MIDDLE MIOCENE THROUGH PLIOCENE SEDIMENTATION AND TECTONICS IN MONTANA: A RECORD OF THE OUTBREAK AND PASSAGE OF THE YELLOWSTONE HOTSPOT

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ABSTRACT

The Neogene Sixmile Creek Formation fills many grabens south of the Lewis and Clark Tectonic Zone in western Montana, preserving a stratigraphic record of the outbreak and passage of the Yellowstone hotspot from ~17 Ma to ~2.5 Ma. The grabens were formed on a broad dome centered on the hotspot outbreak area in southwest Idaho and southeast Oregon, producing an angular unconformity as the underlying Renova Formation and older rocks were tilted, eroded, and buried by graben fill of the Sixmile Creek Formation. Where these grabens were connected to drainages from the hotspot bulge, the Sixmile Creek consists of three spatially and temporally interleaved lithostratigraphic members. From oldest to youngest, they are the Sweetwater Creek, Anderson Ranch, and Big Hole River members, and are best exposed in the Ruby and Beaverhead grabens in southwest Montana. Early in the evolution of the grabens, debris and fluvial flows surged down from horst blocks and accumulated in the grabens. They captured runoff from the hotspot dome, resulting in thick deposits of interbedded fluvially deposited silicic tephra and far-traveled river gravel. As the hotspot track propagated northeastward along the eastern Snake River Plain, the northeasterly gradient increased, resulting in more gravel input and increasingly larger clast sizes. On the plains, northeasterly flowing braided rivers draining the Rocky Mountains to the west deposited widespread gravel called the Flaxville Formation. Around 4 Ma, the middle Miocene grabens were crosscut by northwest-trending Pliocene grabens as crustal stresses changed with the northeasterly passage of volcanic centers along the hotspot track. Some drainages were diverted into the new grabens, creating the present drainage system in southwest Montana.

INTRODUCTION

In this chapter we discuss stratigraphy, sedimentation, and tectonics of the middle Miocene through Pliocene Sixmile Creek and Flaxville Formations. The Sixmile Creek Formation is the upper unit of the Bozeman Group, and can be divided into three spatially and temporally interleaved lithostratigraphic members in some locations. From oldest to youngest, they are the Sweetwater Creek, Anderson Ranch, and Big Hole River members. All three of these members are only present in southwest Montana, where grabens formed on the northeast flank of the Yellowstone thermal bulge in middle Miocene time captured rivers that drained to the northeast into Montana (fig. 1). In areas where rocks of this age were not connected to the track of the Yellowstone hotspot, the Sixmile Creek Formation is mapped as locally derived, coarse-grained deposits that unconformably rest on relatively finer-grained sedimentary rocks of Eocene through middle Miocene Renova Formation or older rocks. The Sixmile Creek Formation is restricted to the Basin and Range Province in southwestern Montana and has not been mapped north of the Lewis and Clark Tectonic Zone in Montana (see fig. 1).

Numerous studies over the years have documented that the members of the Sixmile Creek Formation preserve a stratigraphic record of the evolution of Montana's Basin and Range Province and its relationship to the passage of the Yellowstone hotspot across neighboring Idaho (Burbank and Barnosky, 1990; Fritz and Sears, 1993; Sears and others, 2009; Camp and others, 2015). Well-exposed volcanic deposits provide the chronostratigraphic framework for precision temporal and spatial correlation, and detailed provenance studies have allowed the reconstruction of temporal and spatial trends associated with the passage of the Yellowstone hotspot recorded in several grabens in

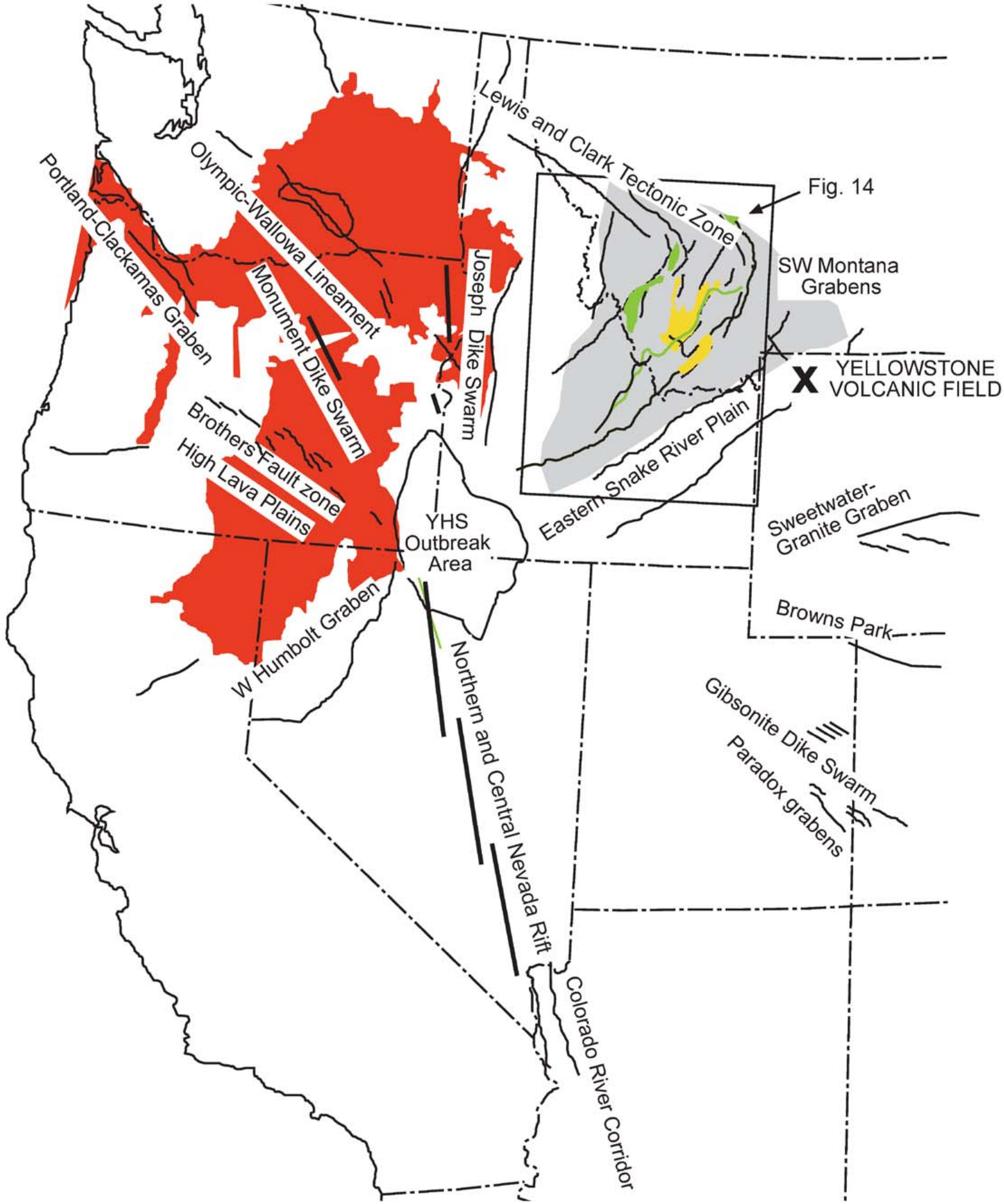


Figure 1. Extensional structures of middle Miocene age in the western United States that are radial to the outbreak area of the Yellowstone hotspot (YHS). Base map from Reed and others (2005). Modified from Sears and others (2009).

southwest Montana (Shane and Sears, 1995; Landon and Thomas, 1999a,b; Nielsen and Thomas, 2004). The youngest volcanic units in the Sixmile Creek Formation, like the Timber Hill basalt, the Kilgore Tuff, and the Huckleberry Ridge Tuff, provide the age control on the Pliocene tectonic disruption of the northeast-trending middle Miocene drainage system (the ancestral Missouri River drainage) and the development of the more complex drainage pattern we see today (fig. 2; Fritz and Sears, 1993; Sears, 2014; Parker, 2016).

The roughly correlative Flaxville Formation in eastern Montana has been less well studied, but early work documented this relatively thin gravel across the High Plains as having been derived from low-gradient, braided rivers flowing generally to the northeast, away from the Rocky Mountains. Ash deposits and fossil data show that it correlates with the upper part of the Sixmile Creek Formation in southwest Montana and may have been deposited by the ancestral Missouri and Yellowstone Rivers prior to redirection of these rivers by Pleistocene glaciation (Meneley and others, 1957; Howard, 1960; Storer, 1969; Whitaker, 1980).

REGIONAL STRATIGRAPHY

The Bozeman Group includes the Paleogene and Neogene post-Laramide deposits of southwestern Montana (Robinson, 1963), mostly preserved within grabens of the Basin and Range Province (Sears and others, 2009). Iddings and Weed (1894) and Peale (1896) originally referred the unit to the Bozeman lake beds in the Livingston and Three Forks Geologic Folios. Robinson (1967) named the Tertiary gravels at the top of the Bozeman Group the Sixmile Creek Formation in the Toston 15′ quadrangle. Kuenzi and Fields (1971) divided the Bozeman Group into the lower Renova Formation and upper Sixmile Creek Formation, on the basis of their work in the Jefferson Basin. Professor Fields and his graduate students at the University of Montana did detailed mapping and stratigraphic analysis of the units as part of their vertebrate paleontology research in the fossil-rich Cenozoic beds of southwestern Montana (Fields and others, 1985).

