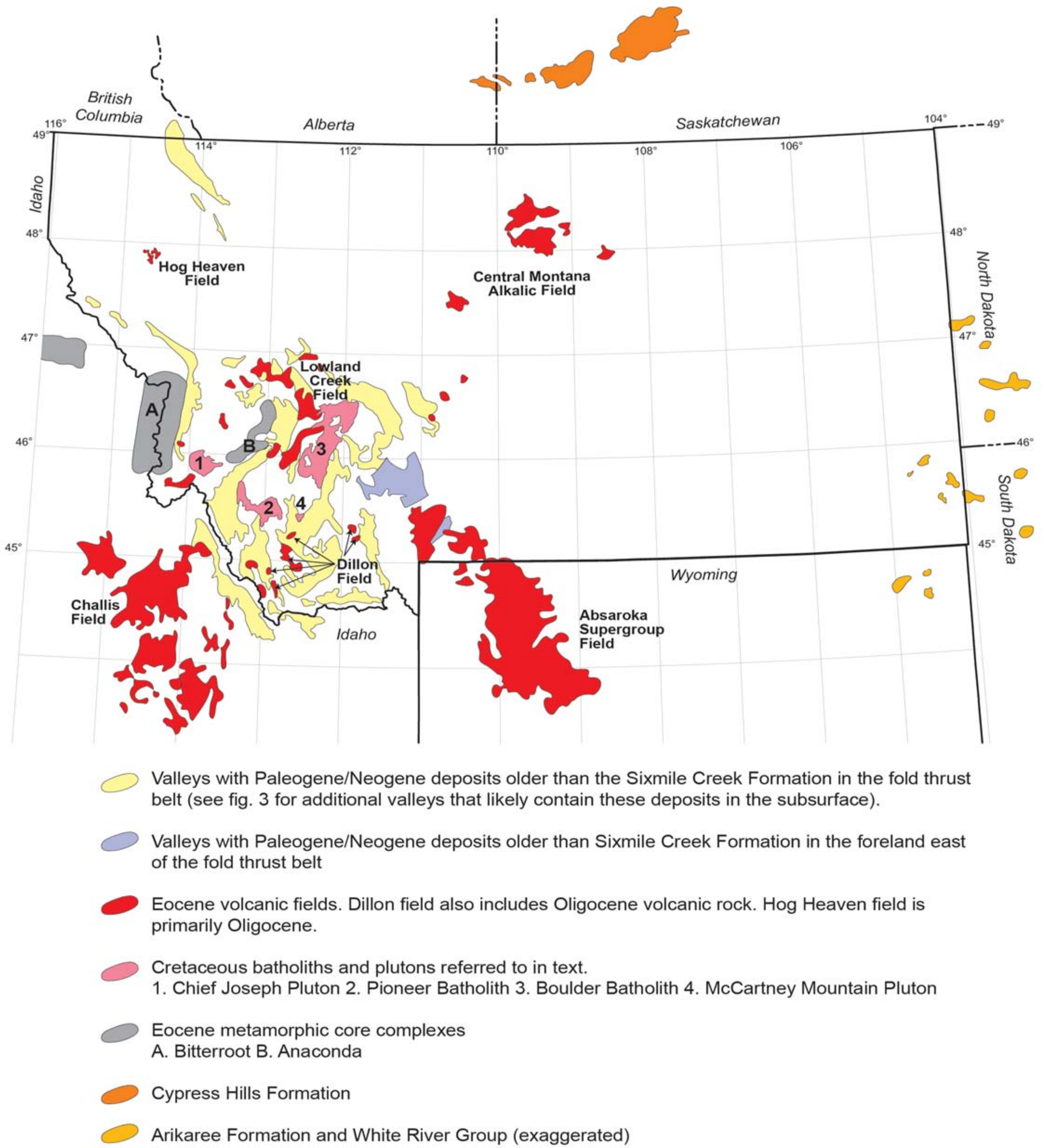



Figure 6. Location of Eocene and Oligocene volcanic fields, batholiths, and core complexes relative to western valleys that contain lower Bozeman Group at surface (see fig. 3); Cypress Hills Formation in Canada; and White River Group (Chadron and Brule Formations, and Arikaree Formation in southeastern Montana and adjacent states).

In three cases detrital zircon data provided Renova ages for fluvial conglomerates that were previously considered Sixmile Creek Formation: on McCartney Mountain near an abandoned schoolhouse along the Burma Road (Rothfuss and others, 2012), in a quarry along Silver Bow Lane just west of the Beaverhead River (Schwartz and others, 2011), and within the Big Hole Canyon (Schricker and others, 2013; fig. 7).

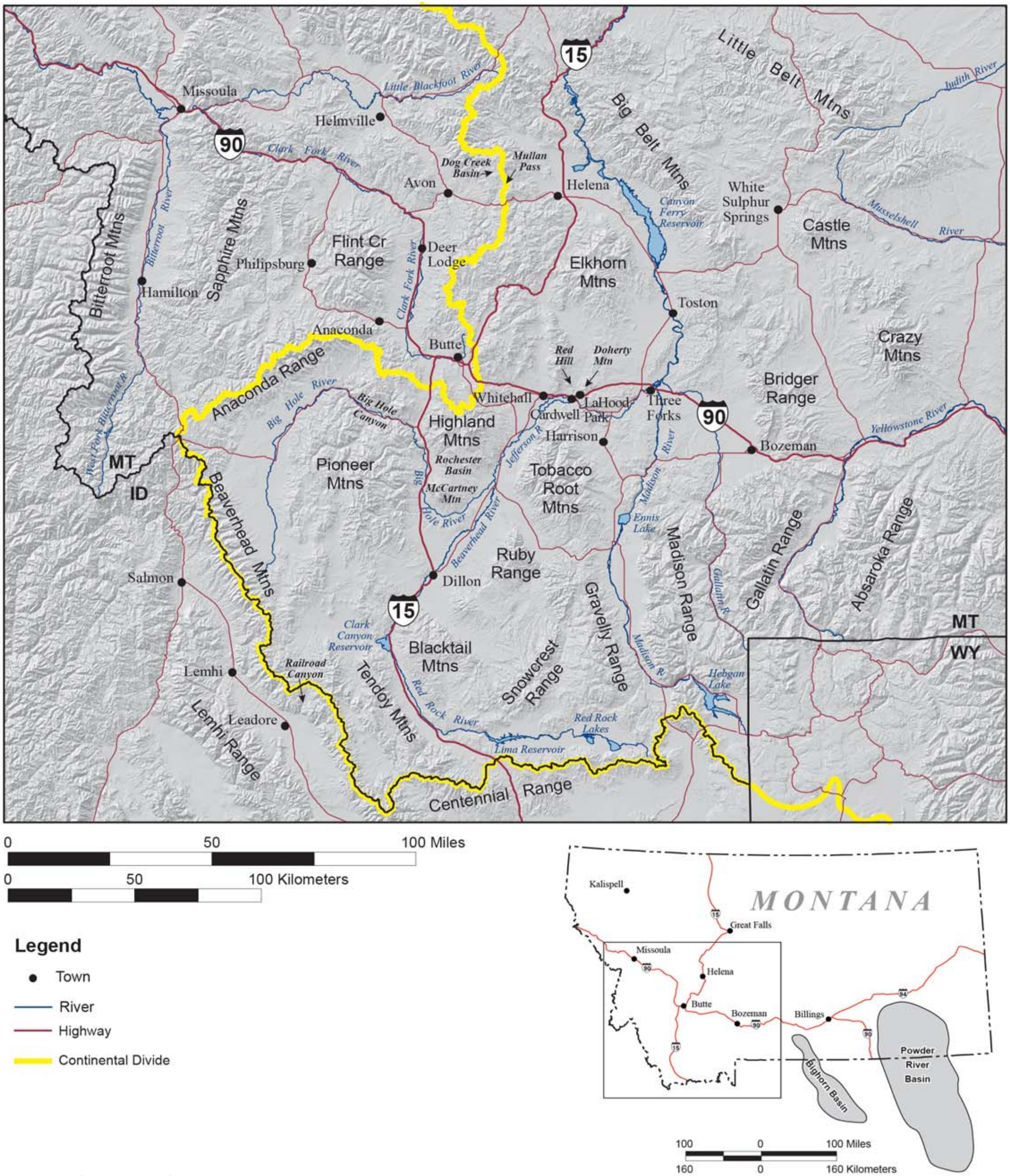



Figure 7. Geographic features.

Detrital zircon-based age constraints have broadly confirmed NALMA designations in the Sage Creek basin (Schwartz and Graham, 2017) and have provided new age data for other basins (Hodges and others, 2004; Link and others, 2008; Stroup and others, 2008; Roe, 2010; Schwartz and others, 2019a). Radiometric ages of interbedded volcanic or paleosol units have also been used to refine or corroborate NALMA ages in western Montana (e.g., M'Gonigle and Dalrymple, 1993; Fritz and others, 2007; Methner and others, 2016; Dawson and Constenius, 2018).

## CAPPING UNCONFORMITY

The significant unconformity that Kuenzi and Fields (1971) used to define the upper contact of the Renova Formation, or the top of Sequence 3 (Hanneman and Wideman, 1991), extends across the intermontane valleys of western Montana (unconformity 5; figs. 1, 2; Robinson, 1960; Kuenzi and Richard, 1969; Rasmussen, 1973; Monroe, 1981; Runkel, 1986; Barnosky and Labar, 1989; Elliott and others, 2003; Hanneman and others, 2003; Barnosky and others, 2007), and was historically age-constrained primarily based on vertebrate fossil assemblages. In western Montana it has been called the "mid-Tertiary" (Robinson, 1960) or "early-Miocene" (Fields and others, 1985) unconformity. The name "mid-Tertiary unconformity" has been formally discarded for several reasons (Harris and others, 2017). It has also been called the "Hemingfordian unconformity," because a distinct Hemingfordian (NALMA, fig. 1) fauna had never been reported in nearly 100 years of vertebrate fossil collecting in western Montana (Fields and others, 1985), even where bracketing late Arikareean and early Barstovian strata are fossiliferous (Lofgren, 1985). However, Hemingfordian fossils have subsequently been reported in the Sage Creek Basin (Tabrum, 2001), Horse Prairie Basin (Retallack, 2007), and Lemhi Basin (Barnosky and others, 2007). Development of the unconformity has been interpreted as a direct response to the onset of Basin and Range extension in southwestern Montana and southeastern Idaho between ca. 18 to 17 Ma (Barnosky and Labar, 1989; Burbank and Barnosky, 1990). The unconformity has been recognized along the extent of the North American Cordillera spanning approximately the same time, and interpreted as the hiatus between regional collapse of the Cordillera and inception of Basin and Range tectonism (Constenius and others, 2003).

The unconformity in parts of some basins is distinctly angular (Thompson and others, 1982; Rasmussen, 2003; Sears and Ryan, 2003), but in others, especially in the center of basins where identified using seismic data, it is only erosional (Rasmussen, 2003) or may be represented by a correlative conformity (Hanneman and Wideman, 2010). Discordance was not recognized, for example, in the Medicine Lodge beds in basins of the Snake River Plain, Idaho (Hodges and Link, 2002). Calcic pedocomplexes mark the unconformity in many places in western Montana and probably at least as far east as southwestern North Dakota (Hanneman and Wideman, 2006).

Age constraints for the unconformity have indicated regional early Miocene synchroneity for its development (Constenius and others, 2003). However, new data from Railroad Canyon near Leadore, Idaho (fig. 7), within 1 or 2 km of the southwestern Montana border, document a significant discrepancy for the age of the hiatus (Lemhi Basin, fig. 1). New age constraints at this location indicate ca. 21.5 to 21.4 Ma (early Miocene, late Arikareean NALMA) timing of unconformity development based on a radiometrically calibrated model that used moderate- and high-precision U-Pb dating of single zircon crystals from four unconformity-spanning ash horizons (Harris and others, 2017). This is significantly older than previous Hemingfordian constraints of ca 17.3 to 13 Ma (Zheng, 1966; Barnosky and others, 2007) based on biostratigraphy and magnetostratigraphy for the unconformity at the same section. The new dates also contrast with data from the upper Yellowstone Valley, Montana and Jackson Hole, Wyoming that constrained the Hemingfordian hiatus to an onset of 17–18 Ma and cessation at 16.8 Ma, also based on magnetostratigraphy and biostratigraphy (Barnosky and Labar, 1989; Burbank and Barnosky, 1990). The refined age range of the unconformity at Railroad Canyon suggests that refined dating in other areas may indicate that the age of the unconformity is not as uniform as previously recognized.

## PALEOGENE BASIN DEVELOPMENT

Interpretations of late early Eocene to early Miocene (lower Bozeman Group age, fig. 1) basin development are varied, in part because of overprinting by subsequent Neogene Basin and Range style (upper Bozeman Group/Sixmile Creek age and younger, fig. 1) faulting (Schmidt and Garihan, 1986; Constenius, 1996; Sears and Fritz, 1998) and in part because of possible geographic differences in basin development. Hypotheses and interpretations for the mechanism of sediment accommodation for lower Bozeman Group deposits include: (1) development of a network of grabens and half grabens throughout the extant Sevier thrust belt; (2) development of grabens and half grabens within a north–south-oriented rift zone within the extant Sevier thrust belt and hinterland, with an alluvial plain on the rift shoulder; (3) development of a single, broad basin in southwestern Montana bordered by Eocene volcanic fields; and (4) development of a network of fluvial paleovalleys during late-stage Laramide-Sevier tectonism, with minimal to moderate overprinting by subsequent extension (fig. 8). Although the models vary, certain aspects overlap from one model to another.

### (1) Extensional Half Graben Network along Reactivated Thrust Faults throughout the Extant Thrust Belt

Contractile Laramide and Sevier orogenesis ceased during late early Eocene time. Subsequent gravitational collapse of the over-thickened fold-thrust belt promoted extension (Dewey, 1988; Constenius, 1996), and consequent normal faulting produced a network of grabens and half grabens that served as Paleogene and early Neogene depositional basins.

Within this framework, one model interprets extension as having started 45 to 40 My after the cessation of thrusting in southwestern Montana (Ruppel, 1993). During this time, a pre-extensional erosion surface developed, forming a subdued topography (Pardee, 1950) that became the surface of a plateau-like feature. Remnants of the erosion surface are preserved on the Gravelly, Lemhi, and Beaverhead Ranges and elsewhere in western Montana. According to this interpretation, high-angle normal faulting that resulted from collapse of the orogenic wedge segmented the plateau into steep-sided grabens and half grabens with intervening high areas, forming a network of Paleogene sedimentary basins in western Montana (Ruppel, 1993).

In contrast, based on chronostratigraphic and geochronologic data, a significantly briefer transition between contractile and extensional deformation (1–5 My) was interpreted (Constenius, 1996). According to this hypothesis, Late Cretaceous–early Eocene crustal contraction was immediately followed by early Eocene–early Miocene (ca. 49–20 Ma) gravitational collapse of the Cordilleran orogen. This resulted in a network of extensional basins, superposed on the Cordilleran fold-thrust belt (Constenius, 1996; fig. 8A). These basins were rooted to the mechanical stratigraphy, structural relief, and most importantly, the extensional reactivation of sole thrusts that dip gently west ($3^o$–$6^o$) above an undeformed Precambrian crystalline basement. Therefore, the same thrust faults that accommodated eastward-directed thrusting and construction of the mountain belt also facilitated orogenic collapse. This episode of crustal extension was coeval with formation of metamorphic core complexes and low-angle detachment faults in the hinterland, and widespread regional magmatism (fig. 6) that tracked the rollback of the subducted oceanic plate.