The Renova Formation is typically fine-grained and ash-rich, whereas by contrast, the Sixmile Creek Formation is typically coarser grained and may contain three distinct members where deposition occurred in northeast-trending grabens that drained the Yellowstone hotpot (Kuenzi and Fields, 1971; Fritz and Sears, 1993). The two formations are nearly everywhere separated by a middle Miocene (Hemingfordian, fig. 3) angular unconformity (Fields and others, 1985; Barnosky and others, 2007; Rasmussen, 1973). The Sixmile Creek Formation has been mapped, and spatially and temporally reconstructed in great detail, in several grabens of the southwestern Montana's Basin and Range Province. But in northwestern Montana, north of the Lewis and Clark Tectonic Zone, it has not been recognized; it may have been eroded, reworked, not been deposited, or possibly buried during Pleistocene time. On the High Plains of eastern Montana, the correlative unit is the Flaxville Formation, a thin, fluvial gravel (Collier, 1917).

SIXMILE CREEK FORMATION

Lithostratigraphy

The Sixmile Creek Formation unconformably overlies both tilted Renova Formation and older rocks throughout southwest Montana. Because deposition of the Sixmile Creek Formation was primarily restricted to grabens in the Basin and Range Province of Montana, its lithostratigraphic and thickness patterns largely depend upon the geometry of its enclosing horsts. Typical of terrestrial deposits everywhere, the lithostratigraphy is spatially and temporally variable, and correlation of deposits can be very difficult and not at all conducive to breaking out mapping units, as geology field camps have discovered. An exception are the many beds of fluvially deposited tephra derived from volcanic eruptions along the track of the Yellowstone hotspot. These voluminous tephra deposits inundated the grabens, so they are spatially continuous, temporally abundant, and have been sourced and dated, providing an excellent chronostratigraphic framework for lithostratigraphic correlation within and between grabens (Shane and Sears, 1995; Perkins and Nash, 2002).

Fritz and Sears (1993) divided the Sixmile Creek Formation into three spatially and temporally interleaved lithostratigraphic members in the middle Miocene Ruby graben of southwest Montana (fig. 3). At the base, the Sweetwater Creek member consists of trough cross-bedded, sandy breccia interpreted as fluvial and debris-flow deposits on alluvial fans that entered grabens from bordering horsts and older, Laramide and Eocene volcanic highlands. The Anderson Ranch member consists primarily of tephra erupted from Yellowstone hotspot calderas, inundating gra-

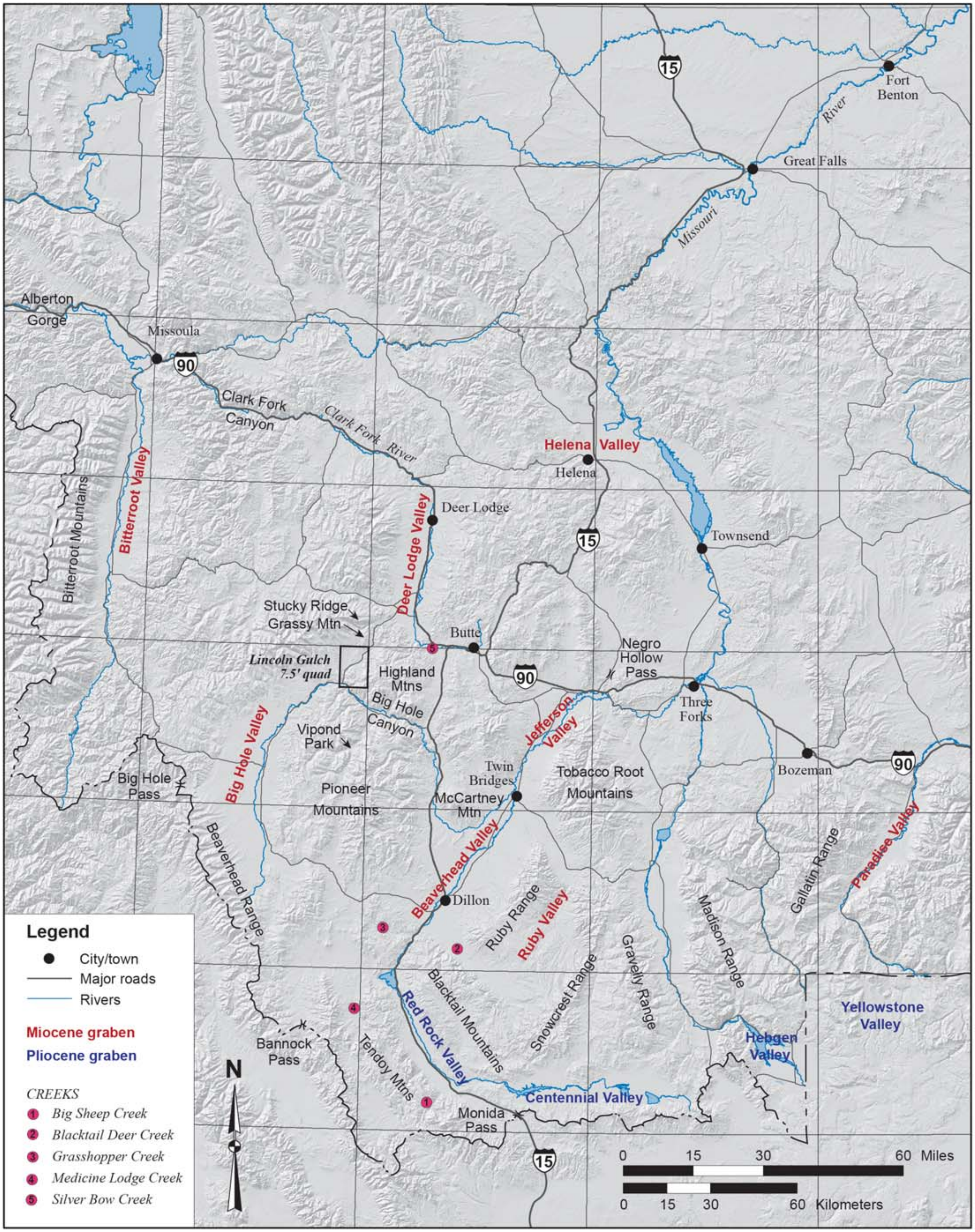


Figure 2. Location map of middle Miocene and Pliocene grabens in southwest Montana with locations of selected creek drainages and other geographic features referred to in this paper.

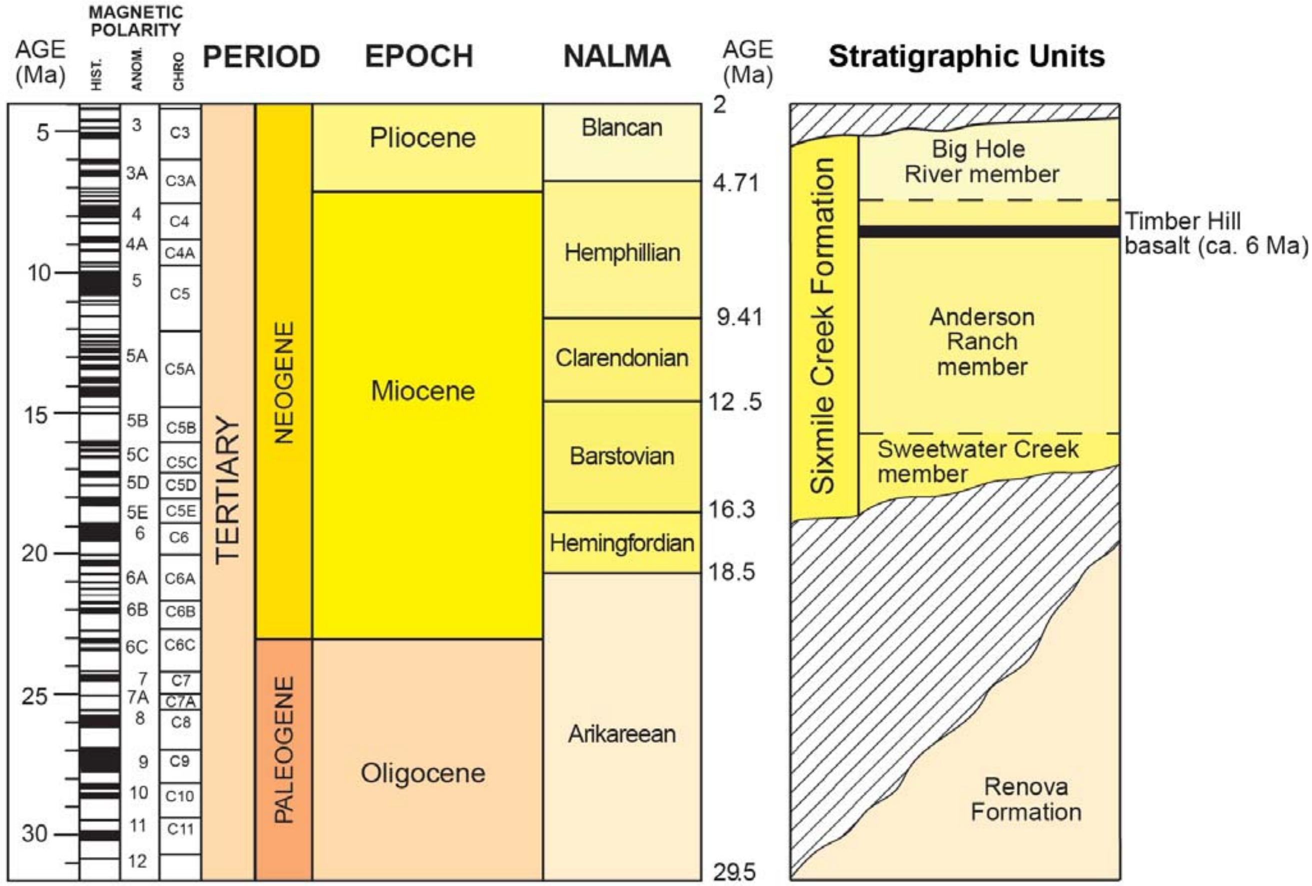


Figure 3. Generalized stratigraphy of the Sixmile Creek Formation (modified from Fritz and Sears, 1993). The Timber Hill basalt occurs only in the Ruby Graben in southwest Montana, and all members are not recognizable in every area where the Sixmile Creek Formation is mapped in Montana. Land mammal ages from Woodburn and Swisher (1995).

bens in southwest Montana, possibly as ashy lahars that were fluvially deposited. The tephra was spread widely across the grabens, depositing not only in the axial drainage, but also across the floodplain and even over the bordering alluvial fans. At the top, the Big Hole River member consists primarily of well-rounded gravel and conglomerate deposited by fluvial systems that followed graben axes. Over time, this member not only came to dominate the graben fill, but its spatial and grain-size distribution also increased as the Yellowstone hotspot migrated closer to the region, increasing the stream gradient (Landon and Thomas, 1999a,b). Although the members generally follow this stratigraphic order, they each occur throughout the Sixmile Creek Formation.