The Kishenehn Basin of northwestern Montana and southeastern British Columbia (fig. 3), a half graben that contains more than 3,000 m of basin fill, is typical of these basins (Constenius, 1996). Interpretation of seismic reflection and borehole data, combined with field mapping by Canadian scientists in the 1960s, led to the conclusion that the basin was bounded by a SW-dipping listric normal fault that soled into and reactivated the extensive Lewis Thrust Fault, as did a listric normal fault that bounded the Rocky Mountain Trench (Bally and others, 1966; Dahlstrom, 1970; fig. 3). In addition, they recognized the basin-wide stratal growth geometry of the Kishenehn Formation in the form of systematic thickening of strata toward the basin-bounding listric normal fault and the gradual flattening of dip in successively younger units (McMechan and Price, 1980). In the Middle Fork region of the basin, middle Eocene strata dip $50^o$ or more at the base and progressively decrease to $32^o$NE near the eroded top of the section (Constenius, 1996), whereas in the North Fork region, middle Eocene to early Miocene strata show a dip change from 41–$37^o$ at the base to 26–$17^o$ higher in the section (McMechan and Price, 1980; Constenius, 1996; fig. 3).

### (2) Extensional Rift Zone with Rift Shoulder Alluvial Plain

A second interpretation also attributes lower Bozeman Group (late early Eocene to early Miocene) basin formation to gravitational collapse of the orogenic wedge, but with extension manifested not as a network of basins throughout the Cordilleran fold-thrust belt, but rather as basins limited to a relatively narrow, N–S-oriented rift zone that extended from British Columbia through western Montana and south

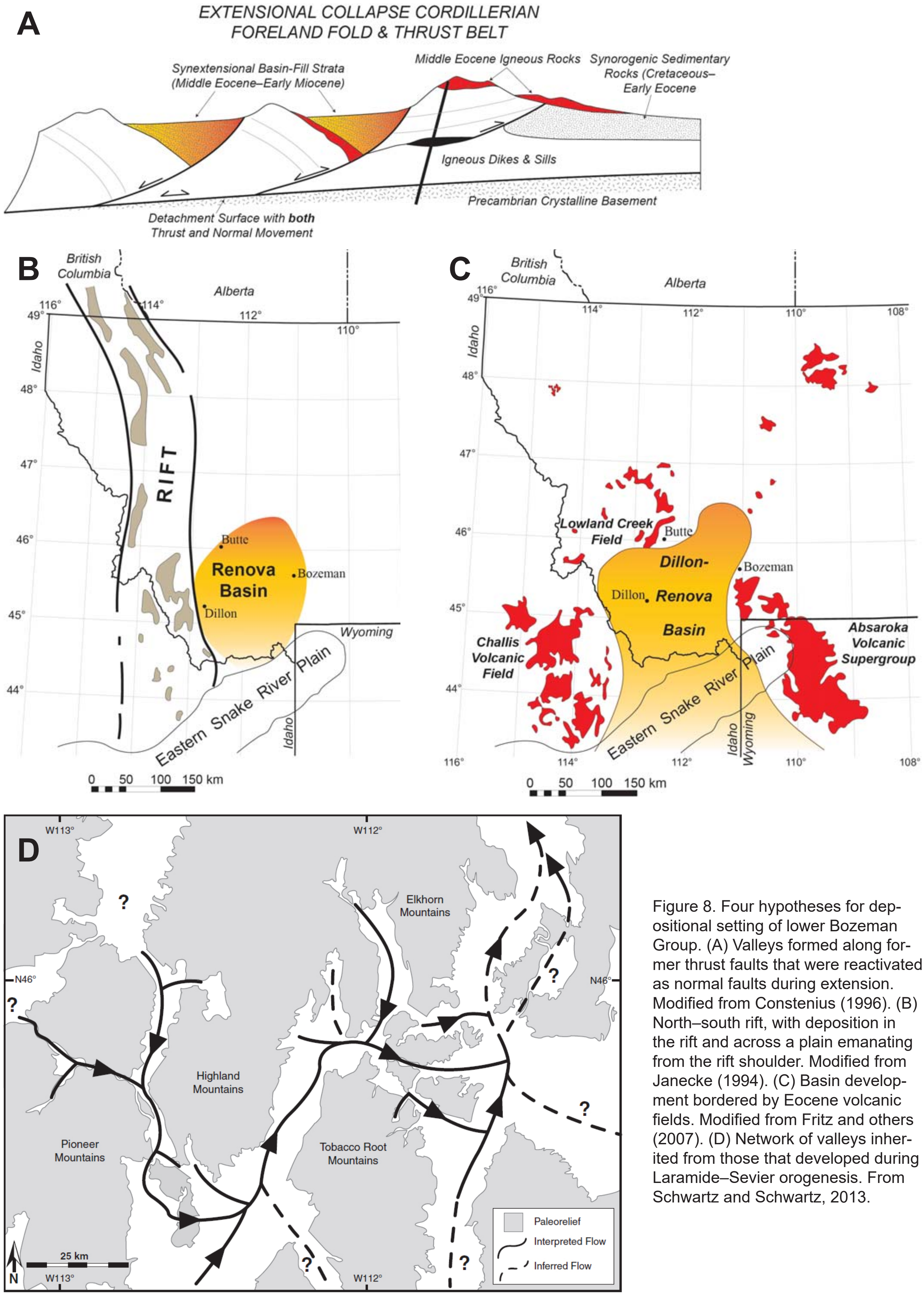



Figure 8. Four hypotheses for depositional setting of lower Bozeman Group. (A) Valleys formed along former thrust faults that were reactivated as normal faults during extension. Modified from Constenius (1996). (B) North–south rift, with deposition in the rift and across a plain emanating from the rift shoulder. Modified from Janecke (1994). (C) Basin development bordered by Eocene volcanic fields. Modified from Fritz and others (2007). (D) Network of valleys inherited from those that developed during Laramide–Sevier orogenesis. From Schwartz and Schwartz, 2013.

to the Great Basin (Janecke, 1994; fig. 8B). According to this hypothesis, sediment was deposited in supradetachment protobasins as they developed within the rift zone. The original basins were subsequently partitioned into the current Grasshopper, Muddy Creek, Horse Prairie, Medicine Lodge, Nicholia Creek, and Salmon Basins (Janecke, 1994; Janecke and others, 2005; Janecke, 2007; fig. 3). Vertical stratigraphic successions in the axial parts of the protobasins differ from successions near the basin margins based on pebble and boulder counts (Janecke, 1994) and detrital zircon data (Stroup and others, 2008; Link and others, 2008), allowing for depositional facies-based determinations of basin margins and fault activity. Assemblages of alluvial fan and lacustrine deposits support the role of extension in basin formation (Harrison, 1985; Janecke and others, 1999; Janecke and Blankenau, 2003).

According to this interpretation, a broad, tectonically quiescent, coeval alluvial plain, the Renova Basin, extended eastward from the eastern rift shoulder, trapping sediment in flexural or erosional valleys within the plain (Janecke, 1994; Thomas, 1995; Stroup and others, 2008). Detrital zircon data suggested that sandstones within the rift have a different provenance than those east of the rift shoulder (Stroup and others, 2008; Link and others, 2008). In particular, two-mica (muscovite and biotite) feldspathic sandstones are present in the rift zone, but not in deposits of the alluvial plain. The micas may have come from the Chief Joseph pluton of the Idaho Batholith (Thomas, 1995), or other granitic plutons in the footwall of the Anaconda Core Complex (Stroup and others, 2008; fig. 6).

Although rift-zone sedimentation was coeval with developing supradetachment basins within the zone, alluvial plain sedimentation east of the rift shoulder was not tectonically disrupted until the formation of grabens during Neogene Basin and Range extension (Thompson and others, 1981; Stroup and others, 2008). The name Renova Formation pertains to deposits of the alluvial plain, whereas informal names such as Medicine Lodge beds, Cabbage Patch beds, and Everson Creek beds were applied to deposits within the rift zone (Stroup and others, 2008). However, other workers (e.g., Dunlap, 1982; Nichols and others, 2001; Barnosky and others, 2007; Fritz and others, 2007; Retallack, 2009; DesOrmeau and others, 2009; Elliott, 2017; Harris and others, 2017; Schwartz and others, 2019a) applied the name Renova Formation to deposits of the interpreted rift zone area. Basin-fill deposits are coarser-grained in the western part of the rift than the eastern part, where they more closely resemble the type Renova Formation (Stroup and others, 2008). The lithologic similarity of the lower Medicine Lodge beds to the Renova Formation was noted as far west as the Snake River plain of Idaho (Hodges and Link, 2002).

### (3) Single Basin Bordered By Eocene Volcanic Fields

A third model based on sedimentology, geochemical correlations, and radiometric dating (Fritz and others, 2007; fig. 8C) is similar to the previous model, but extended the Renova Basin farther to the west into part of the area of the previous model's rift zone, and called it the Dillon–Renova Basin. The single, low-relief depositional basin contained eastward-thinning deposits and was defined by the bordering early to middle Eocene Challis, Lowland Creek, and Absaroka volcanic fields. Volcanic rock that extends from the flanking fields into the basin was designated as part of the Dillon Volcanic Member of the Renova Formation (Fritz and others, 2007; fig. 6). West of the basin, Paleogene fault blocks exposed Challis volcanic rock and pre-Cenozoic bedrock of central Idaho. Gritty sandstone and conglomerate derived from the fault blocks were interpreted to have periodically entered the Dillon–Renova Basin at spill points.

### (4) Erosional Paleovalleys

A fourth interpretation based on depositional facies mapping, paleocurrents, and sediment composition data from southwestern Montana suggests that fluvial erosion prior to extension played a major role in Paleogene basin development (fig. 8D), after which Paleogene extension played only a minimal to moderate role, and was spatially variable (Schwartz and Schwartz, 2009a,b; Schwartz and others, 2009; Rothfuss and others, 2012; Schwartz and Schwartz, 2013; Schwartz and others, 2019a). According to this hypothesis, basins largely developed prior to lower Bozeman Group deposition during a period of extensive fluvial erosion that occurred in the late stages of and immediately following Laramide and Sevier orogenesis, primarily during Paleocene and early Eocene time (Schwartz and Schwartz, 2013; Schwartz and others, 2019a), producing the extensive unconformity at the base of the Bozeman Group (fig. 1). No unequivocal rock record exists in western Montana from this time of intense erosion.

High-energy, Late Cretaceous to early Eocene fluvial systems eroded and removed at least a 5 km thickness of rock along zones of structural and stratigraphic weakness in the Cordilleran orogen, exposing Upper Cretaceous batholiths and other plutons as source rocks to adjacent incised Paleogene basins (Schwartz and Schwartz, 2009b; Stroup and others, 2008; Houston and Dilles, 2013; Schwartz and Schwartz, 2013).

Degraded relict basins unmodified by faulting were identified as far north as the northern Helena Salient of the fold-thrust belt (Runkel, 1986), and no evidence was found indicating that faulting was involved with early stages of basin development east of the fold-thrust belt (Reynolds, 1979). Lielke (2017) attributed the lack of gravitational collapse and associated extension in the foreland east of the Sevier fold-thrust belt in southwestern Montana at this time to variations in the mechanical strength of underlying basement rocks. However, reactivation of thrust faults occurred in parts of southwestern Montana where the foreland and fold-thrust belt overlap (Schmidt and Garihan, 1986; VanDenburg and others, 1998; Schwartz and Graham, 2017), and thrust faults were reactivated as listric normal faults bounding half grabens in northwestern Montana (Constenius, 1996).

The relict erosional basins of southwestern Montana were also modified by multiphase extension in the hanging wall of the Anaconda detachment zone of the Anaconda Core Complex (Elliott, 2019), which lasted at least into Oligocene time (ca. 27 Ma; Foster and others, 2010). Repetitive, thick Oligocene debris flow deposits in the Big Hole basin (fig. 3) along the detachment zone suggest that normal faulting may have provided accommodation space there (Roe, 2010). Eocene volcanism such as in the Sage Creek Basin (Rothfuss and others, 2012; Lielke, 2017) and Flint Creek Basin (Portner and others, 2011), also locally modified the relict topography.

Following Paleocene–early Eocene erosion, assemblages of basin margin (alluvial fan, hillslope) and basin interior (fluvial, lacustrine, floodplain) deposits progressively filled the basin network (Schwartz and Schwartz, 2009a,b; Schwartz and others, 2009; Schwartz and Schwartz, 2013). Detrital zircon and compositional studies (Schwartz and Schwartz, 2009a; Barber and others, 2012; Schricker and others, 2013; Schwartz and Schwartz, 2013; Schwartz, 2014; Schwartz and others, 2019b), including the presence of rare sand-size two-mica plutonic clasts (Schwartz and Schwartz, 2013), suggest that sediment dispersal was widespread and not confined to separate rift and alluvial plain segments as earlier detrital zircon studies suggested (Stroup and others, 2008; Link and others, 2008).

The alluvial fan and other hillslope deposits document the presence of relatively high-relief basin divides with source rocks similar to those of modern environments (Schwartz and Schwartz, 2013). Fluvial deposits range from boulder and cobble conglomerates representing laterally extensive channel complexes to medium-grained, quartzofeldspathic sandstones encased in overbank mudstones (Schwartz and Schwartz, 2013). Alluvial fan and hillslope deposits (e.g., talus, debris flow, and mud flow) unconformably overlie pre-Cenozoic bedrock surfaces with no apparent fault displacement (fig. 9).

Figure 9. Paleoslope deposits at Red Hill near Cardwell.

## PALEOCLIMATE, PALEOTOPOGRAPHY, AND TECTONISM

Paleoclimate, paleotopography, and tectonism are interrelated, such as when mountain development creates rain shadows or highland collapse allows penetration of regional climate; when topographic relief creates stratified local climates; and when the interplay between climate and tectonism drives landscape evolution (Kent-Corson and others, 2006; Chamberlain and others, 2012; Fan and others, 2017; Schwartz and others, 2019a). The relationship among these parameters and to the Paleogene landscape evolution of southwestern Montana was interpreted through a detailed synthesis of sedimentary, tectonic, and paleoenvironmental data (Schwartz and others, 2019a).

### Unconformity 1

**(For the purposes of discussion, major unconformities within the lower Bozeman Group are arbitrarily identified numerically; figs. 1, 2).**

The unconformity at the base of the Bozeman Group (figs. 1, 2) represents deep fluvial erosion into the late-stage Sevier and Laramide orogenic landscape of western Montana (Rasmussen, 2003; Lielke, 2012; Rothfuss and others, 2012; Schwartz and Schwartz, 2013). At the end of Sevier–Laramide contraction, the orogen was likely an eastward-tapering plateau with maximum elevation (>2 km) near the Idaho Batholith, which decreased eastward toward the thrust belt front (e.g., Chase and others, 1998; DeCelles and others, 2004; Snell and others, 2014; Fan and others, 2017; Schwartz and others, 2019a). The warm, wet, subtropical climate promoted deep incision into the orogenic wedge (Schwartz and Schwartz, 2013), initially concurrent with Sevier–Laramide crustal thickening and isostatic adjustment, but continuing into early Eocene (Schwartz and others, 2019a). This climatic regime, correlative to the global Paleocene–Eocene thermal maximum (PETM), is reflected by locally preserved red, saprolitic, kaolinitic soils that developed on the erosion surface (Thompson and others, 1982), identified as lateritic soils (Wolfe, 1964) or ultisols (Hanneman and others, 1994). Elsewhere, coal deposits that underlie the early and middle Eocene volcanic flows that initiated during early extension (Rasmussen, 2003; Portner and others, 2011) also suggest a warm, wet climate. The climate changed to cooler and drier during the transition to extension (Chamberlain and others, 2012).

Locally, sedimentary rock from environments as diverse as coal swamps, lakes, and fluvial channels is preserved between Unconformity 1 and overlying volcanic deposits (Pardee, 1911; Dunlap, 1982; Harrison, 1985; Zen, 1988; M'Gonigle and Dalrymple, 1996; Janecke and others, 1999; Rasmussen, 2003; Portner and others, 2011; Schricker and others, 2013; Scarberry and others, 2015; these geographically limited deposits are not shown in figs. 1 and 2).

### Onset of Extensional Volcanism, Sedimentation, and Core Complex Development (ca. 55–40 Ma; early to middle Eocene)

Extension within the fold-thrust belt occurred 1–5 My after the end of Sevier thrusting and crustal thickening (Harlan and others, 1988; Constenius, 1996) and was heralded by a pulse of volcanism and core complex development (O'Neill and others, 2004). Thermochronology data indicate that relatively rapid extension occurred on the Anaconda Metamorphic Core Complex (fig. 6) in the hinterland immediately west of the fold-thrust belt, starting at 53 ± 1 Ma, during final stages of or immediately following shortening in the fold-thrust belt (Foster and others, 2010). Dominantly low-angle extensional faults within the fold-thrust belt paralleled preexisting contractional structures (Constenius, 1996; VanDenburg and others, 1998; Janecke and Blankenau, 2003).

Isotopic data suggest that maximum surface elevations of ~4 km were attained in the Sevier hinterland between ~50 and 45 Ma (Mulch and others, 2004, 2007; Mulch and Chamberlain, 2007; Mix and others, 2011; Chamberlain and others, 2012; Fan and others, 2017), closely following the initial exhumation of local core complexes (Schricker and others, 2013) and the southwestward delamination of the Farallon slab from beneath the continent at ~55 Ma (after Copeland and others, 2017). Elevation gain and the onset of extension and volcanism have been attributed to various thermally driven mantle processes (Bird, 1998; Thorkelson and Taylor, 1989; Madsen and others, 2006; Humphreys and others, 2008; Jones and others, 2015), and not strictly to gravitational collapse of the orogenic pile, which alone would have lowered paleoelevation (Chamberlain and others, 2012). The increase in thermal energy from the introduction of asthenospheric mantle promoted early to middle Eocene volcanism and augmented crustal flow, resulting in extension and rapid surface uplift (Chamberlain and others, 2012). Augmentation of preexisting Sevier–

Laramide hinterland elevations promoted local relief as fluvial networks carved deep paleovalleys across the orogenic wedge.

The first phase of extension was pre-49.5 Ma in southwestern Montana (VanDenburg and others, 1998) and ca. 49 Ma in the fold-thrust belt of northwestern Montana (Constenius, 1996). Widespread extensional faulting probably did not occur in the fold-thrust belt of southwestern Montana until ca. 45 Ma (VanDenburg and others, 1998; Janecke and Blankenau, 2003). Rapid extension associated with the Montana core complexes (fig. 6) continued through ca. 39 Ma (Foster and others, 2010). Hinterland crust was exhumed from a depth of 12–16 km during this time (Haney, 2008; Bendick and Baldwin, 2009; Foster and others, 2010). Volcanic deposits of the Challis, Lowland Creek, Garnet Range, and other volcanic fields filled developing valleys and preserved underlying and locally interlayered early middle Eocene lacustrine, paludal, and fluvial deposits (Zen, 1988; Dunlap, 1982; Harrison, 1985; M'Gonigle and Dalrymple, 1996; Janecke and others, 1999; Rasmussen, 2003; Portner and others, 2011; Schricker and others, 2013; Scarberry and others, 2015). Elsewhere in Montana, initial Eocene volcanism is represented by Absaroka Supergroup volcanic rock of south-central Montana, and the alkalic province of north-central Montana. (fig. 6).

Research along the Sevier orogenic front in the Kishenehn Basin (fig. 3) also determined that high elevations existed during initiation of extension (Fan and others, 2017). Stable isotope studies in the basin suggested that crustal thickness may have reached more than 55 km with an elevation of at least 4 km at the end of orogenesis, followed by gravitational collapse along the orogenic front concurrent with the presence of a high plateau in the hinterland. High elevation coupled with high-relief topography persisted for 12 Myr along the orogenic front despite the collapse (Fan and others, 2017). Elevation from the inherited orogenically thickened crust remained high during Eocene extension, maintained through thermal uplift from upwelling of hot asthenosphere. Isostatic rebound associated with lower-lithosphere delamination or slab removal may also have contributed to maintenance of the high elevation (Fan and others, 2017). During this time, three disparate types of fossil mollusks coexisted with separate paleoenvironmental affinities—wet tropical, semi-arid subtropical, and temperate—indicating a broad range of paleoclimates and paleoelevations within the Kishenehn Basin catchment (Fan and others, 2017). Similar variations likely also existed in other basins of the extant fold-thrust belt.

### Unconformity 2

The unconformity that developed on the early and middle Eocene extensional volcanic deposits (figs. 1, 2) in western Montana represents a significant, but inadequately studied, regional tectonic event indicated by local folding, faulting, and erosion of the volcanic rock (Rasmussen, 2003). The onset of a global Eocene climatic event—the Middle Eocene Climatic Optimum (MECO)—which ranged from 42 to 38 Ma (Bohaty and Zachos, 2003; Bohaty and others, 2009), also occurred during development of unconformity 2, and may correspond to a second episode of lateritic (Hendrix and others, 2014) or ultisol (Hanneman and Wideman, 2010; 2016) soil development in some areas. Terrestrial stable isotope data from the Dell Member in the Sage Creek Basin of southwestern Montana suggest that the MECO event began there from 41 to 40.0 Ma, after a long episode of Eocene global cooling between the PETM and middle Eocene time (Methner and others, 2016). The MECO interval was marked by rapid, transient global warming (a "hyperthermal event") which produced a warm and semi-arid to sub-humid climate in contrast to the long, cool, and arid episode that preceded it (Mulch and others, 2015; Methner and others, 2016). Evidence from paleosols (Retallack, 2007) and terrestrial stable isotope data (Methner and others, 2016) indicates that warming also produced a transiently wetter climate that may have promoted erosion into the early and middle Eocene volcanic rock (after Schwartz and others, 2019a). The MECO was followed by a progressively cooler, more arid climate (Lielke and others, 2012; Methner and others, 2016; Schwartz and others, 2019a).

### Unconformity 3 (spans unconformities 1 and 2)

In southeastern and parts of southwestern Montana the unconformity beneath upper Eocene (Chadronian) deposits spans unconformities 1 and 2 (figs. 1, 2). In the Jefferson Basin (fig. 3), the contact between the Renova Formation and pre-Cenozoic bedrock locally appears as terraced unconformities (Schwartz and Schwartz, 2013), suggesting continued fluvial incision at the time of volcanism and core complex development elsewhere in western Montana. In parts of southwestern Montana the Renova Formation and equivalents rest on rock as old as Paleoproterozoic and Mesoproterozoic.

In southeastern Montana sparse outcrops of Chadron (Eocene—Chadronian) and Brule (Oligocene—Orellan, and Whitneyan) Formations of the White River Group rest on rock as young as the Paleocene Tongue River Member of the upper Fort Union Formation and as old as the Upper Cretaceous Pierre Formation. The late Oligocene to early Miocene Arikaree Formation (Arikareean) also overlies an angular unconformity in southeastern Montana, resting on progressively older units toward the Black Hills (fig. 10). The underlying units range from Oligocene paleolandslide deposits (fig. 11) that locally preserve the Chadron and Brule Formations to rock also as old as the Late Cretaceous Pierre Formation (fig. 10).

### Subsequent Sedimentation, Relatively Minor Volcanism, and Unconformity 4 (ca. 39–16 Ma)

An intense period of calc-alkaline volcanism occurred during and immediately following the MECO throughout vast areas of the North American Cordillera from Oregon into Mexico (Best and others, 2009, 2013; Mulch and others, 2015, contributing immense quantities of volcanic ash to deposits of the Renova Formation and equivalents (Thompson and others, 1981; Fields and others, 1985). It was particularly pronounced in the southern Great Basin, where one of the greatest global long-lived (36 to 18 Ma) episodes of explosive silicic volcanism occurred (Best and others, 2013). In contrast, only relatively minor volcanism occurred in Montana at this time. It was local, episodic, and of significantly less volume than the earliest extensional volcanism (52–40 Ma) had been. Volcanic rock with age ranges from 39 to 24 Ma is preserved in the Hog Heaven (Zehner, 1987; Zehner and Lange, 1992); Crater Mountain (Mosolf, 2015); Beaverhead Canyon and Big Hole Valley (Fritz and others, 2007); and Virginia City (Lielke, 2012) fields (Chadwick, 1985), and locally, such as in the lower Ruby Basin of southwestern Montana (Fields and others, 1985; fig. 3).

Alluvial fan, talus, debris flow, and mud flow deposits, perhaps reworked from MECO oxidized soils, rest unconformably on bedrock paleoslopes in many areas. One of these deposits on Red Hill near Cardwell (figs. 7, 8) yielded Chadronian (late Eocene) vertebrate fossils (Tabrum, oral commun., 2007; Rothfuss and others, 2008). Another in the Three Forks area (fig. 7), misnamed the Sphinx Conglomerate (fig. 1), was also interpreted as Eocene (Robinson, 1963). Similar deposits are present at Doherty Mountain near Cardwell (Vuke, 2006; fig. 7), the Tobacco Root Mountains near Harrison (Elliott and others, 2003; Vuke, 2006; fig. 7), near LaHood Park (Schwartz and Schwartz, 2013; fig. 7), in the Big Hole Valley (Roe, 2010; fig. 3), Big Hole Canyon (Schricker and others, 2013; fig. 7), the Gravelly Range (Lielke, 2008, 2012; fig. 7), and in the Radersburg–Toston Basin (Vuke, 2007; Michalak and others, 2010; Chamberlin and Schwartz, 2011; fig. 3). Typically, these deposits are breccias with red or reddish matrix (fig. 9), probably having incorporated the older oxidized soils that had dominantly developed on Paleozoic carbonate bedrock. The deposits may include clasts as large as multi-meter boulders and suggest local relief as much as ~2 km based on modern map relationships (Schwartz and Schwartz, 2013).

Progressive Eocene cooling and aridification in southwestern Montana was followed by rapid cooling at the Eocene–Oligocene boundary (ca. 34 Ma; Chamberlain and others, 2012), which accompanied ongoing extension within the fold-thrust belt until ca. 28 Ma (VanDenburg and others, 1998; Janecke and Blankenau, 2003). Basin-margin relief was locally amplified as a result of extension, but the prior high elevations of the extant Sevier hinterland diminished as the crust thinned (Lielke and others, 2012; Schwartz and others, 2019a). The depositional area of the Renova Formation to the east of the thrust front remained relatively high (2–3 km) into early Oligocene time (Lielke and others, 2012; Schwartz and others, 2019).

Unconformity 4 separates rocks that are compositionally similar. Although the unconformity has been recognized regionally, it was likely not a result of tectonism (Hanneman and Wideman, 1991; Cheney, 1994; Constenius, 2003). Eustatic changes were proposed as the cause (Hanneman and Wideman, 1991), although Portner and others (2011) noted that western Montana is beyond the extent of eustatic influence. Warming during late Oligocene time (Barnosky and Carrasco, 2002) may have promoted erosion of older rock and development of the unconformity. The warming was followed by rapid cooling at the Oligocene–Miocene boundary (ca. 23 Ma; Chamberlain and others, 2012).

### Unconformity 5 and Initiation of Basin and Range Tectonism

The unconformity between the Renova and Sixmile Creek Formations and equivalents occurs throughout western Montana (fig. 1) and is recognized on the basis of abrupt lithologic change (e.g., Pierson and Schwartz, 2005), and locally on the presence of

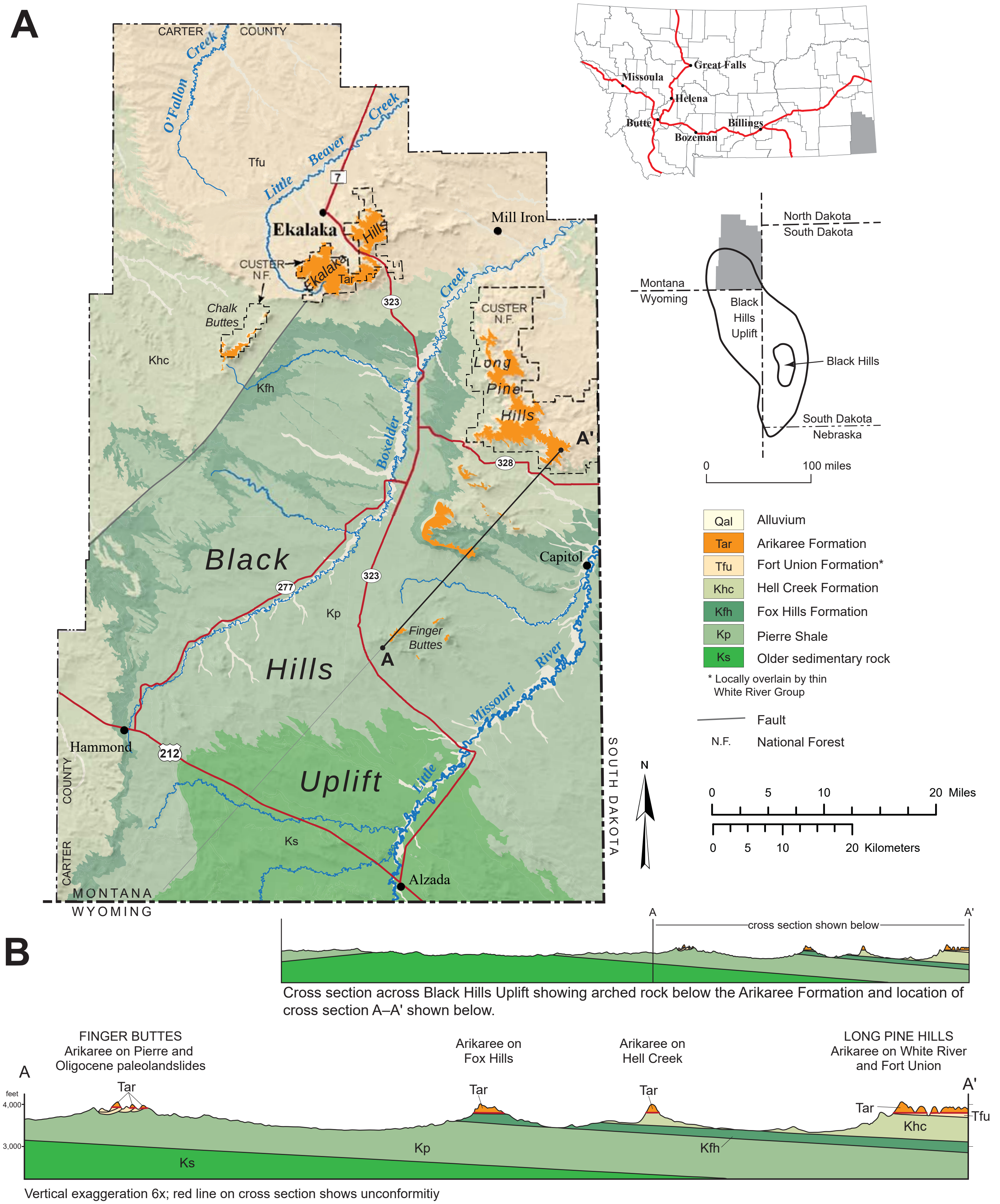
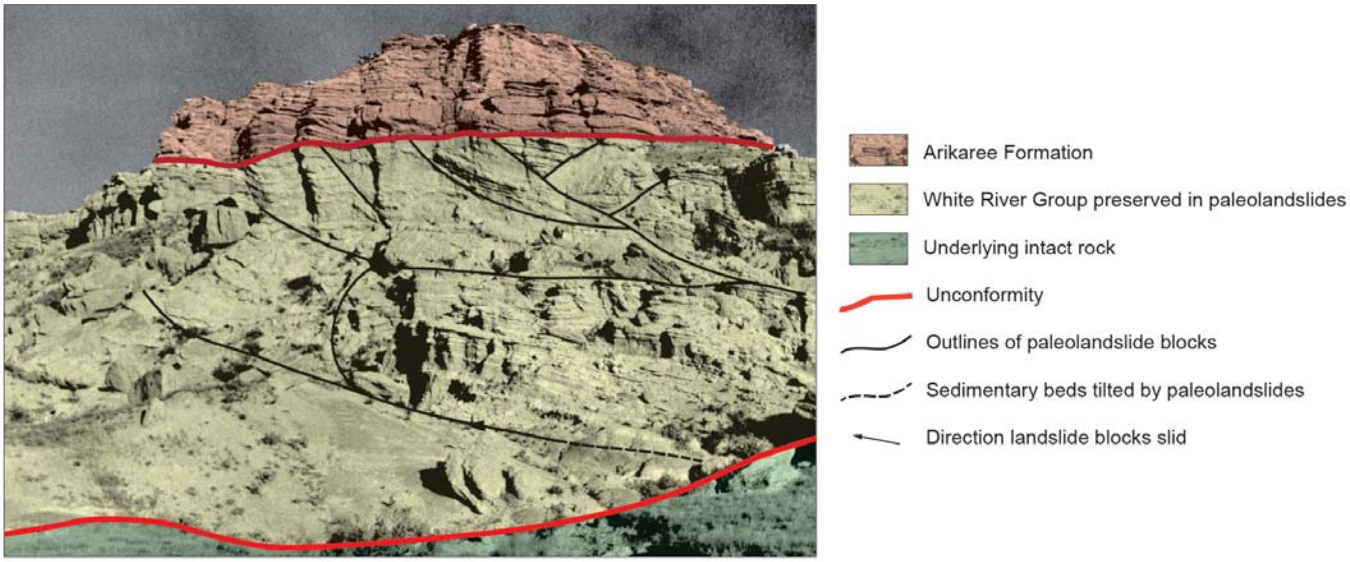



Figure 10. (A) Geologic map of Carter County, southeastern Montana, showing location of Arikaree Formation and cross section line. (B) Cross section A–A' showing White River Group and Arikaree Formation resting unconformably on units that range from Upper Cretaceous Pierre, Fox Hills, and Hell Creek Formations to the Paleocene Ludlow and Tongue River Members of the Fort Union Formation.