Lithostratigraphic correlation of the Sixmile Creek Formation in locations not connected to the Yellowstone hotspot and its associated tephra can be much more problematic. Absent the tephra, the formation may simply consist of coarse-grained sedimentary deposits resting on the Renova Formation or older rocks. Some of these deposits are late Pliocene (based on ages obtained from interbedded and overlying volcanic units) alluvial fan and bajada deposits that mark the culmination of valley filling by the Sixmile Creek Formation, but some are Pleistocene glacial deposits or Holocene alluvium, so care must be given in mapping the Sixmile Creek Formation. The entire formation is typically deeply dissected by Pleistocene stream valleys and gullies, or buried under Pleistocene glacial deposits, outwash fans, and post-glacial alluvium and colluvium.

Sweetwater Creek Member

The Sweetwater Creek member is dominant at the base of the Sixmile Creek Formation, but it spans middle Miocene through Pliocene time, the duration of deposition of the Sixmile Creek Formation. Basal deposits contain Barstovian (middle Miocene) fossils, so the member and formation are at least this old. It records alluvial and debris-flow fan deposition into extensional basins developed around 17 million years ago, about the same time as the outbreak of the Yellowstone hotspot and the development of the Basin and Range Province in southwest Montana.

The Sweetwater Creek member consists primarily of trough cross-bedded deposits of angular pebbles and cobbles in a coarse, sandy matrix, likely deposited by fluvial processes over relatively short distances on alluvial fans (fig. 4). Some deposits are inversely graded, showing that debris-flow deposition occurred on the alluvial fans as well. Provenance and paleoenvironmental reconstruction studies show that the sediment was derived from local sources, primarily horsts adjacent to the grabens. For example, alluvial fan deposits on the northwest flank of the northeast-trending, middle Miocene Ruby graben east of Dillon are dominated by angular fragments of Archean igneous and metamorphic rocks and Eocene volcanic rocks, both exposed in what was then the adjacent horst. Paleoflow data show a strong southeast flow trend, and where individual beds can be laterally traced, grain size decreases to the southeast, away from the source and toward the graben axis (Landon and Thomas, 1999a,b).

There are important temporal and spatial lithostratigraphic trends that support the interpretation that this member records alluvial fan deposition into the grabens. Spatially, the more proximal to the source (the horst), the higher the percentage of this member in the formation and the thicker the individual beds. The percentage and thickness (and associated grain size) both decrease towards the axis of the drainage, recording the transition from proximal to distal regions of the alluvial fans. Temporal trends show a general upsection decrease in alluvial fan deposition at the expense of axial drainage deposition (Anderson Ranch and Big Hole River members), probably as a result of basin filling and gradient changes related to the encroaching Yellowstone hotspot.

In several places in southwest Montana (fig. 5), the mapped base of the Sixmile Creek Formation consists of megadebris flow deposits composed of unusually large blocks of locally derived, matrix-supported clasts. For example, the east flank of McCartney

Figure 4. Trough cross-bedded alluvial fan deposits of the Sweetwater Creek member of the Sixmile Creek Formation in the Ruby graben, southwest Montana. Most of the clasts are composed of locally derived, angular Archean metamorphic and Eocene volcanic rocks.

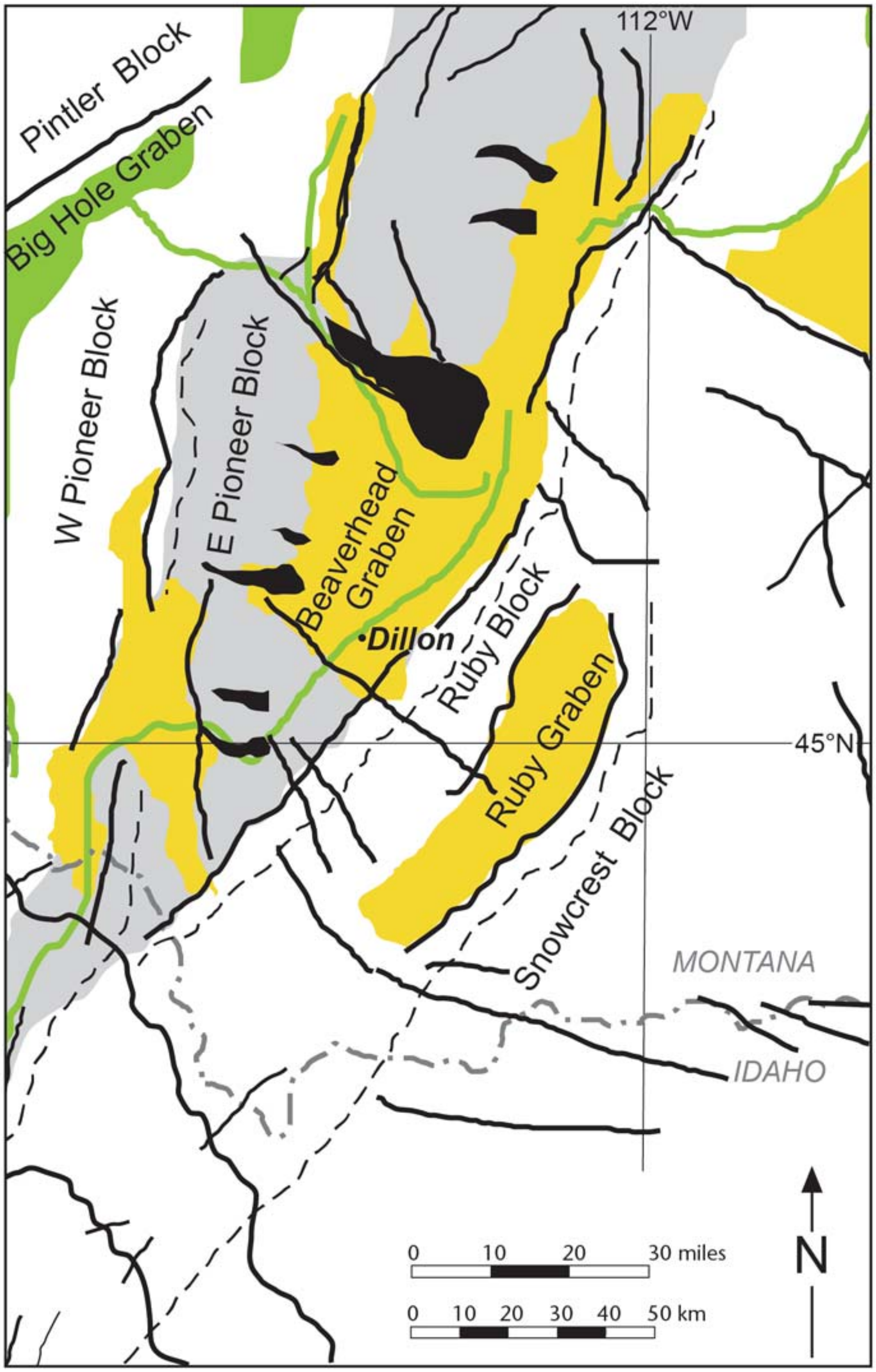


Figure 5. Map showing the location of debris flow deposits (solid black areas) at the base of the Sweetwater Creek member of the Sixmile Creek Formation in southwest Montana. The gray area is the East Pioneer horst, and the yellow areas are middle Miocene graben fill deposits. The solid black lines are faults and the dashed black lines show the trend of middle Miocene horst crests. Modified from Sears and others, 2009.

Mountain north of Dillon (fig. 2), a range composed in part of granitic rock, is peppered with gigantic granitic blocks in a granitic grus matrix; the largest block is 15 m (49 ft) long. The matrix of many of the megadebris flow deposits consists of recycled Renova Formation mudstone with "popcorn" weathering characteristic of abundant smectitic clay. The debris flows may have occurred on a wet, clay-rich surface of Renova Formation, caused by the brief, wet, middle Miocene climatic optimum interval and triggered by crustal tilting and earthquakes associated with the outbreak of the Yellowstone hotspot and the onset of Basin and Range faulting in southwest Montana.