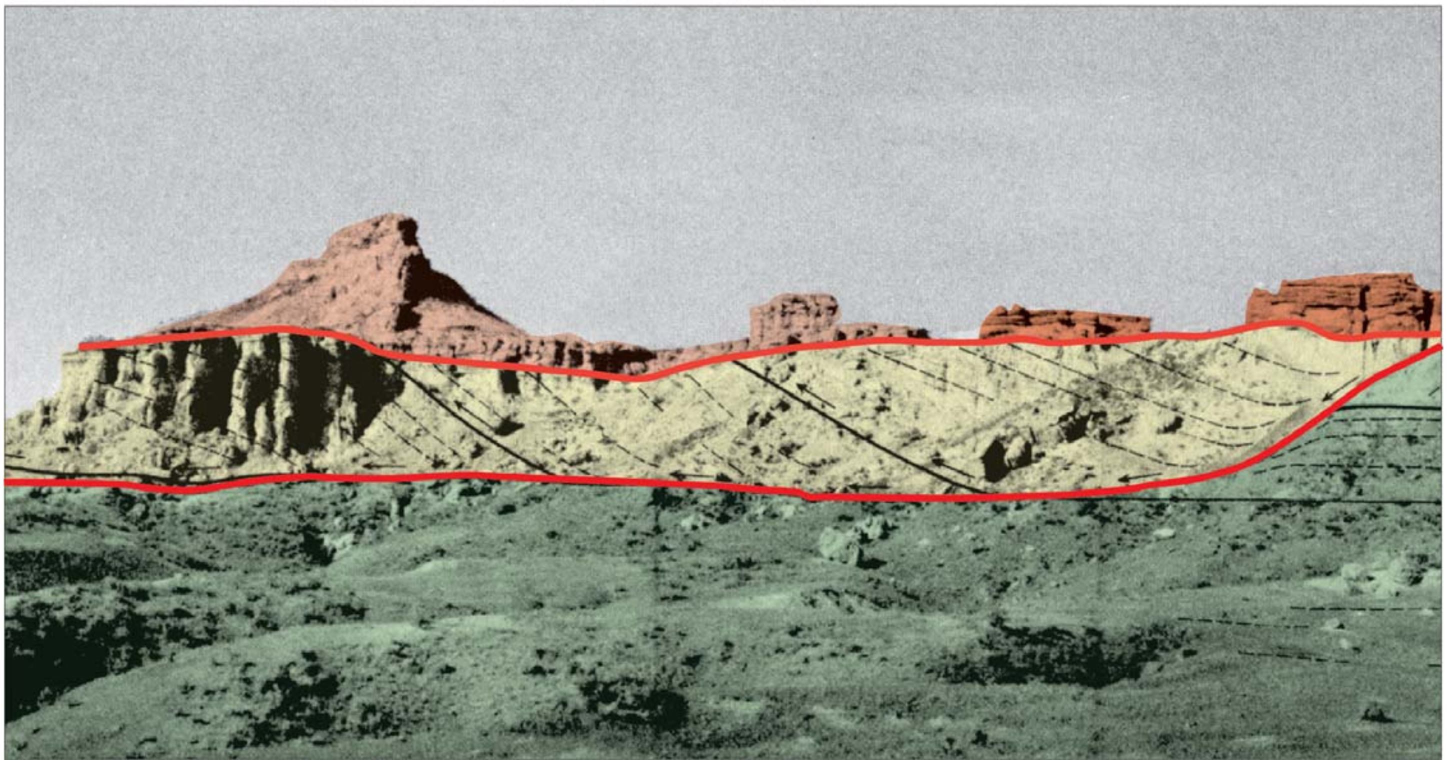



Figure 11. Unconformities that bound the White River Group (Chadron and Brule Formations) preserved in paleolandslides in Finger Buttes, southeastern Montana (see fig. 10 for location; from Gill, 1962).

calcic paleosols, erosional features, and angular stratal relationships (Hanneman and Wideman, 1991). It is known as the early Miocene unconformity (Fields and others, 1985; Harris and others, 2017) or late Hemingfordian unconformity (Barnosky and others, 2007). The unconformity was originally interpreted as a result of change from an arid to a humid climate (Thompson and others, 1982). More typically, development of the unconformity has been attributed to the onset of Basin and Range extension (Barnosky and Labar, 1989; Burbank and Barnosky, 1990; Fritz and Sears, 1993; Constenius, 1996; Fritz and others, 2007) which began abruptly at 17–16 Ma as a result of gravitational collapse (Chamberlain and others, 2012; Camp and others, 2015). Basin-and-range development allowed penetration of monsoonal storms from the south that had been restricted by the previous higher elevation topography (Chamberlain and others, 2012).

The emplacement of the Yellowstone hotspot plume was considered the trigger that set off the collapse of the high plateau, which was already under regional stress and on the verge of wholesale collapse (Camp and others, 2015). Alternatively, the Yellowstone outbreak point may have produced radial extension around the initial thermal dome (Sears and others, 2009).

Faulting and doming, including from the Yellowstone hotspot plume, during the Basin and Range episode of extension augmented the topographic relief of some of the basins (Reynolds, 1979) and segmented others (Janecke, 1994; Sears and Ryan, 2003; Janecke and others, 2005; Janecke, 2007), in some cases elevating Paleogene and early Neogene basin deposits (lower Bozeman Group) as much as 5,300 m (17,400 ft) above corresponding valley parts of the original basin (Luikart, 1997). Examples of such elevated fine-grained deposits include Duchesnean to Chadronian (39–33 Ma) and Whitneyan (32–31 Ma) deposits in the Gravelly Range (Hanneman and Lofgren, 2017; fig. 7) that may correspond to deposits in the Ruby Basin (Rasmussen, 2003); “Oligocene” (probably Eocene) lignitic, tuffaceous deposits in the small Dog Creek Basin just below Mullan Pass northwest of Helena along the Continental Divide (fig. 7) that may correspond to deposits in the Avon and Helena Valleys (Erdmann, 1959); and lacustrine deposits in the Garnet Range that unconformably overlie bedrock and are lithologically similar to deposits in the Avon and Flint Creek Valleys (fig. 3). Other examples of fine-grained Paleogene deposits at relatively high elevations include Chadronian deposits in the southern Elkhorn Mountains on a divide between the North Boulder and the Radersburg–Toston Basins (Freeman and others, 1958; Hanneman and others, 2003), and in the Big Belt, Little Belt Mountains, and Castle Mountain areas (fig. 7).

## PALEODRAINAGE

### Waning Stages of Sevier and Laramide Deformation (ca. 65–55 Ma)

During the waning stages of Sevier and Laramide deformation, a network of fluvially connected intermontane basins developed as rivers incised into the Sevier and Laramide terranes during a warm/wet climate (Schwartz and Schwartz, 2013; Schwartz and Graham, 2017; Schwartz and others, 2019a). Fluvial systems with headwaters in the Sevier hinterland drained eastward into the fold-thrust belt and adjacent foreland of southwestern Montana (Janecke and others, 1999; Schwartz and Schwartz, 2013; Schwartz and Graham, 2017). Two deep valleys developed across thrust sheets along the modern continental divide between southwestern-most Montana and the Idaho Challis volcanic field (Janecke, 2000; figs. 3, 12). Sediment transported through these valleys and through southwestern-most Montana was deposited as the Beaverhead–Harebell–Piñon Megafan, which crossed the eastern Snake River Plain in Idaho into northwestern Wyoming (Janecke and others, 2000; Sears and Ryan, 2003). Evidence for distal sources was also indicated from Mesoproterozoic clasts derived from Idaho in the latest Cretaceous–Paleocene(?) Beaverhead Group conglomerates in southwestern-most Montana, although local sources were recognized as well (Garber and others, 2020).

In contrast to western Montana where erosion dominated, the fluvial systems from the west deposited sediment of the Paleocene Fort Union Formation and earliest Eocene Wasatch Formation in Laramide basins in central and eastern Montana (Roberts, 1972; Seeland and others, 1988). In south-central and southeastern Montana, earliest Eocene rivers flowed northeastward out of the Big Horn and Powder River Basins in southern Montana (fig. 4) and joined the eastward drainage toward the northward-retreating Cannonball Sea east of Montana (Denson and Gill, 1965; Seeland, 1985, 1988, 1992; Vuke, 2020).

In northern Montana an extensive north–northeast-dipping erosional pediment surface developed east of the fold-thrust belt from which as much as 1280 m of Upper Cretaceous through lower Eocene rock was likely removed in north-central Montana (Hearn, 1989).

### Late Early Eocene (ca. 55–48 Ma)

At the onset of extension, the eastward-flowing rivers that had developed during Sevier thrusting in southwestern Montana were overwhelmed with volcanic rock, which backfilled some of the basins that had transected the fold-thrust belt (Janecke and others, 1999; Janecke, 2007). Collectively, isotopic, geochemical, and sedimentary evidence suggests a drainage reorganization at ca. 49 Ma that likely resulted from the addition of higher-elevation source areas associated with the Challis volcanic field, or with dissection of the landscape that allowed waters from the higher-elevation Idaho Batholith to reach southwestern Montana (Kent-Corson and others, 2010). The oldest Absaroka volcanic eruptions or a structural change also blocked and deflected the Big Horn Basin river from northeast to southwest (Seeland, 1985). Further drainage reorientation occurred with development of an interpreted rift zone along the axis of the Cordillera (fig. 8B) that paralleled the Sevier orogenic belt and cross-cut the earlier drainage pattern (Janecke, 1994; Janecke and

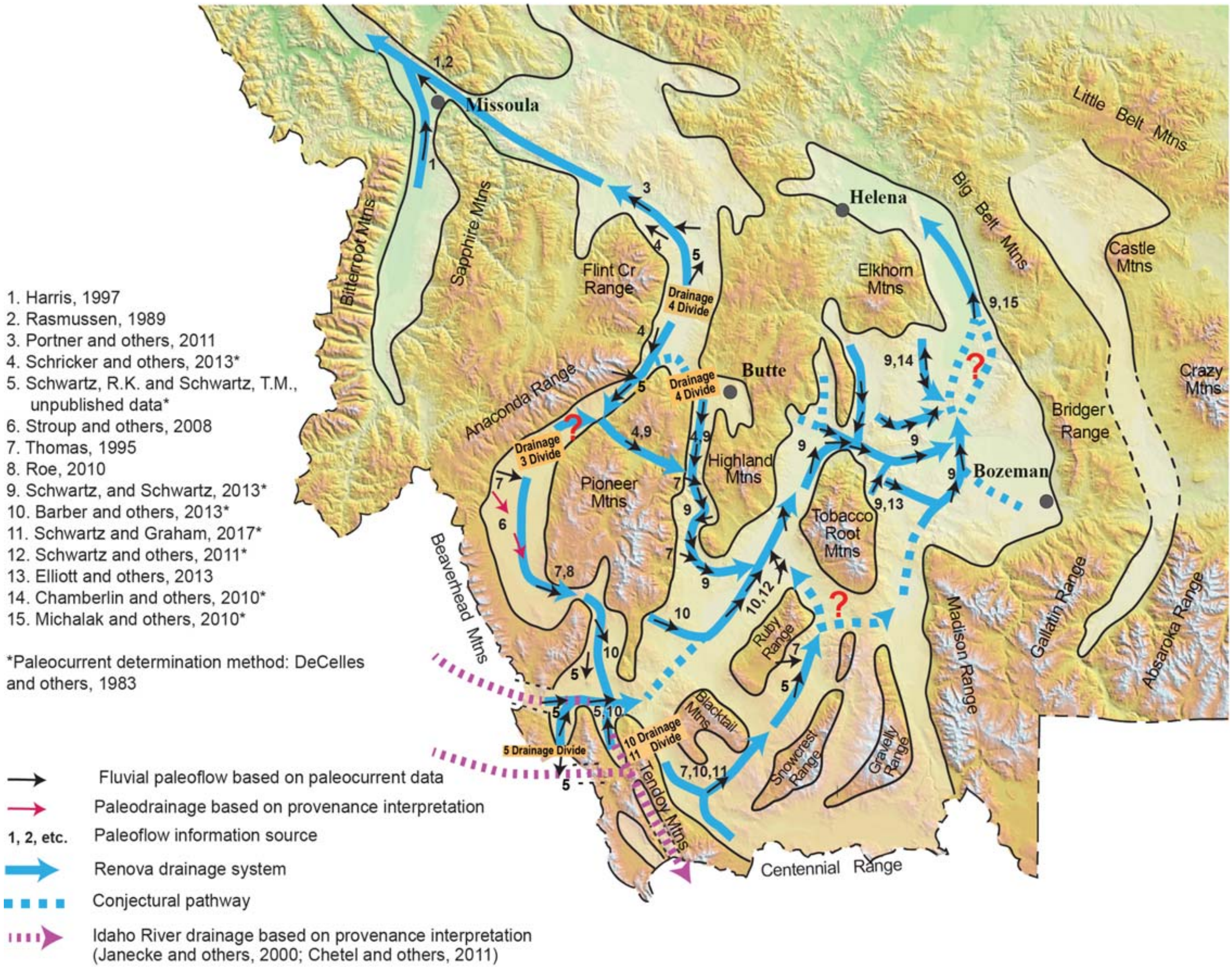



Figure 12. Fluvial paleocurrent directions for lower Bozeman Group (Renova Formation and equivalents) from middle Eocene to early Miocene. Black outlines indicate interpreted valleys at that time based on modern extent of deposits, including those that now occur in the Garnet and Gravelly Ranges, the Big Belt and Little Belt Mountains, and the mountains west of Helena. Paleoslope deposits also help define basin margins. The fluvial paleocurrent directions are not meant to indicate a particular time slice within the middle Eocene to early Miocene time range. Ephemeral lakes that developed in certain areas during this time span are not represented in the figure, nor are possible drainage reversals or shifts.

others, 1997; Sears and Ryan, 2003). Farther east in the extant fold-thrust belt and western parts of the foreland, extension had only a minimal effect, and drainages followed the valleys created from the prior episode of deep erosion (Schwartz and Schwartz, 2013; fig. 8D).

### Middle Eocene (ca. 48–38 Ma)

The presence of abundant Challis-derived sediment in Eocene deposits of the Green River Basin of Wyoming indicated that a southeast-flowing Eocene fluvial system connected the Challis volcanic field in Idaho with the Green River Basin. The main course of the river was inferred to have crossed into Montana from the Challis volcanic field through the two deep paleovalleys that were incised during latest Cretaceous and Paleocene time (Janecke and others, 2000) and from there through southwestern-most Montana along a rift margin (Janecke and others, 2000; Chetel and others, 2011; figs. 8B, 12). However, based on paleocurrent and provenance data, the dominant paleodrainage in most of southwestern Montana was to the northeast (Schwartz and Schwartz, 2009a; Schwartz and others, 2009; Barber and others, 2012; Rothfuss and others, 2012; Schwartz and Schwartz, 2013; Schwartz and others, 2019a; fig. 12).

Continued extension in the extant Sevier fold-thrust belt of southwestern Montana further segmented some of the older drainages (e.g., Schwartz and others, 2019a). Closed to semi-closed, lacustrine-dominated basins with local source areas developed within the fold-thrust belt of southwestern Montana by ca. 40 Ma (Janecke and others, 1999; Janecke and Blankenau, 2003; Schwartz and Graham, 2017; Schwartz and others, 2019a). The basins were short-lived, lacked throughgoing drainage, and reflected episodic extension (Hodges and others, 2004; Stroup and others, 2008). To the east, a significant increase in Archean grains in middle Eocene rocks suggests initiation of Laramide uplift exhumation at this time, with sediment transport in a paleo-Yellowstone River (Li, 2018).

During Uintan time (fig. 1), coarse-grained sediment of the Cypress Hills Formation (fig. 6) was deposited in braid plains of northeast-flowing rivers in southern Alberta and Saskatchewan (Leckie, 2006). The generally north-dipping, previously developed pediment topography in northern Montana east of the fold-thrust belt was augmented by uplift from Paleocene to middle Eocene alkalic igneous activity in northern Montana (Hearn, 1989; Leckie, 2006; fig. 6). In southeastern Montana erosion continued through middle Eocene time.

**Late Eocene (ca. 38–34 Ma)**

By Chadronian time (fig. 1), the Boulder Batholith (fig. 6) was exposed, and separate fluvial systems had developed on the eastern and western sides of the batholith (Schwartz and Schwartz, 2009b; Rothfuss and others, 2012; Schwartz and Schwartz, 2013). The Tobacco Root Batholith and McCartney Mountain Pluton (fig. 7) were also exposed in highlands by this time, contributing granitic clasts to fluvial systems (Elliott and others, 2003; Schwartz and Schwartz, 2013).

Crystalline basement rocks (Archean or Paleoproterozoic) from Laramide uplifts were also exhumed in highlands by this time. Clasts of basement rocks are present in an Eocene braided stream deposit, dated by detrital zircon analysis, near the juncture of the Beaverhead and Ruby Basins (Schwartz and others, 2011). Crystalline basement was also exposed and incorporated into Eocene deposits in the upper Jefferson Basin (Vuke, 2006; Schwartz and Schwartz, 2009b; Schwartz and Schwartz, 2013), in late Eocene or Oligocene fluvial deposits in the Harrison Basin (Elliott, and others, 2003; Vuke, 2006), and in the Rochester Basin south of the Highland Mountains (Schwartz and Schwartz, 2009b; Carrapa and others, 2019; fig. 7).

In the Laramide foreland area of southwest Montana, one model has drainage dominantly to the east across a braid plain emanating from a N–S-oriented rift shoulder (Thomas and others, 1995; Sears and Fritz, 1998; Sears and Ryan, 2003; Stroup and others, 2008; fig. 8B). Another interprets a northeastward-flowing inter-basinal trunk drainage network that persisted in the segmented foreland region throughout Renova Formation deposition (Schwartz and Schwartz, 2013; Schwartz and Graham, 2017; fig. 8D). Studies of paleo-meteoric water suggest that late Eocene topography in southwestern Montana was likely similar to present-day topography (Li and others, 2017) with drainages in valleys roughly similar to modern valleys (Schwartz and Schwartz, 2013; fig. 12). Coal; paper shale, including oil shale; diatomite; fossil fish; and other organisms (e.g., Dunlap, 1982; Constenius and Dyni, 1983; Monroe, 1981; Rasmussen, 1977, 1989; Pierce, 1993; Ripley, 1995; Pierce and Constenius, 2001; Rasmussen and Prothero, 2003) also indicate the presence of lakes and swamps at this time.

**Oligocene–Early Miocene (ca. 34–16 Ma)**

By Oligocene time a drainage divide had developed in the Deer Lodge Basin (fig. 12). North of the divide, paleodrainage was to the north and northwest toward the Flint Creek and Missoula Basins (Portner and others, 2011; Schricker and others, 2013; fig. 12). Paleocurrent data from the southern Deer Lodge Basin suggest southeasterly paleodrainage south of the divide (Schricker and others, 2013). These data were obtained from deposits along the Old Works trail in Anaconda that were recently dated as probable late Eocene to early Oligocene (Elliott, 2019; Scarberry and others, 2019). Paleocurrent data also suggest northward drainage from the Bitterroot Valley into the Missoula Basin and northwestward drainage within the Missoula basin at this time (Harris, 1997; fig. 12).

Supradetachment basins within the interpreted rift zone of southwestern Montana contained axial meandering river drainages and lacustrine environments (Janecke and others, 2007; Stroup and others, 2008). Research in southwestern-most Montana (Barber and others, 2012) interpreted a linked and throughgoing fluvial system that exited the supradetachment region toward the east, and flowed northward as part of the paleo-Beaverhead River system, joining the northeastward-flowing inter-basinal trunk drainage network in the segmented foreland region (Schwartz and Schwartz, 2013; Schwartz and Graham, 2017; fig. 12). A shallow, large, perennial lake was interpreted to have occupied the closed Ruby Basin in the Laramide foreland area during late Oligocene and earliest Miocene time (Monroe, 1981), and a lacustrine environment is also indicated in the Canyon Ferry Lake area at this time (CoBabe and others, 2002). An Amazon-scale river is hypothesized to have transported sediment at this time from the Colorado Grand Canyon region through the Great Basin Rift, and northeastward toward southwestern Montana (Sears, 2013; Sears and others, 2014).

In southeastern Montana, presence of clasts from the Absaroka volcanic field at the base of the Oligocene Brule Formation, the lack of clasts from the Black Hills, and the configuration of the erosion surface on the underlying unconformity suggest drainage from southwest to northeast (Gill, 1962; Pipiringos and others, 1965; Seeland, 1985; Lisenbee and DeWitt, 1993). The overlying Oligocene–early Miocene Arikaree Formation contains clasts that indicate derivation from a distal crystalline and metamorphic source mixed with crystal-vitric ash from a nearby source deposited in fluvial and lacustrine environments (Denson and others, 1959).

## FUTURE WORK

More data are needed to refine and perhaps partly integrate the multiple hypotheses about tectonics, climate, basin evolution, drainage patterns, stratigraphic correlation of units and associated unconformities, and ages of the lower Bozeman Group stratigraphic units. Use of the name Renova Formation needs formal clarification regarding its geographic extent and if it applies to rock contemporaneous with and genetically related to initial post-Laramide–Sevier volcanism.

Should thick units referred to as "beds" such as the Cabbage Patch and Medicine Lodge beds be designated as formal members or formations, and should other informal names be formally abandoned and replaced with formal stratigraphic names? In which situations should lithostratigraphic units vs. sequence stratigraphic units apply?

Further paleocurrent and provenance (compositional and detrital zircon) data would help determine which, if any, basins ultimately drained northwest to the paleo-Columbia River, northeast toward the paleo-Labrador Sea, east to the lowland that was occupied by the Cannonball Sea during Paleocene time, or southeast toward the Green River Basin in Wyoming, all of which have been proposed.

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## REFERENCES CITED

American Commission on Stratigraphic Nomenclature, 1961, Code of stratigraphic nomenclature: Bulletin of the American Association of Petroleum Geologists, v. 45, no. 5, p. 645–665.

Bally, A.W., Gordy, P.L., and Stewart, G.A., 1966, Structure, seismic data, and orogenic evolution of the southern Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 14, no. 3, p. 337–381.

Barber, D.E., Schricker, L., Schwartz, R.K., Weislogel, A.L., and Thomas, R.C., 2012, Paleogeographic and tectonic implications of the Paleogene paleo-Missouri headwater system in southwest Montana: Geological Society of America Abstracts with Programs, v. 44, no. 7, p. 547, poster doi: https://doi.org/10.13140/RG.2.2.32281.77925/1

Barber, D.E., Schwartz, R.K., Weislogel, A.L., Schricker, L., and Thomas, R.C., 2013, Implications for tectonic control on paleogeography and sediment dispersal pathway: Integrated U-Pb detrital zircon age-analysis of the Paleogene Missouri River headwater system, SW Montana: American Association of Petroleum Geologists Search and Discovery article with poster #50863 [Accessed 12/30/2019].

Barnosky, A.D., and Labar, W.J., 1989, Mid-Miocene (Barstovian) environmental and tectonic setting near Yellowstone Park, Wyoming and Montana: Geological Society of America Bulletin v. 101, no. 11, p. 1448–1456, doi: https://doi.org/10.1130/0016-7606(1989)101<1448:MMBEAT>2.3.CO;2

Barnosky, A.D., and Carrasco, M.A., 2002, Effects of Oligo–Miocene global climate changes on mammalian species richness in northwestern quarter of the USA: Evolutionary Ecology Research, v. 4, p. 811–841.

Barnosky, A.D., Bibi, F., Hopkins, S.S.B., and Nichols, R., 2007, Biostratigraphy and magnetostratigraphy of the mid-Miocene Railroad Canyon sequence, Montana and Idaho, and age of the mid-Tertiary unconformity west of the Continental Divide: Journal of Vertebrate Paleontology, v. 27, no. 1, p. 204–224, doi: https://doi.org/10.1671/0272-4634(2007)27[204:BAMOTM]2.0.CO;2

Barnosky, A.D., Holmes, M., Kirchholtes, R., Lindsey, E., Maguire, K.C., Poust, A.W., Stegner, M.A., Sunseri, J., Swartz, B., Swift, J., Villavicencio, N.A., Wogan, G.O.U., 2014, Prelude to the Anthropocene: Two new North American Land Mammal Ages (NALMAs): The Anthropocene Review, v. 1, no. 3, p. 225–242, doi: https://doi.org/10.1177/2053019614547433

Becker, H.F., 1973, The York Ranch flora of the upper Ruby River Basin, southwestern Montana: Paleontographica Abt. B, v. 143, p. 18–93.

Bendick, R., and Baldwin, J., 2009, Dynamic models for metamorphic core complex formation and scaling: The role of unchannelized collapse of thickened continental crust: Tectonophysics, v. 477, p. 93–101, doi: https://doi.org/10.1016/j.tecto.2009.03.017

Best, M.G., Barr, D.L., Christiansen, E.H., Gromme, S., Deino, A.L., and Tingey, D.G., 2009, The Great Basin Altiplano during the middle Cenozoic ignimbrite flareup: Insights from volcanic rocks: International Geology Review, v. 51, p. 589–633, doi: https://doi.org/10.1080/00206810902867690

Best, M.G., Christiansen, E.H., and Gromme, S., 2013, Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup: Swarms of subduction-related supervolcanoes: Geosphere, v. 9, no. 2, p. 260–274, doi: https://doi.org/10.1130/GES00870.1

Bohaty, S.M., and Zachos, J.C., 2003, Significant Southern Ocean warming event in the late middle Eocene: Geology, v. 31, no. 11, p. 1017–1020, doi: https://doi.org/10.1130/G19800.1

Bohaty, S.M., Azchos, J.C., Florindo, F., and Delaney, M.L., 2009, Coupled greenhouse warming and deep-sea acidification in the middle Eocene: Paleoceanography, v. 24, PA2207, doi: https://doi.org/10.1029/2008PA001676

Briggs, D.E.G., 2013, A mosquito's last supper reminds us not to underestimate the fossil record: Proceedings of the National Academy of Sciences, Commentary, v. 110, no. 46, p. 18353–18354, doi: https://doi.org/10.1073/pnas.1319306110

Burbank, D.W., and Barnosky, A.D., 1990, The magnetochronology of Barstovian mammals in southwestern Montana and implications for the initiation of Neogene crustal extension in the northern Rocky Mountains: Geological Society of America Bulletin v. 102, p. 1093–1104, doi: https://doi.org/10.1130/0016-7606(1990)102<1093:TMOBMI>2.3.CO;2

Calede, J.J., and Rasmussen, D.L., 2015, Field guide to the geology and paleontology of the Cabbage Patch beds in the Flint Creek Basin (Renova Formation, Arikareean), *in* Mosolf, J., and McDonald, C., eds., Geology of the Elliston area, Montana and other papers: Tobacco Root Geological Society 40th Annual Field Conference Guidebook, Northwest Geology, v. 44, p. 157–199.

Camp, V.E., Pierce, K.L., and Morgan, L.A., 2015, Yellowstone plume trigger for Basin and Range extension, and coeval emplacement of the Nevada–Columbia Basin magmatic belt: Geosphere, v. 22, no. 2, p. 203–225, doi: https://doi.org/10.1130/GES01051.1

Carrapa, B., DeCelles, P.G., and Romero, M., 2019, Early inception of the Laramide orogeny in southwestern Montana and northern Wyoming: Implications for models of flat-slab subduction: Journal of Geophysical Research-Solid Earth, v. 124, p. 2102–2123, doi: https://doi.org/10.1029/2018JB016888

Chadwick, R.A., 1985, Overview of Cenozoic volcanism in the west-central United States, *in* Flores, R.M. and Kaplan, S.S., eds., Rocky Mountain Section SEPM, p. 359–382.

Chamberlain, C.P., Mix, H.T., Mulch, A., Hren, M.T., Kent-Corson, M.L., Davis, S.J., Horton, T.W., and Graham, S.A., 2012, The Cenozoic climate and topographic evolution of the western North America Cordillera: American Journal of Science, v. 312, p. 213–262, doi: https://doi.org/10.2475/02.2012.05.

Chamberlin, E.P., Michalak, S.A., and Schwartz, R.K., 2010, Radersburg–Toston intermontane basin of southwest Montana: Facies and drainage patterns define structurally partitioned Paleogene sub-basin and Sevier-uplift source areas: Geological Society of America Abstracts with Programs, v. 42, no. 5, p. 135, doi: https://doi.org/10.13140/RG.2.2.19698.86720

Chamberlin, E.P., and Schwartz, R.K., 2011, Facies and provenance analysis of Eocene deposits in the Radersburg–Toston region: Understanding the role of Cenozoic tectonics on changing intermontane basin geometry in southwestern Montana: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 315.

Chase, C.G., Gregory-Wodzicki, K.M., Parrish-Jones, J.T., and DeCelles, P.G., 1998, Topographic history of the western Cordillera of North America and controls on climate, *in* Crowley, T. J., and Burke, K., eds., Tectonic boundary conditions for climate model simulations: New York, Oxford University Press, p. 73–99.