Anderson Ranch Member

The ash-fall tephra beds of the Anderson Ranch member were derived from explosive silicic calderas that erupted as the Yellowstone hotspot progressed northeastward along the eastern Snake River Plain

(Shane and Sears, 1995; Thomas and others, 1995; Perkins and Nash, 2002). The tephra provides the chronostratigraphic framework for most of the Sixmile Creek Formation. Initial fission-track studies of the tephra beds in southwest Montana showed ages ranging from 11.3 Ma to 6 Ma (Shane and Sears, 1995). Perkins and Nash (2002) correlated fluvially deposited tephra layers in the Anderson Ranch member in the Blacktail Deer Creek area with the 14 Ma Owyhee–Humbolt, 12.5 Ma Bruneau–Jarbidge, 10 Ma Twin Falls–Picabo, and 6 to 4 Ma Heise volcanic fields of the Yellowstone hotspot, as outlined by Pierce and Morgan (1992). Silicic sands from the Anderson Ranch member contain 16 Ma to 6 Ma detrital zircons with a concentration at 10 Ma (Link and others, 2008; Stroup and others, 2008), indicating long-term fluvial reworking of Yellowstone hotspot ash in the Sixmile Creek depositional system.

The Anderson Ranch member consists of tabular to lenticular beds of trough cross-bedded, fluvially transported, and deposited tephra. The tephra is a mix of ash and pumice, silicic sand and gravel, and tabular to irregular fragments of ripped-up, transported, and redeposited finer-grained tephra (fig. 6). The ash consists mostly of sand-sized particles of glass that are tubular, commonly hollow, and relatively unbroken. The silicic sand and gravel typically occur at the base of the tephra deposits and consist of locally derived lithologies picked up during initial deposition of the tephra. The rip-up clasts range from rounded pebbles to large, angular fragments (>0.75 m, 2.5 ft) of finer-grained tephra and can occur anywhere within a tephra bed. Some are concentrated at the base of trough cross beds, some are imbricated, and others are scattered throughout the deposit with no discernible orientation (fig. 7). Paleoflow studies show a dominant flow to the northeast, with abundant variance around the mean flow direction, typical of braided streams (Landon and Thomas, 1999a,b; Nielsen and Thomas, 2004).

Although some fluvially deposited tephra beds exceed 30 m (98 ft) in thickness, the airfall ash in the area was minimal, with most known beds less than 10 cm (12 in) thick (Nielsen and Thomas, 2004). The thick, fluvially deposited tephra beds rest on axial drainage deposits, floodplain paleosols, and alluvial fan deposits, showing that the grabens were completely inundated by ash during initial fluvial deposition. Closer to the drainage axis, some tephra beds are more massive, with inverse grading and very large, angular floating fragments of ripped-up tephra, more typical of debris-flow deposition than fluvial deposition. A basal tephra deposit overlying a floodplain paleosol in the Ruby graben east of Dillon shows probable antidune crossbedding, formed by standing waves (fig. 8). This structure suggests the basal surge of tephra was a very high-flow velocity event, probably a lahar that spread out well beyond the channel during deposition. Subsequent reworking by braided streams in this tephra-overloaded system produced the intensely cross-bedded deposits with rip-up clasts of once sticky, fine-grained layers of tephra. Caliche soils

Figure 6. Trough cross-bedded tephra of the Anderson Ranch member of the Sixmile Creek Formation in the Ruby graben, southwest Montana. The tephra is mostly a mix of fluvially deposited ash, pumice, and ashy rip-up clasts from an explosive, silicic caldera eruption of the Yellowstone hotspot in Idaho.

Figure 7. Rip-up clasts of finer-grained tephra in a matrix of sandy tephra. Anderson Ranch member of the Sixmile Creek Formation in the Ruby graben. Pocket knife for scale.

Figure 8. Antidune crossbedding overlying a blocky weathering paleosol in the Anderson Ranch member of the Sixmile Creek Formation in the Ruby graben, southwest Montana. This deposit was likely from a very high-flow velocity lahar that spread well beyond the channel and onto the floodplain.

commonly developed at the top of tephra deposits as the widespread flow dissipated, exposing new floodplains and forming new axial stream channels that transported silicic gravel. Caliche zones with abundant rhizoliths indicate that vegetation colonized the ash, probably shortly after deposition, since some paleosols have polygonal cracks (fig. 9; Landon and Thomas, 1999a,b; Nielsen and Thomas, 2004).

Figure 9. Cross-sectional view of a branching rhizolith in a caliche soil zone developed in tephra of the Anderson Ranch member of the Sixmile Creek Formation in the Ruby graben, southwest Montana.

Big Hole River Member

The Big Hole River member consists of well-rounded, pebble and cobble gravel and conglomerate deposited by fluvial processes in the axial drainages of the northeast-trending, middle Miocene grabens (fig. 10). The clast composition includes distinctive pebbles and cobbles derived from distant sources, some of which can be traced and correlated from southwest to northeast for hundreds of kilometers, now crossing numerous northwest-trending mountain ranges that must not have been there during middle Miocene deposition. Provenance studies show that some lithologies match bedrock lithologies that are found in Idaho, Nevada, and Utah, but are absent in Montana, except locally as clasts within exposures of the Late Cretaceous Beaverhead Group (Sears, 2013; Parker, 2016). These distinctive clasts can be traced from the Continental Divide near Monida Pass to Fort Benton (Sears, 2014). Paleocurrent studies of imbricated cobbles indicate northeastward flow with moderate variance from the mean flow direction, suggesting that low-sinuosity braided fluvial systems migrated across its floodplain. The clasts also systematically decrease in size northeastward, away from southwest source areas (Landon and Thomas, 1999a,b). Paleoenvironmental reconstructions of the Ruby and Beaverhead grabens near Dillon (fig. 2) show that this member increases spatially with time across each graben at the expense of the other two members, becoming the dominant depositional environment by the end of Sixmile Creek deposition. Interestingly, grain size also increases with time. Both the temporal increase in gravel and grain size likely record gradient steepening with encroachment of the Yellowstone thermal bulge (Landon and Thomas, 1999a,b; Nielsen and Thomas, 2004).

High-level stream-rounded gravel in various mountain ranges of southwest Montana show the interconnectedness between graben basins prior to their tectonic disruption in late Miocene and early Pliocene time. In the Lincoln Gulch 7.5′ quadrangle, fluvial gravels of apparent Neogene age occur at elevations above 1,800 m (6,000 ft; Elliott, 2017); and at Big Hole Pass, “Negro Hollow pass,” Vipond Park, Stucky Ridge, Grassy Mountain, and in the Gravelly Range (fig. 2), Sixmile Creek gravel occurs above 2,400 m (8,000 ft). Numerous datable marker beds provide time constraints on the termination of deposition in the Sixmile Creek Formation grabens and the development of the modern fluvial drainage system. Parker (2016) found deformed fluvial gravel above 2,400 m (8,000 ft) that was interlayered with the 4.5 Ma Kilgore Tuff. He included these gravels in the Sixmile Creek Formation, although they were formerly mapped as part of the Late Cretaceous Beaverhead Group (Scholten and others, 1955; Ryder and Scholten, 1973).

Figure 10. Fluvially deposited conglomerate of the Big Hole River member of the Sixmile Creek Formation, Beaverhead graben, southwest Montana. Some of the clast lithologies match bedrock sources in Idaho, suggesting long-distance transport and deposition in the northeast-trending, middle Miocene grabens of Montana.

One thick caliche-cemented conglomerate provides a prominent marker bed in southwestern Montana. The conglomerate overlies the Blacktail Creek tephra (6.62 Ma), locally underlies an undated welded tuff that may represent a remnant of the 6.27 Ma Walcott Tuff, and elsewhere underlies the 6 Ma Timber Hill basalt. The youngest Big Hole River member fluvial gravel overlies the Timber Hill basalt and may contain clasts of 4.45 Ma Kilgore Tuff (Sears, 2014). Deposition of the Sixmile Creek Formation in northeast-trending grabens was terminated shortly after deposition of the Kilgore Tuff, when northwest-trending basins and ranges started to develop, diverting streams into new grabens and lifting the Sixmile Creek Formation into new ranges. The change in crustal extension coincides in time with and was likely caused by the passage of the Yellowstone thermal bulge to the northeast.

Initial understanding of the timing of the development of the northwest-trending extensional topography in southwest Montana came from studies of the 6 Ma Timber Hill basalt flow in the Sweetwater Range east of Dillon (Fritz and Sears, 1993; Thomas and others, 1995). At this location, the 10-m-thick (33 ft) basalt flow lies within fluvial gravel beds of the Big Hole River member and is cut by the active, northwest-trending Sweetwater normal fault (fig. 11). Shoestring remnants of the now topographically inverted basalt can be traced to the southwest for over 50 km (31 mi) along the length of the Ruby graben, where it overlies a welded tuff that may be the 6.2 Ma Walcott Tuff (Thomas and others, 1995; Lonn and others, 2000). Numerous northwest-trending extensional faults tilt and displace the Timber Hill basalt into more than 20 blocks along its length as a result of changes in crustal stresses associated with the passage of the Yellowstone thermal bulge (Hurlow, 1995; Lonn and others, 2000).

FLAXVILLE FORMATION

The Flaxville Formation is a thin gravel bed on the High Plains of eastern Montana (fig. 12). It overlies a middle Miocene unconformity, was incised by Pleistocene erosion, and was locally overlain by glacial deposits (Collier, 1917; Collier and Thom, 1918). It caps

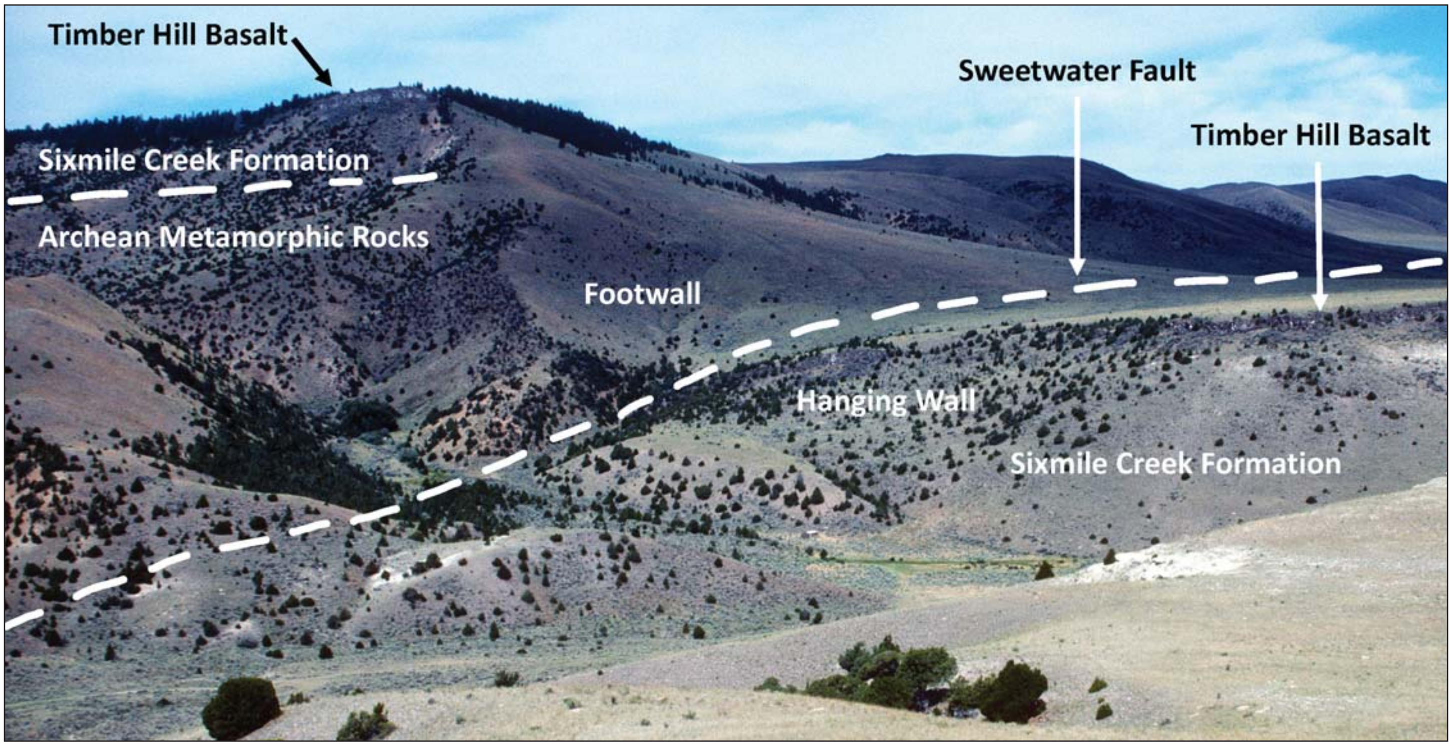


Figure 11. Cross-sectional view of the northwest-striking Sweetwater normal fault cutting the 6 Ma Timber Hill basalt flow in the Ruby graben, southwest Montana. Erupted from the Heise Volcanic Field in Idaho, the offset of this channel deposit records the oldest possible timing of the change from deposition in northeast-trending, middle Miocene grabens to the development of cross-cutting, northwest-trending extensional topography in Pliocene time. This change in crustal extension was caused by the relative passage of the Yellowstone thermal bulge to the northeast, followed by crustal collapse along northwest-striking normal faults in its wake. Photo courtesy of Marli Miller.

Figure 12. Typical exposure of the Flaxville Gravel on the High Plains of eastern Montana. Photo courtesy of Don Hyndman.

erosion surfaces on four extensive plateaus that stand 90 to 180 m (295 to 590 ft) above modern floodplains (Howard, 1960). The Flaxville surface slopes eastward across the High Plains, descending from elevations of 975 m (3,200 ft) in the west to 790 m (2,790 ft) in the east (Leckie, 2006). The formation ranges in age from Clarendonian to late Hemphilllian (Storer, 1969), and contains volcanic ash dated to 9 Ma and 6.5 Ma (Whitaker, 1980). It is correlative with the upper part of the Sixmile Creek Formation, and the middle to upper Miocene Ogallala Formation on the High Plains to the southeast (Seeland, 1985).

The Flaxville Formation averages 12 m (40 ft) thick but ranges up to 37 m (121 ft) thick where it fills deeper paleochannels (Leckie, 2006). It represents the deposits of low-sinuosity braided river systems generally flowing to the northeast (Leckie, 2006). It is generally unconsolidated, with well-rounded pebbles and cobbles of quartzite and argillite that were largely derived from the Belt Supergroup of the Rocky Mountains (Collier and Thom, 1918). Clasts of chert, chert–pebble conglomerate, breccia, chalcedony, petrified wood, fossil bones, and limestone also occur (Patton, 1987). Igneous rock clasts derived from the Bears Paw and Highwood Mountains occur as pebbles and grains in the clay and sand matrix (Whitaker, 1980). The Flaxville Formation is locally overlain by marl deposits as much as 8.8 m (29 ft) thick, which were derived from calcareous dust blown in from the Rocky Mountains (Collier and Thom, 1918; Whitaker, 1980; Patton, 1987).

The Flaxville Formation may have been deposited on a broad floodplain by the ancestral Missouri and Yellowstone Rivers when they flowed northeast towards Canada until as recently as Pleistocene glaciation, when continental ice sheets advanced from Canada and blocked the northward drainage (Meneley and others 1957; Howard,1960; Whitaker, 1980).

SEQUENCE STRATIGRAPHY

Hanneman and Wideman (1991) advocated a sequence stratigraphic division of the Cenozoic deposits of southwestern Montana, based on internal unconformities. They assigned the Sixmile Creek Formation to Sequence 4, bounded below by the Hemingfordian unconformity (“unconformity 5 hiatus”; see Vuke, 2020), and bounded above by the sub-Pleistocene unconformity.

The Hemingfordian unconformity is an angular unconformity that separates faulted and tilted early Eocene to early Miocene volcanics and sediments of the Renova Formation and older rocks from the overlying middle Miocene to Pliocene Sixmile Creek Formation (fig. 13; Robinson, 1960; Kuenzi and Richard, 1969; Rasmussen, 1973, 2003; Fields and others, 1985; Harris and others, 2017). Regionally extensive middle Miocene laterite paleosols and profound erosion at the sub-Sixmile Creek Formation unconformity correlate with the brief, wet, middle Miocene climatic optimum interval (Thompson and others, 1982; Zachos and others, 2001; Chamberlain and others, 2012), which abetted the organization of new drainage patterns, with large rivers and deep lakes. Similar conditions are recorded by flora that occur in sediments between flows of the Columbia River Basalt Group, as well as by the lateritic tops of the individual basalt flows.

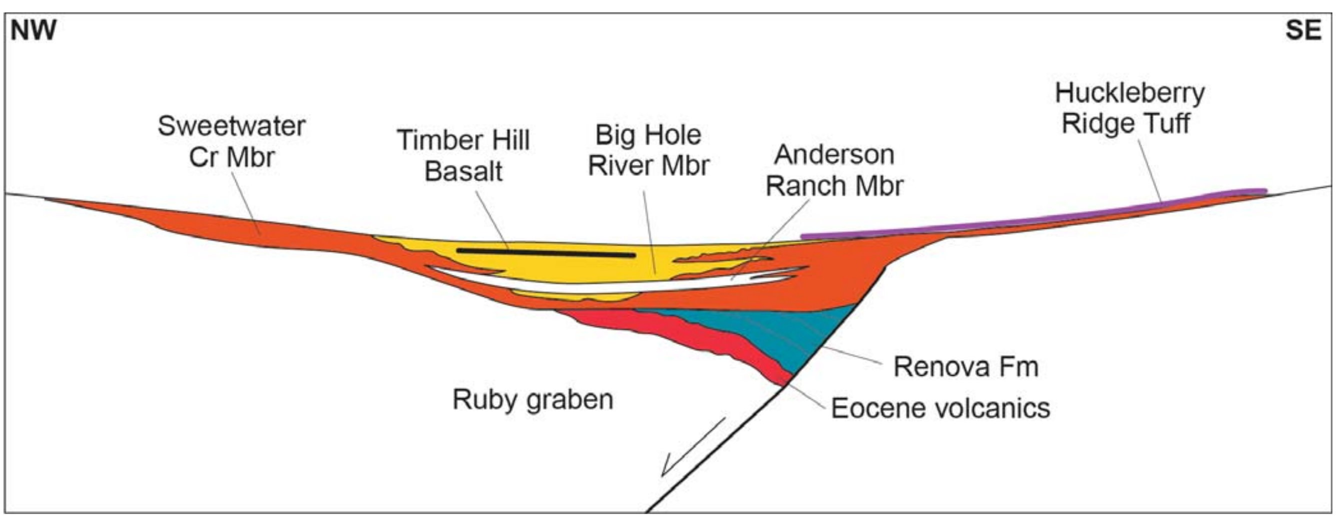


Figure 13. Schematic cross section of the middle Miocene Ruby graben in southwest Montana showing the Hemingfordian unconformity between the Renova Formation and older rocks and the overlying Sixmile Creek Formation. Modified from Sears and others, 2009.