Cheney, E.S., 1994, Cenozoic unconformity-bounded sequences of central and eastern Washington: Washington Division of Geology and Earth Resources, Bulletin 80, p. 115–139.

Chetel, L.M., Janecke, S.U., Carroll, A.R., Beard, B.L., Johnson, C.J., and Singer, B.S., 2011, Paleogeographic reconstruction of the Eocene Idaho River, North American Cordillera: Geological Society of America Bulletin, v. 123, no. 1/2, p. 71–88, doi: https://doi.org/10.1130/B30213.1

CoBabe, E.A., Chamberlain, K.R., Ivie, M.A., and Giersch, J.J., 2002, A new insect and plant Lagerstätte from a Tertiary lake deposit along the Canyon Ferry Reservoir, southwestern Montana: Rocky Mountain Geology, v. 37, no. 1, p. 13–30.

Constenius, K.N., 1996, Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20–39, doi: https://doi.org/10.1130/0016-7606(1996)108<0020:LPECOT>2.3.CO;2

Constenius, K.N., and Dyni, J.R., 1983, Lacustrine oil shales and stratigraphy of part of the Kishenehn Basin, northwestern Montana: Colorado School of Mines Mineral and Energy Resources, v. 26, p. 1–16.

Constenius, K.N., Esser, R.P., and Layer, P.W., 2003, Extensional collapse of the Charleston-Nebo Salient and its relationship to space-time variations in Cordilleran orogenic belt tectonism and continental stratigraphy, *in* Raynolds, R.G., and Flores, R.M., eds., Cenozoic systems of the Rocky Mountain Region: Rocky Mountain SEPM, p. 303–353.

Copeland, P., Currie, C.A., Lawton, T.F., and Murphy, M.A., 2017, Location, location, location: The variable lifespan of the Laramide orogeny: Geology, v. 45, p. 223–2276, doi: https://doi.org/10.1130/G38810.1

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, no. 3, p. 332–406.

Daly, R.A., 1912, Geology of the North American Cordillera at the forty-ninth parallel: Canada Geological Survey Memoir 38, 857 p.

Dawson, M.R., and Constenius, K.N., 2018, Mammalian fauna of the middle Eocene Kishenehn Formation, Middle Fork of the Flathead River, Montana: Annals of Carnegie Museum, v. 85, no. 1, p. 25–61.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and Foreland Basin System, Western U.S.A.: American Journal of Science, v. 304, p. 105–168, doi: https://doi.org/10.2475/ajs.304.2.105.

DeCelles, P.G., Langford, R.P., and Schwartz, R.K., 1983, Two new methods of paleocurrent determination from trough cross-stratification: Journal of Sedimentary Petrology, v. 53, no. 2, p. 0629–0642.

Denson, N.M., Bachman, G.O., and Zeller, H.D., 1959, Uranium-bearing lignite in northwestern South Dakota and adjacent states: U.S. Geological Survey Bulletin 1055-B, p. 11–57.

Denson, N.M., and Gill, J.R., 1965, Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston Basin—A regional study: U.S. Geological Survey Professional Paper 463, 75 p.

DesOrmeau, J.W., Baldwin, J., and Sears, J., 2009, Sedimentary record and detrital zircon provenance of the Eocene–Oligocene Renova Formation, Bitterroot Valley, western Montana: Geological Society of America Abstracts with Program, 41, p. 49.

Dewey, J.F., 1988, Extensional collapse of orogens: Tectonics, v. 7, no. 6, p. 1123–1139, doi: https://doi.org/10.1029/TC007i006p01123

Dorr, J.A., and Wheeler, W.H., 1964, Cenozoic paleontology, stratigraphy, and reconnaissance geology of the Upper Ruby River Basin, southwestern Montana: University of Michigan Museum, Paleontological Contributions, v. 13, p. 297–339.

Douglass, E., 1901, Fossil Mammalia of the White River beds of Montana: American Philosophical Society Transactions, no. 20, p. 237–279.

Douglass, E., 1903, New vertebrates from the Montana Tertiary: Carnegie Museum Annals, v. 2, p. 145–199.

Dunlap, D.G., 1982, Tertiary geology of the Muddy Creek Basin, Beaverhead County, Montana: Missoula, University of Montana, M.S. thesis, 133 p.

Dyni, J.R., and Schell, E.M., 1982, Tertiary coals in the Medicine Lodge Creek Valley, Beaverhead County, Montana: Montana Bureau of Mines and Geology Geologic Map 29, 18 p., 3 sheets.

Elliott, C.G., 2017, Geologic map of the Lincoln Gulch 7.5' quadrangle, southwestern Montana: Montana Bureau of Mines and Geology Geologic Map 70, scale 1:24,000.

Elliott, C.G., 2019, Multiphase extension in the hanging wall of the Anaconda detachment zone, *in* Scarberry, K., ed., Geology of the Deer Lodge and Boulder areas: Northwest Geology, v. 48, p. 71–82.

Elliott, W.S., Jr., Douglas, B.J., and Suttner, L.J., 2003, Structural control on Quaternary and Tertiary sedimentation in the Harrison Basin, Madison County, Montana: The Mountain Geologist, v. 40, no. 1, p. 1–18.

Erdmann, C.E., 1959, Geologic road log, Helena over McDonald Pass via U.S. Highway 10N and return via Mullan Pass and Austin, *in* Hammond, C.R., and Trapp., H., Jr., Sawtooth–Disturbed Belt area: Billings Geological Society 10th Anniversary Field Conference Guidebook, p. 171–177.

Fan, M., Constenius, K.N., and Dettman, D.L., 2017, Prolonged high relief in the northern Cordilleran orogenic front during middle and late Eocene extension based on stable isotope paleoaltimetry: Earth and Planetary Science Letters, v. 457, p. 376–384, doi: https://doi.org/10.1016/j.epsl.2016.10.038

Fields, R.W., Rasmussen, D.L., Tabrum, A.R., and Nichols, R., 1985, Cenozoic rocks of the intermountain basins of western Montana and eastern Idaho: a summary, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States: Rocky Mountain Section, Society of Economic and Petroleum Geologists, p. 9–36.

Foster, D.A., Grice, W.C., Jr., and Kalakay, T.J., 2010, Extension of the Anaconda metamorphic core complex: $^{40}$Ar/$^{39}$Ar thermochronology and implications for Eocene tectonics of the northern Rocky Mountains and the Boulder Batholith: Lithosphere, v. 2, no. 4, p. 232–246, doi: https//doi.org/10.1130/L94.1

Freeman, V.L., Ruppel, E.T., and Klepper, M.R., 1958, Geology of part of the Townsend Valley, Broadwater and Jefferson Counties, Montana: U.S. Geological Survey Bulletin 1042-N, p. 481–556.

Fritz, W.J., and Sears, J.W., 1993, Tectonics of Yellowstone hotspot wake in southwestern Montana: Geology, v. 21, p. 427–430, doi: https://doi.org/10.1130/0091-7613(1993)021<0427:TOTYHW>2.3.CO;2

Fritz, W.J., Sears, J.W., McDowell, R.J., and Wampler, J.M., 2007, Cenozoic volcanic rocks of southwestern Montana, *in* Thomas, R.C., and Gibson, R.I., eds., Dillon, Montana: Tobacco Root Geological Society 32nd Annual Field Conference Guidebook, Northwest Geology, v. 36, p. 91–110.

Garber, K.L., Finzel, E.S., and Pearson, D.M., 2020, Provenance of syn-orogenic foreland basin strata in southwestern Montana requires revision of existing models for Laramide tectonism: North American Cordillera: American Geophysical Union, doi: https://doi.org/10.1029/2019TC005944

Gill, J.R., 1962, Tertiary landslides, northwestern South Dakota and southeastern Montana: Geological Society of America Bulletin, v. 73, p. 725–736.

Greenwalt, D.E., and Labandeira, C., 2013, The amazing fossil insects of the Eocene Kishenehn Formation in northwestern Montana: Rocks and Minerals, v. 88, no. 5, p. 434–441, doi: https://doi.org/10.1080/00357529.2013.809972

Greenwalt, D.E., Goreva, Y.S., Siljeström, S.M., Rose, T., and Harbach, R.E., 2013, Hemoglobin-derived porphyrins preserved in a middle Eocene blood-engorged mosquito: Proceedings of the National Academy of Sciences, USA, v. 110, no. 46, p. 18496–18500, doi: https://doi.org/10.1073/pnas.1310885110

Haney, E., 2008, Pressure-temperature evolution of metapelites within the Anaconda Metamorphic Core Complex, southwestern Montana: Missoula, University of Montana, M.S. thesis, 110 p.

Hanneman, D.L., and Wideman, C.J., 1991, Sequence stratigraphy of Cenozoic continental rocks, southwestern Montana: Geological Society of America Bulletin, v. 103, p. 1335–1345, doi: https://doi.org/10.1130/0016-7606(1991)103<1335:SSOCCR>2.3.CO;2

Hanneman, D.L., and Wideman, C.J., 2006, Calcic pedocomplexes—Regional sequence boundary indication in Tertiary deposits of the Great Plains and western United States, *in* Alonso-Zarza, A.M., and Tanner, L.H., eds., Paleoenvironmental record and applications of calcretes and palustrine carbonates: Geological Society of America Special Paper 416, p. 1–15, doi: https://doi.org/10.1130/2006.2416(01)

Hanneman, D.L., and Wideman, C.J., 2010, Continental sequence stratigraphy and continental carbonates, *in* Alonzo-Zarza, A.M., and Tanner, L.H., eds.; van Loon, A.J., series ed., Carbonates in continental settings: Geochemistry, diagenesis, and applications: The Netherlands, Elsevier, Developments in Sedimentology, v. 62, ch. 5, p. 215–273, doi: https//doi.org/10.1016/S0070-4571(09)06205-0

Hanneman, D.L., and Wideman, C.J., 2016, Cenozoic stratigraphy in western Montana: Current status and a way forward: Geological Society of America Abstracts with Programs, v. 48, no. 7, doi: https://doi.org/10.1130/abs/2016AM-279878

Hanneman, D.L., Wideman, C.J., and Halvorson, J.W., 1994, Calcic paleosols: Their use in subsurface stratigraphy: American Association of Petroleum Geologists Bulletin, v. 78, no. 9, p. 1360–1371.

Hanneman, D.L., Cheney, E.S., and Wideman, C.J., 2003, Cenozoic sequence stratigraphy of northwestern USA, *in* Raynolds, R.G., and Flores, R.M., Cenozoic systems of the Rocky Mountain Region: Denver, Colo., Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 135–155.

Hanneman, D.L., and Lofgren, D., 2017, Vertebrate paleontology and geology of high elevation Tertiary deposits in Gravelly Range, southwestern Montana: Geological Society of America Abstracts with Programs, v. 49, no. 5, doi: https://doi.org/10.1130/abs/2017RM-293156

Harlan, S.S., Geissman, J.W., Lageson, D.R., and Snee, L.W., 1988, Paleomagnetic and isotopic dating of thrust-belt deformation along the eastern edge of the Helena Salient, northern Crazy Mountains Basin, Montana: Geological Society of America Bulletin, v. 100, p. 492–499.

Harris, W.J., 1997, Defining benefit and hazard: Distribution of upper and lower Tertiary units on the northeast flank of the Missoula Valley, Montana, Missoula, University of Montana, M.S. thesis, 80 p., map scale 1:24,000.

Harris, E.B., Strömberg, C.A.E., Sheldon, N.D., Smith, S.Y., and Ibañez-Mejia, M., 2017, Revised chronostratigraphy and biostratigraphy of the early-middle Miocene Railroad Canyon section of central-eastern Idaho, USA: Geological Society of America Bulletin, v. 129, p. 1241–1251, doi: https://doi.org/10.1130/B31655.1

Harrison, S., 1985, Sedimentology of Tertiary sedimentary rocks near Salmon, Idaho: Missoula, University of Montana, Ph.D. dissertation, 175 p.

Hearn, B.C., Jr., 1989, Introduction—Montana high-potassium igneous province, *in* Hearn, B.E., Jr., ed., Montana High Potassium Igneous Province: 28th International Geological Congress Field Trip Guidebook, v. T346, American Geophysical Union, p. 1–5.

Hendrix, M.S., Krueger, L., and Roschlaub, M., 2014, Initial description of a new rock core from the Paleogene Renova Formation, Ninemile Valley, western Montana: A well-preserved archive of paleoclimate and tectonics: Geological Society of America Abstracts with Programs, v. 46, no. 5, p. 21.

Hibbard, C.W., and Keenmon, K.S., 1950, New evidence of the lower Miocene age of the Blacktail Deer Creek formation in Montana: Michigan University Museum Paleontology Contributions, v. 8, p. 193–204.

Hodges, M.K.V., and Link, P.K., 2002, Oligocene–Miocene Medicine Lodge beds, northeastern Snake River Plain: Correlative to the Renova and Sixmile Creek Formations, Montana: Geological Society of America Abstracts with Programs, v. 34, no. 4, p. A48.

Hodges, M.K.V., Miggins, D.P., and Link, P.K., 2004, New radiometric ages from tuffaceous strata in the Idaho Medicine Lodge Valley indicate multiple episodes of basin formation: Geological Society of America Abstracts with Programs, v. 36, no. 4, p. 7.

Hoganson, J.S., Murphy, E.D., and Forsman, N.F., 1998, Lithostratigraphy, paleontology, and biochronology of the Chadron, Brule, and Arikaree Formations in North Dakota, *in* Terry, D.O., Jr., LaGarry, H.E., and Hunt, R.M., Jr., eds., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (late Eocene to early Miocene), North America: Geological Society of America Special Paper 325, p. 185–196.

Janecke, S.U., 1994, Sedimentation and paleogeography of an Eocene to Oligocene rift zone, Idaho and Montana: Geological Society of America Bulletin, v. 106, p. 1083–1095, doi: https://doi.org/10.1130/0016-7606%281994%29106%3C1083%3Asapoae%3E2.3.co%3B2

Janecke, S.U., 2007, Cenozoic extensional processes and tectonics in the northern Rocky Mountains: Southwest Montana and eastern Idaho: Northwest Geology, v. 36, p. 111–132.

Janecke, S.U., Hammond, B.F., Snee, L.W., and Geissman, J.W., 1997, Rapid extension in an Eocene volcanic arc: Structure and paleogeography of an intra-arc half graben in central Idaho: Geological Society of America Bulletin, v. 109, no. 3, p. 253–267, doi: https://doi.org/10.1130/0016-7606(1997)109<0253:REIAEV>2.3.CO;2

Janecke, S.U., McIntosh, W., and Good, S., 1999, Testing models of rift basins: Structure and stratigraphy of an Eocene–Oligocene supradetachment basin, Muddy Creek half graben, southwest Montana: Basin Research, v. 11, p. 143–165, doi: https://doi.org/10.1046/j.1365-2117.1999.00092.x

Janecke, S.U., VanDenburg, C.J., Blankenau, J.J., and M'Gonigle, J.W., 2000, Long-distance longitudinal transport of gravel across the Cordilleran thrust belt of Montana and Idaho: Geology, v. 28, no. 5, p. 439–442, doi: https://doi.org/10.1130/0091-7613(2000)28<439:LLTOGA>2.0.CO;2

Janecke, S.U., and Blankenau, J.C., 2003, Extensional folds associated with Paleogene detachment faults in SE part of the Salmon Basin: Northwest Geology, v. 32, p. 51–73.

Janecke, S.U., Dorsey, R.J., Kickham, J.C., Matoush, J.P., and McIntosh, W., 2005, Geologic map of the Bachelor Mountain 7.5-minute quadrangle, southwest Montana: Montana Bureau of Mines and Geology Open-File Report 525, scale 1:24,000.

Kent-Corson, M.L., Sherman, L.S., Mulch, A., and Chamberlain, C.P., 2006, Cenozoic topographic and climatic response to changing tectonic boundary conditions in western North America: Earth and Planetary Science Letters, v. 252, no. 3–4, p. 453–466, doi: https://doi.org/10.1016/j.epsl.2006.09.049

Kent-Corson, M.L., Mulch, A., Graham, S.A., Carroll, A.R., Ritts, B.D., and Chamberlain, C.P., 2010, Diachronous isotopic and sedimentary responses to topographic change as indicators of mid-Eocene hydrologic reorganization in the western United States: Basin Research, v. 22, no. 6, p. 829–845, doi: https://doi.org/10.1111/j.1365-2117.2009.00456.x

Koerner, H.E., 1940, The geology and vertebrate paleontology of the Fort Logan and Deep River formations of Montana, Part 1, new vertebrates: American Journal of Science, v. 238, p. 837–862.

Konizeski, R.L., and Donohoe, 1958, Faunal and stratigraphic relationships of the Cabbage Patch beds, Granite County, Montana, *in* Eighth Annual Field Conference Guidebook: Society of Vertebrate Paleontologists, p. 45–49.

Korth, W., and Tabrum, A.R., 2016, A new genus of Cylillendrodontid rodent from the Chadronian (Late Eocene) of southwestern Montana and a reassessment of the genus Pseudocylinodrodon Burke, 1935: Annals of Carnegie Museum, v. 84, no. 1, p. 75–93, doi: https://doi.org/10.2992/007.084.0101

Korth, W., and Tabrum, A.R., 2017, A unique rodent fauna from the Whitneyan (Middle Oligocene) of southwestern Montana: Annals of Carnegie Museum, v. 84, no. 4, p. 319–340, doi: https://doi.org/10.2992/007.084.0401

Kuenzi, W.D., 1966, Tertiary stratigraphy in the Jefferson River Basin, Montana: Missoula, University of Montana, Ph.D. dissertation, 293 p.

Kuenzi, W.D., and Richard, B.H., 1969, Middle Tertiary unconformity, North Boulder and Jefferson Basins, southwestern Montana: Geological Society of America Bulletin, v. 80, p. 115–120.

Kuenzi, W.D., and Fields, R.W., 1971, Tertiary stratigraphy, structure and geologic history, Jefferson Basin, Montana: Geological Society of America Bulletin, v. 82, p. 3374–3394.

Leckie, D.A., 2006, Tertiary fluvial gravels and evolution of the western Canadian prairie landscape: Sedimentary Geology, v. 190, p. 139–158, doi: https://doi.org/10.1016/j.sedgeo.2006.05.019

Li, L., Fan, M., and Hanneman, D.L., 2017, Stable isotope evidence (δ18O and δD) for late Eocene–late Miocene topography and climate in the northern Rocky Mountains, southwestern Montana: Geological Society of America Abstracts with Programs, v. 49, no. 6, doi: https://doi.org/10.1130/abs/2017AM-299842

Lielke, K., 2008, The Butcher Creek conglomerate: An enigmatic Paleogene deposit from the northern Gravelly Range of southwestern Montana: Northwest Geology–The Red Lodge area, v. 37, p. 85–96.

Lielke, K., 2012, The climatic, biotic, and tectonic evolution of the Paleogene Renova Formation of southwestern Montana: Missoula, University of Montana, Ph.D. dissertation, 208 p.

Lielke, K., 2017, A geodynamic model for gravity-driven extension—Implications for the Cenozoic evolution of southwestern Montana, *in* Cox, B., Hargrave, P.A., and McDonald, C., eds., Geology of the Leadore area and other papers: Northwest Geology, v. 46, p. 37–44.

Lielke, K., Manchester, S., and Meyer, H., 2012, Reconstructing the environment of the northern Rocky Mountains during the Eocene/Oligocene transition: Constraints from the palaeobotany and geology of southwestern Montana, USA: Acta Palaeobotanica, v. 52, no. 2, p. 317–358.

Lillegraven, J.A., 1970, Stratigraphy, structure and vertebrate fossils of the Oligocene Brule Formation, Slim Buttes, northwestern South Dakota: Geological Society of America Bulletin, v. 81, p. 831–850, doi: https://doi.org/10.1130/0016-7606(1970)81[831:SSAVFO]2.0.CO;2

Link, P.K., Fanning, C.M., and Stroup, C.N., 2008, Detrital zircon U-Pb geochronologic data for selected Cretaceous, Paleogene, Neogene, and Holocene sandstones and river sands in southwest Montana and east-central Idaho: Montana Bureau of Mines and Geology Open-File Report 569, 5 p.

Lisenbee, A.L., and DeWitt, E., 1993, Laramide evolution of the Black Hills uplift, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir 5, p. 374–412.

Loen, J.S., 1986, Origin of gold placers in the Pioneer District, Powell County, Montana: Fort Collins, Colo., Colorado State University, M.S. thesis, 164 p.

Lofgren, D.L., 1985, Tertiary vertebrate paleontology, stratigraphy, and structure, North Boulder River Basin, Jefferson County, Montana: Missoula, University of Montana, M.S. thesis, 113 p.

Lofgren, D.L., Hotton, C.L., and Runkel, A.C., 1990, Reworking of Cretaceous dinosaurs into Paleocene channel deposits, upper Hell Creek Formation, Montana: Geology, v. 18, p. 874–877, doi: https://doi.org/10.1130/0091-7613(1990)018%3C0874:ROCDIP%3E2.3.CO;2

Luikart, E.J., 1997, Syn- and post-Laramide geology of the south-central Gravelly Range, southwestern Montana: Bozeman, Montana State University, M.S. thesis, 96 p.

Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006, Cenozoic to Recent plate configurations in the Pacific Basin: Ridge subduction and slab window magmatism in western North America: Geosphere, v. 2, p. 11–34, doi: https://doi.org/10.1130/GES00020.1

McDonald, C., and Vuke, S.M., 2017, Geologic map of the Helmville 7.5' quadrangle, Powell County, Montana: Montana Bureau of Mines and Geology Open-File Report 687, 1 sheet, scale 1:24,000.

McMechan, R.D., and Price, R.A., 1980, Reappraisal of a reported unconformity in the Paleogene (Oligocene) Kishenehn Formation: Implications for Cenozoic tectonics in the Flathead Valley graben, southeastern British Columbia: Bulletin of Canadian Petroleum Geology, v. 28, no. 1, p. 37–45.

Methner, K., Mulch, A., Fiebig, J., Wacker, U., Gerdes, A., Graham, S.A., and Chamberlain, C.P., 2016, Rapid Middle Eocene temperature change in western North America: Earth and Planetary Science Letters 450, p. 132–139, doi: https://doi.org/https://dx.doi.org/10.1016/j.epsl.2016.05.053

M'Gonigle, J.W., and Dalrymple, G.B., 1993, $^{40}$Ar/$^{39}$Ar ages of Challis volcanic rocks and initiation of Tertiary sedimentary basin in southwestern Montana: The Mountain Geologist, v. 30, p. 112–118.

M'Gonigle, J.W., and Dalrymple, G.B., 1996, $^{40}$Ar/$^{39}$Ar ages of some Challis Volcanic Group rocks and the initiation of Tertiary sedimentary basins in southwestern Montana: U.S. Geological Survey Bulletin 2131, 17 p.

Michalak, S.A., Chamberlin, E.P., and Schwartz, R.K., 2010, Townsend intermontane basin in the Helena Thrust Salient of southwest Montana: Mountainous Early Cenozoic landscape and trunk-fluvial dispersal similar to the modern Missouri: Geological Society of America, Abstracts with Programs, v. 42, no. 5, p. 135.

Miller, C.N., 1980, Road log no. 2, Missoula to florule locales near Drummond and Lincoln, *in* Miller, M.R., ed., Guidebook of the Drummond-Elkhorn areas, west-central Montana: Montana Bureau of Mines and Geology Special Publication 82, p. 11–16.

Mix, H.T., Mulch, A., Kent-Corson, M.L., and Chamberlain, C.P., 2011, Cenozoic migration of topography in the North American Cordillera: Geology, v. 39, no. 1, p. 87–9, doi: https://doi.org/10.1130/G31450.1

Monroe, J.S., 1981, Late Oligocene–early Miocene facies and lacustrine sedimentation, upper Ruby River Basin, southwestern Montana: Journal of Sedimentary Petrology, v. 51, p. 939–951.

Mosolf, J.G., and Vuke, S.M., 2017, Geologic map of the Gravely Mountain 7.5' quadrangle, Powell County, Montana: Montana Bureau of Mines and Geology Open-File Report 693, scale 1:24,000.

Mosolf, J.G., 2015, Geologic field guide to the Tertiary volcanic rocks in the Elliston 30'x60' quadrangle, west-central Montana, *in* Mosolf, J., and McDonald, C., eds., Geology of the Elliston area, Montana, and other papers: Tobacco Root Geological Society 40th Annual Field Conference Guidebook, Northwest Geology, v. 44, p. 213–231.

Mosolf, J.G., Kalakay, T.J., and Foster, D.A., 2020, Eocene magmatism and coeval crustal extension in Montana, *in* Metesh, J.J., and Vuke, S.M., eds., Geology of Montana—Geologic History: Montana Bureau of Mines and Geology Special Publication 122, v. 1.

Mulch, A., Teyssier, C., Cosca, M.A., Vanderhaeghe, O., and Vennemann, T.W., 2004, Reconstructing paleoelevation in eroded orogens: Geology, v. 32, p. 525–528, doi: https://doi.org/10.1130/G20394.1

Mulch, A., Teyssier, C., Cosca, M.A., and Chamberlain, C.P., 2007, Stable isotope paleoaltimetry of Eocene core complexes in the North American Cordillera: Tectonics, v. 24, TC4001, doi: https://doi.org/10.1029/2006TC001995

Mulch, A., and Chamberlain, C.P., 2007, Stable isotope paleoaltimetry in orogenic belts—The silicate record in surface and crustal geological archives: Reviews in Mineralogy and Geochemistry, v. 66, p. 89–118, doi: https://doi.org/10.2138/rmg.2007.66.4

Mulch, A., Chamberlain, C.P., Cosca, M.A., Teyssier, C., Methner, K., Hren, M.T., and Graham, S.A., 2015, Rapid change in high-elevation precipitation patterns of western North America during the Middle Eocene Climatic Optimum (MECO): American Journal of Science, v. 315, no. 4, p. 317–336, doi: https://doi.org/10.2475/04.2015.02

Nichols, R., Tabrum, A.R., and Hill, C.L., 2001, Introduction: Cenozoic mammals, southwest Montana, *in* Nichols, R., Cenozoic vertebrate paleontology and geology of southwestern Montana and adjacent areas: Society of Vertebrate Paleontology 61st Annual Meeting Guidebook: Bozeman, Museum of the Rockies, Montana State University, p. 79–82.

O'Neill, J.M., Lonn, J.D., Lageson, D.R., and Kunk, M.J., 2004, Early Tertiary Anaconda Metamorphic Core Complex, southwestern Montana: Canadian Journal of Earth Science, v. 41, p. 63–72.

Pardee, J.T., 1911, Coal in the Tertiary lake beds of southwestern Montana: U.S. Geological Survey Bulletin 531, p. 229–244.

Pardee, J.T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America Bulletin, v. 61, p. 359–406.

Petkewich, R.M., 1972, Tertiary geology and paleontology of the Beaverhead East area, southwestern Montana: Missoula, University of Montana, M.S. thesis, 365 p.

Pierce, H.G., 1993, The nonmarine mollusks of the late Oligocene–early Miocene Cabbage Patch fauna of western Montana. III. Aquatic mollusks and conclusions: Journal of Paleontology, v. 67, no. 6, p. 980–993, https://www.jstor.org/stable/1306113

Pierce, H.G., and Constenius, K.N., 2001, Late Eocene–Oligocene nonmarine mollusks of the northern Kishenehn Basin, Montana and British Columbia: Annals of the Carnegie Museum, v. 70, no. 1, p. 1–112.

Pierson, J.S., and Schwartz, R.K., 2005, Paleoclimate and facies development across the mid-Tertiary unconformity in the Madison intermontane basin, southwestern Montana: Geological Society of America Abstracts with Programs, v. 37, no. 1, p. 71.

Portner, R.A., Hendrix, M.S., Stalker, J.C., Miggins, D.P., and Sheriff, S.D., 2011, Sedimentary response to orogenic exhumation in the northern Rocky Mountain Basin and Range Province, Flint Creek Basin, west-central Montana: Canadian Journal of Earth Sciences, v. 48, no. 7, p. 1131–1154, doi: https://doi.org/10.1139/e10-107

Prothero, D.R., and Swisher, C.C., III, 1992, Magnetostratigraphy and geochronology of the terrestrial Eocene–Oligocene transition in North America, *in* Prothero, D.R., and Berggren, W.A., eds., Eocene–Oligocene climatic and biotic evolution: N.J., Princeton University Press, p. 46–73.

Prothero, D.R., and Emry R.J., 2004, The Chadronian, Orellan, and Whitneyan North American Land Mammal Ages, *in* Woodburne, M., ed., Late Cretaceous and Cenozoic mammals of North America: Biostratigraphy and geochronology: New York, Columbia University Press, ch. 5, p. 156–168.

Rasmussen, D.L., 1973, Extension of the middle Tertiary unconformity into western Montana: Northwest Geology, v. 2, p. 27–35.

Rasmussen, D.L., 1977, Geology and mammalian paleontology of the Oligocene–Miocene Cabbage Patch Formation, central-western Montana: Missoula, University of Montana, Ph.D. dissertation, 775 p.

Rasmussen, D.L., 1989, Depositional environments, paleoecology, and biostratigraphy of Arikareean Bozeman Group strata west of the Continental Divide in Montana, *in* French, D.E., and Grabb, R.F., eds., Geological Resources of Montana: Montana Geological Society, Field Conference Guidebook, v. 1, p. 205–215.

Rasmussen, D.L., 2003, Tertiary history of western Montana and east-central Idaho: A synopsis, *in* Raynolds, R.G., and Flores, R.M., Cenozoic systems of the Rocky Mountain region: Denver, Colo., Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 459–477.

Rasmussen, D.L., and Fields, R.W., 1985, Cenozoic structure and depositional history, Jefferson and Madison intermontane basins, southwestern Montana, *in* Beaver, P.C., ed., Geology and mineral resources of the Tobacco Root Mountains and adjacent region: Tobacco Root Geological Society 10th Annual Field Conference Guidebook, p. 14.

Rasmussen, D.L., and Prothero, D.R., 2003, Lithostratigraphy, biostratigraphy, and magnetostratigraphy of Arikareean strata west of the Continental Divide in Montana, *in* Raynolds, R.G., and Flores, R.M., Cenozoic systems of the Rocky Mountain region: Denver, Colo., Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 479–499.

Retallack, G.J., 2007, Cenozoic paleoclimate on land in North America: Journal of Geology, v. 115, p. 271–294, doi: https://doi.org/10.1086/512753

Retallack, G.J., 2009, Refining a pedogenic-carbonate $CO_2$ paleobarometer to quantify a middle Miocene greenhouse spike: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 281, no. 1–2, p. 57–65, doi: https://doi.org/10.1016/j.palaeo.2009.07.011

Reynolds, M.W., 1979, Character and extent of basin-range faulting, western Montana and east-central Idaho, *in* Newman, G.W., and Goode, H.D., eds., Basin and Range Symposium: Rocky Mountain Association of Geologist and Utah Geological Association, p. 185–193.

Ripley, A.A., 1987, Paleoenvironmental interpretation of Tertiary carbonates in western Montana: Missoula, University of Montana, M.S. thesis, 93 p.

Ripley, A.A., 1995, Tertiary carbonates in the upper Ruby and Jefferson River Valleys, Montana: Northwest Geology, v. 25, p. 47–77.