The massive debris flows at the base of the Sixmile Creek Formation may have been triggered by the wet conditions together with tectonic unrest at the onset of Basin and Range faulting, which tilted land surfaces to unstable configurations. The change from the wet middle Miocene climatic optimum to a resumption of aridity through later Miocene and Pliocene times was reflected in the aggradation of thick alluvial fan deposits of the Sweetwater Creek member of the Sixmile Creek Formation in the graben basins.

Deep Pleistocene valleys segmented the Sixmile Creek Formation and in places all of the Sixmile Creek Formation was removed down to basal bedrock erosional surfaces. Small remnants of 2.1 Ma Huckleberry Ridge Tuff are locally preserved on alluvial fans above the Ruby Valley. After the Huckleberry Ridge Tuff erupted onto the fans, the fans were erosionally dissected. Pleistocene glacial outwash and till occupy valleys eroded through the Pliocene fans. Pleistocene erosion incised into as much as 100 m (328 ft) of the Sixmile Creek Formation, and although incision slowed as a result of Holocene climate change, it continues to this day owing to active extension and regional uplift.

CHRONOSTRATIGRAPHY AND GEOCHRONOLOGY

Abundant vertebrate fossils have been collected from the Sixmile Creek Formation, representing North American Land Mammal Ages corresponding to the middle and late Miocene Barstovian, Clarendonian, and Hemphillian ages, and Pliocene Blancan age. The range of these ages is 16.3 Ma to at least 4.4 Ma. Hemingfordian age fossils (20.6 Ma to 16.3 Ma) are only known from a couple of basins (Tabrum, 2001; Barnosky and others, 2007; Retallack, 2007; Harris and others, 2017), and the age generally marks the hiatus between the Renova and Sixmile Creek Formations.

Smith (1992) K-Ar dated basalt flows at the base of the Sixmile Creek Formation in the Gravelly Range at 16.9 ± 0.3 Ma. Perkins and Nash (2002) correlated tephra beds within the Sixmile Creek Formation to regional Yellowstone hotspot tephra deposits dated at 14, 12.5, 10, and 6 to 4 Ma. These yielded fission-track dates from 11.3 Ma to 6 Ma (Shane and Sears, 1995). Detrital zircons from the Anderson Ranch member ranged from 16 Ma to 6 Ma (Link and others, 2008; Stroup and others, 2008). The Timber Hill basalt flow gave a K-Ar whole-rock age of 6 Ma. The 6.62 Ma Blacktail Tuff and 4.45 Ma Kilgore Tuff bracket deposition of parts of the Big Hole River member, and the 2.1 Ma Huckleberry Ridge Tuff, caps the Sixmile Creek Formation in the Ruby River drainage.

INITIATION OF BASIN AND RANGE STRUCTURE

Extension in the northeastern edge of the Basin and Range Province disturbed the southwestern Montana Rockies beginning in middle Miocene time (Ruppel, 1993; Sears and Fritz, 1998). Several northeast-trending middle Miocene Basin and Range extensional faults crossed southwest Montana and abutted the Lewis and Clark Tectonic Zone, which acted as a right-lateral, transtensional fault zone, as it had previously acted in the Eocene (Sears and Fritz, 1998). Eocene extensional faults in the Bitterroot, Deer Lodge, Helena, and other valleys were reactivated during the middle Miocene disturbance.

Pardee (1950) documented late Cenozoic block faulting in western Montana. Basin and Range grabens include parts of the Ruby, Beaverhead, Big Hole, Deer Lodge, Medicine Lodge–Grasshopper, Three Forks, Canyon Ferry, Jefferson, Melrose, Wise River, and Paradise Valleys (fig. 2). Ranges include parts of the Beaverhead, Pioneer, Ruby, Snowcrest, Gravelly, Madison, Gallatin, and Highland Mountains. The spacing between grabens varies from 50 to 80 km (31 to 50 mi). Most are half-grabens, with the main normal faults on one side. Horst blocks tilt toward the half-grabens.

As much as 250 to 3,000 m (820 to 9,842 ft) of sediment accumulated along the axes of the valleys, as shown by locally exposed sections, seismic reflection profiles, and industry boreholes (Fields and others, 1985; McLeod, 1987; Hanneman and Wideman, 1991; Fritz and Sears, 1993; Sears and others, 2009). Most of the Sixmile Creek Formation was deposited passively in the middle Miocene grabens without distinctive internal angular unconformities or drainage reversals (Nielsen and Thomas, 2004), although wedge-shaped accumulations indicate growth faulting during deposition. In late Miocene or Pliocene time, sets of northwest-trending normal faults crosscut the older northeast-trending grabens. These appear to be related to tectonism along the northern shoulder of the Yellowstone hotspot track (Anders and others, 1989; Pierce and Morgan, 1992; Sears, 1995; Sears and Thomas, 2007).

The disturbance that initiated the graben development coincided with the outbreak of the Yellowstone hotspot and Columbia River Flood Basalt Group in southwest Idaho and southeast Oregon (Sears, 1995; Hooper and others, 2007; Sears and Thomas, 2007; Camp and others, 2015), and with initiation of Basin and Range extension (Atwater, 1970; Wernicke and Snow, 1998). The northeast-trending grabens are radial to the outbreak region of the hotspot (see fig. 1).

Radial extensional features are consistent with a model that suggests that outbreak points of hotspots mark the centers of broad extensional domes, immediately prior to eruptions of Large Igneous Provinces (LIPs), such as the Columbia River Basalt Group (Rainbird and Ernst, 2001). Radial grabens capture runoff from a hotspot dome and augment rapid incision of deep radial valleys, such as those of southwest Montana. In southwest Montana, the sub-Sixmile Creek Formation unconformity commonly spans the interval from 20 Ma to 17 Ma (Fields and others, 1985) and may manifest doming, radial faulting, and erosion during some 3 million years prior to eruption of the Columbia River Basalt Group LIP. Faunal data from eastern Idaho suggest a shorter hiatus of approximately 1 million years immediately prior to eruption of the LIP (Barnosky and others, 2007).

MIDDLE MIOCENE PALEODRAINAGES

A wet period filled large lakes and established new throughgoing drainage systems in the wake of the middle Miocene crustal disturbance. These included the headwaters of the Clark Fork and Missouri Rivers. Broad valley floors incised bedrock horsts between grabens and are presently exhumed as strath terraces (Sears and Ryan, 2003). Karst development etched some middle Miocene valleys in Paleozoic limestone; associated collapsed caverns contain terra rosa soils (Sears, 2007).

The Deer Lodge and Big Hole grabens were sites of deep middle Miocene lakes, superimposed on Paleogene rift valleys on the flanks of core complexes (fig. 14; Janecke and others, 2000). The Deer Lodge graben has been explored for hydrocarbons, and seismic reflection profiles and boreholes show that it has a 4-km-thick fill of Tertiary units (McLeod, 1987). The lower 1.0 km is composed of down-faulted Renova Formation and Eocene volcanics, and the remainder is composed of flat-lying lake beds and massive debris flows of middle Miocene age (McLeod, 1987). Seismic reflection profiles indicate that the 3-km section of lake beds is horizontally bedded rather than wedge-shaped (McLeod, 1987). It therefore appears to represent the fill of a deep lake basin rather than an evolving rift-wedge. The lake in the Deer Lodge Valley appears to have spilled out along the Lewis and Clark Tectonic Zone, cutting a broad canyon along the Clark Fork River from Garrison to Missoula. As the outflow canyon deepened, the Deer Lodge graben filled with fine-grained lacustrine sediment, likely stripped from the uplifted Renova Formation on the rift shoulders, until the entire system was an evenly graded river valley. Near Deer Lodge, the outlet valley eroded through tilted sections of Renova-equivalent beds with excellent early Miocene fossil control (Rasmussen, 1969), overlain by flat-lying fluvial conglomerates of the Sixmile Creek Formation containing 16 Ma Barstovian fossils (Rasmussen, 1969). A middle Miocene strath-terrace has been traced along the Clark Fork River from Deer Lodge to Missoula. Near Missoula, the strath-terrace developed on steeply tilted and faulted Bitterroot River paleovalley deposits, likely equivalent to the Renova Formation, and is overlain by fluvial gravel derived from both the Clark Fork Valley to the east and the Bitterroot Valley to the south (Harris, 1997). Sears and Ryan (2003) suggested that middle Miocene faulting along the Lewis and Clark Tectonic Zone diverted the flow of the ancestral Bitterroot River into the modern course of the Clark Fork River. New canyons downstream from Missoula, such as Alberton Gorge (fig. 2), were eroded through bedrock ridges between grabens along the Lewis and Clark Tectonic Zone.

A seismic reflection profile and borehole reveal >5 km (3.1 mi) of Cenozoic fill in the Big Hole graben. These Cenozoic units include down-faulted Eocene volcanic rock and Renova Formation, overlain by kilometers-thick Miocene lake beds (Roe, 2010). The Big Hole lake appears to have spilled into a river that eroded the Big Hole Canyon through the Pioneer Mountains and entered the Beaverhead graben near Twin Bridges, where it deposited a large alluvial fan (Sears and others, 2009).