Roberts, A.E., 1972, Cretaceous and early Tertiary depositional and tectonic history of the Livingston area, southwestern Montana: U.S. Geological Survey Professional Paper 526-C, 120 p. doi: https://doi.org/10.3133/pp526C

Robinson, G.D., 1960, Middle Tertiary unconformity in southwestern Montana: U.S. Geological Survey Professional Paper 400-B, Article 101, p. 227–228.

Robinson, G.D., 1963, Geology of the Three Forks quadrangle, Montana: U.S. Geological Survey Professional Paper 370, 143 p., doi: https://doi.org/10.3133/pp370

Robinson, G.D., 1967, Geologic map of the Toston quadrangle, southwestern Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-486, scale 1:24,000.

Roe, W.P., 2010, Tertiary sediments of the Big Hole Valley and Pioneer Mountains, southwestern Montana: Age, provenance, and tectonic implications: Missoula, University of Montana, M.S. thesis, 117 p.

Rothfuss, J.L., Schwartz, T.M., and Schwartz, R.K., 2008, Alluvial facies of the Eocene Red Hill map unit of the Renova Formation, southwest Montana—Paleotopographic and extensional tectonic significance: Geological Society of America Abstracts with Programs, v. 40, no. 2, p. 83.

Rothfuss, J.L., Lielke, K., and Weislogel, A.L., 2012, Application of detrital zircon provenance in paleogeographic reconstruction of an intermontane basin system, Paleogene Renova Formation, southwest Montana, *in* Rasbury, E.T., Hemming, S.R., and Riggs, N.R., eds., Mineralogical and geochemical approaches to provenance: Geological Society of America Special Paper 487, p. 63–95, doi: https://doi.org/10.1130/2012.2487(04)

Runkel, A.C., 1986, Geology and vertebrate paleontology of the Smith River Basin, Montana: Missoula, University of Montana, M.S. thesis, 1 plate, 80 p.

Ruppel, E.T., 1993, Cenozoic tectonic evolution of southwest Montana and east-central Idaho: Montana Bureau of Mines and Geology Memoir 65, 62 p.

Scarberry, K.C., 2019, Geologic map of the Ramsay 7.5' quadrangle, southwestern Montana: Montana Bureau of Mines and Geology Geologic Map 72, 1 sheet, scale 1:24,000.

Scarberry, K.C., Elliott, C.G., and Yakovlev, P.V., 2019, Geology of the Butte North 30' x 60' quadrangle, southwest Montana: Montana Bureau of Mines and Geology Open-File Report 715, 30 p., 1 sheet, scale 1:100,000.

Scarberry, K.C., and Elliott, C., 2016, Geologic map of the Opportunity 7.5' quadrangle, southwestern Montana: Montana Bureau of Mines and Geology Open-File Report 683, 1 sheet, scale 1:24,000.

Scarberry, K.C., Korzeb, S.L., and Smith, M.G., 2015, Origin of Eocene volcanic rocks at the south end of the Deer Lodge Valley, Montana, *in* Mosolf, J., and McDonald, C., eds., Geology of the Elliston area, Montana, and other papers: Tobacco Root Geological Society 40th Annual Field Conference Guidebook, Northwest Geology, v. 44, p. 201–212.

Schmidt, C.J., and Garihan, J.M., 1986, Role of recurrent movement of northwest-trending basement faults in the tectonic evolution of southwestern Montana, *in* Aldrich, M.J., Jr., and Laughlin, A.W., eds., Proceedings of the Sixth International Conference of Basement Tectonics: Salt Lake City, Utah, International Basement Tectonics Association, p. 1–15.

Scholten, M.R., Keenmon, K.A., and Kupsh, W.O., 1955, Geology of the Lima region, southwestern Montana: Geological Society of America Bulletin, v. 66, p. 345–404.

Schricker, L., Statza, M., Barber, D.E., Schwartz, R.K. and Elliott, C., 2013, Paleogene record of Anaconda Metamorphic Core Complex unroofing and sediment dispersal in the Deer Lodge Basin of southwest Montana: Geological Society of America Abstracts with Programs, v. 45, no. 7, p. 604.

Schwartz, R.K., and Schwartz, T.M., 2009a, The Renova Formation as a record of paleolandscape, paleodrainage, and early Tertiary basin development upon the Cordilleran orogenic wedge, SW Montana: Geological Society of America Abstracts with Programs, v. 41, no., 7, p. 125.

Schwartz, T.M. and Schwartz, R.K., 2009b, Sedimentologic evidence for Early Paleogene basin development atop the Cordilleran orogenic wedge in the vicinity of the Boulder Batholith, southwest Montana: Geological Society of America Abstracts with Programs, v. 41, no. 6, p. 37.

Schwartz, R.K., Schwartz, T.M., and Chamberlin, E.P., 2009, New evidence for an early Paleogene trunk-fluvial system in the Helena thrust-belt salient of southwestern Montana—Through-going transport between post-Laramide intermontane basins: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 125.

Schwartz, R.K., O'Brien, T., Barber, D.E., Ness, J., and Weislogel, A.L., 2011, Braided channel system in the Paleogene Beaverhead intermontane basin: A longitudinal segment in the Paleo-Missouri headwater system of southwest Montana—Detrital zircon age and provenance: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 431.

Schwartz, T.M., and Graham, S.A., 2017, Depositional history and provenance of Paleogene strata in the Sage Creek Basin in southwestern Montana: Geosphere, v. 13, no., 4, p. 1285–1309, doi: https://doi.org/10.1130/GES01450.1

Schwartz, T.M., and Schwartz, R.K., 2013, Paleogene postcompressional intermontane basin evolution along the frontal Cordilleran fold-and-thrust belt of southwestern Montana: Geological Society of America Bulletin, v. 125, no. 5/6, p. 961–984, doi: https://doi.org/10.1130/B30766.1

Schwartz, T.M., Methner, K., Mulch, A., Graham, S.A., and Chamberlain, C.P., 2019a, Paleogene topographic and climatic evolution of the northern Rocky Mountains from integrated sedimentary and isotopic data: Geological Society of America Bulletin, v. 131, no. 7/8, p. 1448–1456, doi: https://doi.org/10.1130/B32068.1

Schwartz, T.M., Schwartz, R.K., and Weislogel, A.L., 2019b, Orogenic recycling of detrital zircons characterizes age distributions of North American Cordilleran strata: Tectonics, v. 38, doi: https://doi.org/10.1029/2019TC005810

Sears, J.W., 2013, Late Oligocene–early Miocene Grand Canyon: A Canadian connection?: Geological Society of America, GSA Today, v. 23, no. 11, p. 4–10, doi: https://doi.org/1130/GSATG178A.1.

Sears, J.W., and Fritz, W.J., 1998, Cenozoic tilt domains in southwestern Montana: Interference among three generations of extensional fault systems, *in* Faulds, J.E., and Stewart, J.H., eds.: Accommodation zones and transfer zones: The regional segmentation of the Basin and Range Province: Geological Society of America Special Paper 323, p. 241–247.

Sears, J.W., Hendrix, M.S., Thomas, R.C., and Fritz, W.J., 2009, Stratigraphic record of the Yellowstone hotspot track, Neogene Sixmile Creek Formation grabens, southwest Montana: Journal of Volcanology and Geothermal Research, v. 188, no. 1, p. 250–259, doi: https://doi.org/10.1016/j.jvolgeores.2009.08.017

Sears, J.W., and Ryan, P.C., 2003, Cenozoic evolution of the Montana Cordillera: Evidence from paleovalleys, *in* Raynolds, R.G., and Flores, R.M., eds., Cenozoic systems of the Rocky Mountain region: Rocky Mountain SEPM (Society for Sedimentary Geology), p. 289–301.

Sears, J.W., Link, P.K., and Karlstrom, K.E., 2014, Amazon-scale, mid-Cenozoic "Bell River" drainage basin of North America: Implications for tectonics of the Western Interior: Geological Society of America Abstracts with Programs, v. 46, no. 5, p. 20.

Seeland, D., 1985, Oligocene paleogeography of the northern Great Plains and adjacent mountains, in Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States: SEPM (Society for Sedimentary Geology), p. 187–205.

Seeland, D., 1988, Laramide paleogeographic evolution of the eastern Powder River Basin, Wyoming and Montana, *in* Diedrich, R.P., Dyka, M.A.K., and Miller, W.R., eds., Eastern Powder River Basin–Black Hills: Wyoming Geological Association 39th Annual Field Conference Guidebook, p. 29–34.

Seeland, D.A., Flores, R.M., Johnson, E.A., and Pierce, F.W., 1988, Some paleogeographic inferences from the paleocurrents of the Tongue River Member, Fort Union Formation, Powder River, Bull Mountains, and southwestern Williston Basins, Montana, *in* Flores, R.M., ed., An integrated view of the depositional systems of the Paleocene coal-bearing rocks in the Powder River Basin, Wyoming and Montana: Colorado School of Mines Professional Contributions 12, p. 191–194.

Seeland, D.A., 1992, Depositional systems of a synorogenic continental deposit—The upper Paleocene and lower Eocene Wasatch Formation of the Powder River Basin, northeast Wyoming: U.S. Geological Survey Bulletin 1917-H, 20 p., doi: https://doi.org/10.3133/b1917H

Snell, K.E., Koch, P.L., Druschke, P., Foreman, B.Z., and Eiler, J.M., 2014, High elevation of the 'Nevadaplano' during the Late Cretaceous: Earth and Planetary Science Letters, v. 386, p. 52–63, doi: https://doi.org/10.1016/j.epsl.2013.10.046

Stroup, C.N., Link, P.K., Janecke, S.U., Fanning, C.M., Yaxley, G.M., and Beranek, L.P., 2008, Eocene to Oligocene provenance and drainage in extensional basins of southwest Montana and east-central Idaho: Evidence from detrital zircon populations in the Renova Formation and equivalent strata: Arizona Geological Society Digest 22, p. 529–546.

Tabrum, A.R., 2001, Sage Creek Basin, *in* Hill, C.L. Mesozoic and Cenozoic paleontology in the western plains and Rocky Mountains: Guidebook for field trips, Society of Vertebrate Paleontology 61st Annual Meeting: Museum of the Rockies Occasional Paper, no. 3, p. 97–102.

Tabrum, A.R., Prothero, D.R., and Garcia, D., 1996, Magnetostratigraphy and biostratigraphy of the Eocene–Oligocene transition, southwestern Montana, *in* Prothero, D.R., and Emry, R.J., eds., The terrestrial Eocene–Oligocene transition in North America: Cambridge University Press, p. 278–311.

Tedford, R.H., Albright, L.B., and Barnosky, A.D., Ferrusquia-Villafrance, I., Hunt, R.M., Jr., Storer, J.E., Swisher, C.C., III, Voorhies, M.R., Webb, S.D., and Whistler, D.P., 2004, Mammalian biochronology of the Arikareean through Hemphillian interval (late Oligocene through early Pliocene epochs), *in* Woodburne, M.O., ed., Late Cretaceous and Cenozoic mammals of North America: Biostratigraphy and geochronology, New York, Columbia University Press, p. 169–231.

Thomas, R.C., 1995, Tectonic significance of Paleogene sandstone deposits in southwestern Montana, *in* Mogk, D.W., ed., Field guide to geologic excursions in southwest Montana: Rocky Mountain Section, GSA 47th Annual Meeting: Northwest Geology, v. 24, p. 237–244.

Thomas, R.C., Sears, J.W., Ripley, A.A., and Berg, R.B., 1995, Tertiary extensional history of southwestern Montana: Field trip guide for the Sweetwater and Upper Ruby Valleys, Montana, *in* Thomas, R.C., ed., Geologic history of the Dillon area, southwestern Montana: Northwest Geology, v. 25, p. 5–25.

Thompson, G.R., Fields, R.W., and Alt, D., 1981, Tertiary paleoclimates, sedimentation patterns, and uranium distribution in southwestern Montana, *in* Tucker, T.E., ed., Southwest Montana: Montana Geological Society Field Conference Guidebook, p. 105–110.

Thompson, G.R., Fields, R.W., and Alt, D., 1982, Land-based evidence for Tertiary climatic variations: Northern Rockies: Geology, v. 10, p. 413–417, doi: https://doi.org/10.1130/0091-7613(1982)10%3C413:LEFTCV%3E2.0.CO;2

Thorkelson, D.J., and Taylor, P.P., 1989, Cordilleran slab windows: Geology, v. 17, no. 9, p. 833–836, doi: https://doi.org/10.1130/0091-7613(1989)017%3C0833:CSW%3E2.3.CO;2

VanDenburg, C.J., Janecke, S.U., and McIntosh, W.C., 1998, Three-dimensional strain produced by >50 My of episodic extension, Horse Prairie Basin area, SW Montana, USA: Journal of Structural Geology, v. 20, p. 1747–1767, doi: https://doi.org/10.1016/S0191-8141(98)00084-4

Vuke, S.M., 2003, Geology of western and northern Gallatin Valley, southwestern Montana: Montana Bureau of Mines and Geology Open-File Report 481, 40 p., 1 sheet, scale 1:50,000.

Vuke, S.M., 2004, Geologic map of the Divide area, southwest Montana: Montana Bureau of Mines and Geology Open-File Report 502, 36 p., 1 sheet, scale 1:50,000.

Vuke, S.M., 2006, Geologic map of the Cenozoic deposits of the lower Jefferson Valley, southwestern Montana: Montana Bureau of Mines and Geology Open-File Report 537, scale 1:50,000.

Vuke, S.M., 2007, Geologic map of the Radersburg–Toston Basin, Montana: Montana Bureau of Mines and Geology Open-File Report 561, 17 p., 1 sheet, scale 1:50,000.

Vuke, S.M., 2020, Synorogenic basin deposits and associated Laramide uplifts in the Montana part of the Cordilleran Foreland Basin System, *in* Metesh, J.J., and Vuke, S.M., eds., Geology of Montana—Geologic History: Montana Bureau of Mines and Geology Special Publication 122, v. 1, 39 p.

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2018, Geologic time scale v. 5.0: Geological Society of America, doi: https://doi.org/10.1130/2018.CTS005R3C

Wolfe, P.E., 1964, Late Cenozoic uplift and exhumed Rocky Mountains of central western Montana: Geological Society of America Bulletin, v. 75, p. 493–502.

Wood, H.E., Chaney, R.W., Clark, J., Colert, E.H., Jepsen, G.L., Reeside, J.B., Jr., and Stock, C., 1941, Nomenclature and correlation of the North American continental Tertiary: Geological Society of America Bulletin, v. 52, p. 1–48.

Woodburne, M.O., and Swisher, C.C., III, 1995, Land mammal high-resolution geochronology, intercontinental overland dispersals, sea level, climate, and vicariance, *in* Berggren, W.A., Kent, D.V., Aubry, M-P., and Hardenbol, J., eds., Geochronology, time scales, and global stratigraphic correlations: Unified temporal framework for an historical geology: SEPM Special Publication 54, p. 337–364.

Zehner, R.E., 1987, Petrology, structure, and tectonic setting of the Hog Heaven volcanics and their relationship to mineralization: Missoula, University of Montana, M.S. thesis, 139 p.

Zehner, R.E., and Lange, I.M., 1992, Geologic map of the Hog Heaven volcanic field, northwestern Montana: Montana Bureau of Mines and Geology Geologic Map 53, scale 1:50,000.

Zen, E-An, 1988, Bedrock geology of the Vipond Park 15′, Stine Mountain 7.5′, and Maurice Mountain 7.5′ quadrangles, Pioneer Mountains, Beaverhead County, Montana: U.S. Geological Survey Bulletin 1625, 49 p., scale 1:62,500, doi: https://doi.org/10.3133/b1625

Zheng, J., 1966, Magnetostratigraphy of a Miocene sedimentary sequence in Railroad Canyon, Idaho: Pittsburgh, University of Pittsburgh, Ph.D. dissertation, 248 p.