Distinctive pebbles and cobbles occur in Big Hole River member fluvial conglomerates, especially in the Ruby and Beaverhead grabens. These include clasts that had ultimate sources in east-central Idaho. They occur as far north as Fort Benton, Montana (Landon and Thomas, 1999a). One clast type of note is black

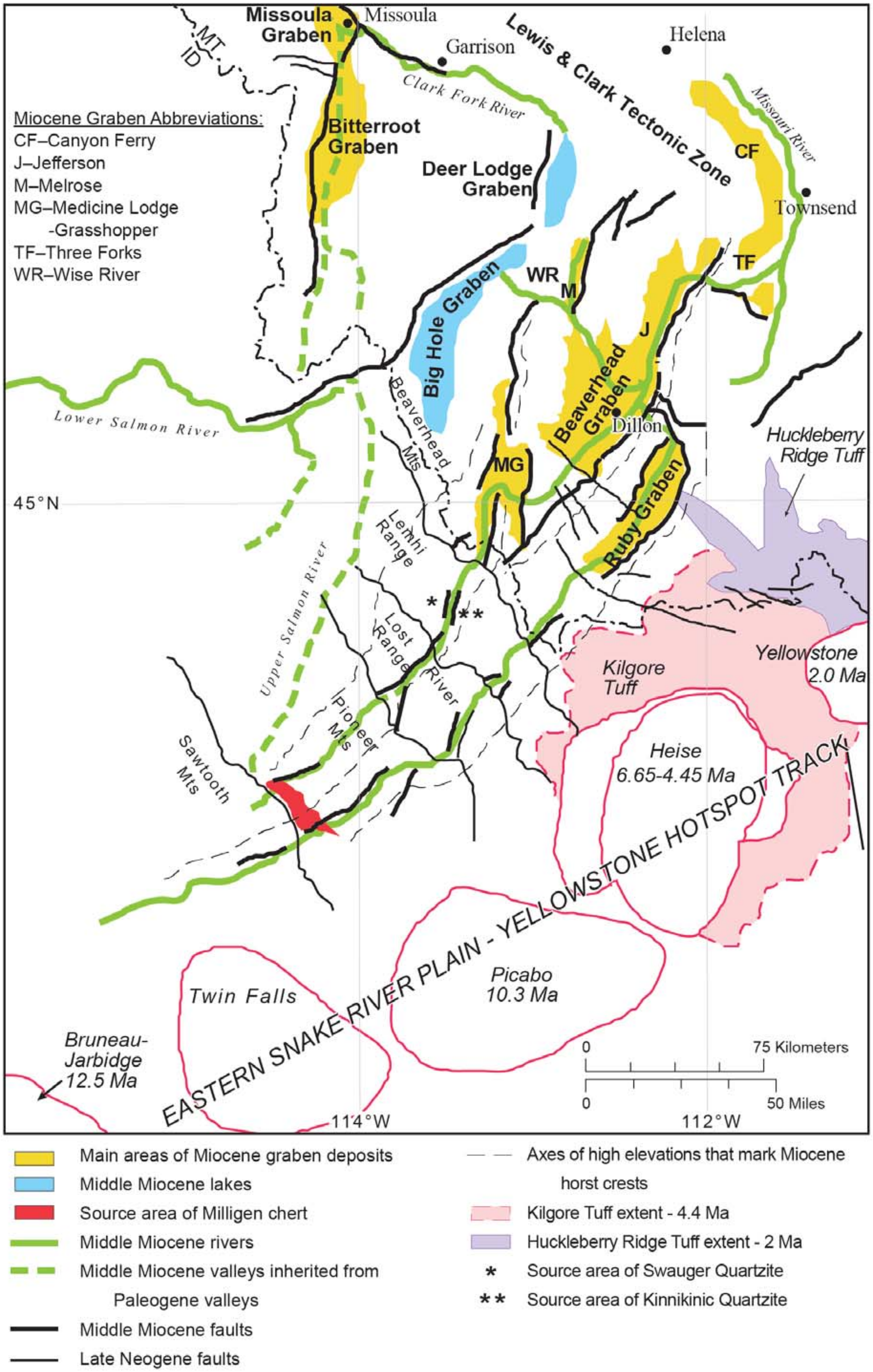


Figure 14. Southwest Montana–East-central Idaho middle Miocene graben system. See figure 1 for location.

meta-chert that is crisscrossed with quartz veins. It matches the unusual Devonian Milligen chert in east-central Idaho, a thick, basinal, bedded black chert deposit in the Roberts Mountain thrust plate that was polydeformed and metamorphosed during the Antler and Cordilleran Orogenies and crisscrossed with quartz veins (Sears and Ryan, 2003). Sears and others (2009) matched the chert to the Milligen Formation because its unusual metamorphic character distinguishes it from black chert nodules in unmetamorphosed limestones of southwest Montana. Stroup and others (2008) identified Middle Devonian detrital zircons in the Sixmile Creek Formation near Timber Hill, consistent with east-central Idaho provenance in the Antler orogenic belt. Sears and others (2009) matched other exotic clasts to the Middle Proterozoic Swauger Quartzite, Ordovician Kinnikinick Quartzite, Mississippian Copper Basin conglomerate, and Eocene Challis volcanic rocks of east-central Idaho. Sears (2013) speculated that the ultimate source of the chert could be in the Antler orogenic belt of central Nevada, rather than east-central Idaho, because the Idaho rocks were buried by Eocene volcanics at the time of deposition of the Big Hole River member fluvial conglomerates and were only later exposed by younger normal faulting on the shoulder of the Yellowstone hotspot track (fig. 14).

The presence of possible east-central Idaho or central Nevada clasts and detrital zircon in middle and upper Miocene gravel of southwest Montana may indicate that the Lost River, Lemhi, and Beaverhead Ranges (fig. 14) beheaded the graben drainages in late Miocene time when northwest-trending faults on the north flank of the eastern Snake River Plain grew in displacement and established the ranges. The paleovalleys were left as wind gaps in the mountain ranges, as described by Anderson (1947). He proposed that a paleodrainage that he named the Arco River once flowed northeastward across east-central Idaho.

Some workers suggest that the east-central Idaho clasts were recycled out of the Beaverhead conglomerate of southwest Montana, which would not require migration of the drainage divides (Scholten and others, 1955; Ryder and Scholten, 1973). However, the silicic ash deposits of the Anderson Ranch member in the Ruby and Beaverhead grabens indicate a definite fluvial connection to the Yellowstone hotspot eruptive centers in Idaho during deposition of the Sixmile Creek Formation, so the clasts in the Big Hole River member are not essential to the argument (Shane and Sears, 1995; Landon and Thomas, 1999b).

The 6 Ma Timber Hill basalt is interlayered with well-rounded stream gravel and conglomerate that has a possible east-central Idaho provenance. The gravel displays northeast paleoflow indicators such as imbricated cobbles. The basalt flow is 10 m (33 ft) thick and about 2 km (2.1 mi) wide and has been mapped for 50 km (31 mi) along the axis of the Ruby graben (Lonn and others, 2000). It locally overlies a welded tuff that may correlate with the 6.27 Ma Walcott Tuff of the Heise volcanic field of Pierce and Morgan (1992). No dikes or volcanic feeders are present along the preserved trace of the basalt flow. Sears and others (2009) suggest that the flow may have originated on the flank of the Heise volcanic field, perhaps in Medicine Lodge Creek (Hodges and Link, 2002), and proceeded down a northwest-trending graben valley to its intersection with the Ruby graben, where it turned to the northeast (fig. 15). This pattern is analogous to the Hepburn Mesa flow, which followed a northwest-trending graben from the edge of the Yellowstone Plateau volcanic field, then turned into the northeast-trending Paradise graben (Christiansen, 2001). Sears and others (2009) noted the loss of east-central Idaho clasts in the Ruby graben at about 5 Ma, based on correlations of tephra interbedded with the gravel. That change in provenance corresponds to the appearance of east-central Idaho detrital zircons along the western Snake River Valley, which Beranek and others (2006) interpreted to date establishment of the Continental Divide along the Beaverhead Mountains.

At about the time that possible east-central Idaho clasts disappear from the Ruby graben section, basalt flowed down the northwest-trending Red Rock River graben from the Heise volcanic field; basalt remnants date to 5.5 and 4.9 Ma (Fritz and others, 2007). A well-imbricated conglomerate with platy cobbles resembling the 4.45 Ma Kilgore Tuff occurs near the top of the Sixmile Creek Formation in the Ruby graben. Sears and others (2009) suggest that drainage flowed down the Red Rock graben from the Heise volcanic field, then turned northeastward into the Ruby graben to deposit the cobbles. This pattern is analogous to that suggested for the Timber Hill basalt.

Significantly, a thin pediment veneer directly overlies the Kilgore age (?) cobble layer, with all clasts derived from the neighboring Snowcrest Mountains to the east. The 2.1 Ma Huckleberry Ridge Tuff locally

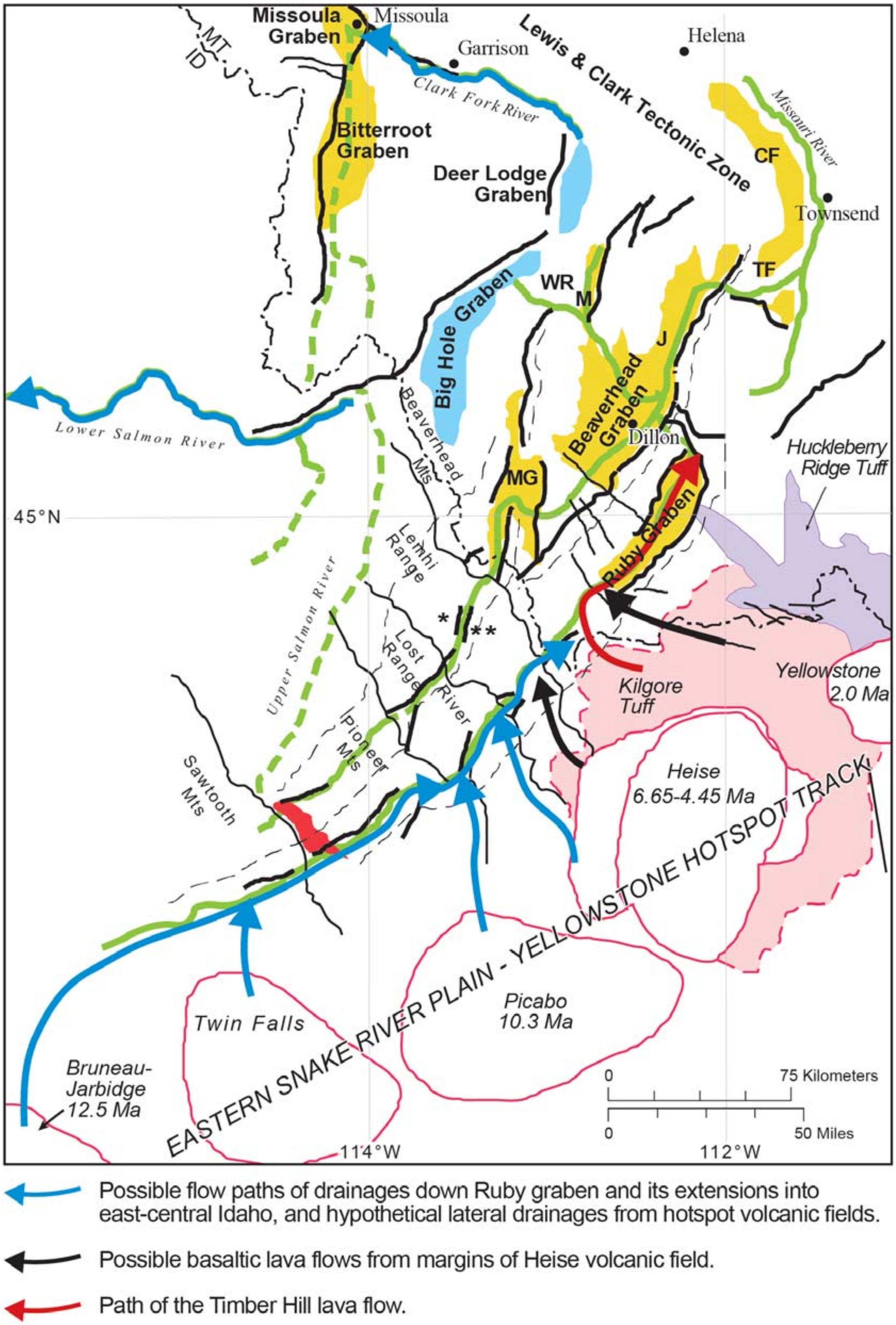


Figure 15. Possible interference between middle Miocene grabens and the Yellowstone hotspot track. Abbreviations, symbols, and references are the same as those for figure 14. Modified from Sears and others, 2009.

caps the pediment in small buttes (Garson and others, 1992). These observations potentially indicate that tectonic activity disturbed the throughgoing stream along the Ruby graben between 4 and 2 Ma. Big Sheep Creek may represent a surviving remnant of the Miocene Ruby graben drainage that now crosses the Neogene Tendoy Mountains horst block in a deep, narrow canyon, then turns northwest along the Red Rocks graben (Landon and Thomas, 1999a). The entire Sixmile Creek section of the eastern Ruby graben dips 1.5° to the west and is truncated by the late Neogene pediment veneer. That tilt potentially dates uplift of the Yellowstone volcanic dome to before eruption of the Huckleberry Ridge Tuff.

Christiansen (2001) showed that the Huckleberry Ridge Tuff erupted into the Madison, Centennial, Hebgen, Gallatin, and Yellowstone graben valleys on the northwest flank of the Yellowstone volcanic field. Morgan and McIntosh (2005) showed that the northern Teton Range and Jackson Hole graben were not significant topographic features until after eruption of the 4.45 Ma Kilgore Tuff. The Yellowstone dome had evidently begun to rupture into radial grabens prior to eruption of the Huckleberry Ridge Tuff, the first cycle of caldera-forming eruptions from the Yellowstone Plateau volcanic field.

PLIOCENE DRAINAGE CHANGES

The northeast-trending middle Miocene Basin and Range faults of Montana were cross-cut by a pattern of northwest-trending Pliocene faults on the north shoulder of the Yellowstone hotspot track (fig. 16; Sears and others, 1995). Drainages were diverted from their northeast-trending middle Miocene graben valleys into new northwest-trending graben valleys (Sears and Ryan, 2003). Many of the northwest-trending faults have Pleistocene to recent scarps and remain seismically active (Stickney, 2007).

The middle Miocene Ruby graben aggraded as much as 300 m (984 ft) of valley fill, including fluvial and alluvial sediments, fluvially deposited tephra from Yellowstone hotspot eruptions, and the >50 km (31 mi) long Timber Hill basalt flow, before it was segmented by Pliocene cross faults like the Sweetwater fault that diverted the drainage into new graben valleys (Fritz and Sears, 1993). The youngest dated unit in the Ruby graben that predates the cross faulting is the 6 Ma Timber Hill basalt flow. It is both underlain and overlain by thick river gravel with exotic cobbles. By 2 Ma, the northwest-trending cross faults had segmented the graben into its present form, as shown by the emplacement of the Huckleberry Ridge Tuff onto unconformably overlying alluvial fans in the present drainage basins (see fig. 13; Garson and others, 1992).

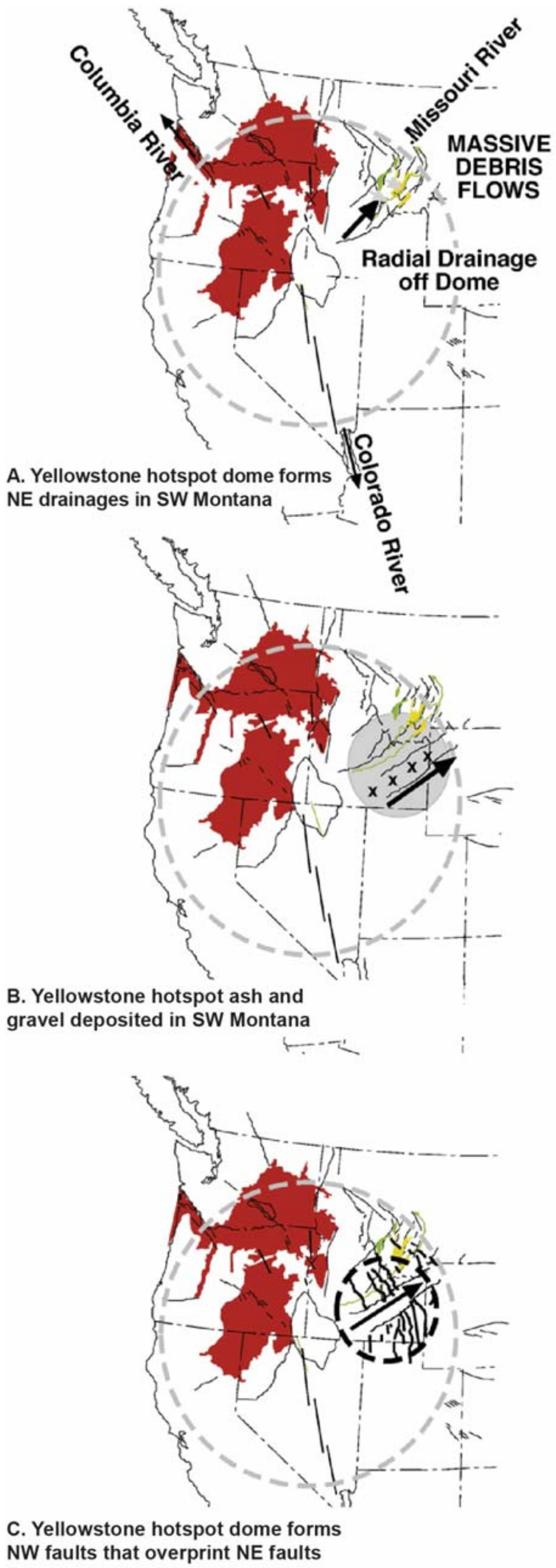
Quaternary erosion deeply incised the alluvial fans after eruption of the Huckleberry Ridge Tuff. In southwestern Montana, the northwest-trending cross faults shunted drainage from the axis of the Ruby graben northwestward into the Beaverhead graben. In central Idaho, cross faults beheaded the Ruby graben drainage and isolated distinctive source areas from southwestern Montana. Faulting diverted the Big Hole River from a middle Miocene graben into an active Neogene graben. The Big Hole River then cut a new canyon across its own gravel fill (Sears and others, 1995). The Continental Divide appears to have shifted to the south ~20 km (12.4 mi) as faulting added Silver Bow Creek to the Clark Fork drainage basin.

Some debris flow deposits in the Sweetwater Creek member contain large boulders that are currently isolated from bedrock sources by deep erosional or structural valleys. The deposits may represent debris flows that were channeled down east-trending Paleogene paleovalleys into northeast-trending middle Miocene grabens of the Basin and Range Province. In some cases, source regions are separated from debris flow deposits by tens of kilometers.

A 10-km-wide (6.2 mi) section of the Continental Divide at Monida Pass (fig. 2) is underlain by a gravel- and tuff-filled paleovalley that was hundreds of meters deep. Exotic lithologies indicate that the clasts were derived from sources south of the Snake River Plain, and paleocurrents indicate northerly transport. The 4.45 Ma Kilgore Tuff is interlayered with the gravel and erupted from the nearby Heise volcanic field when the Yellowstone hotspot was near Monida Pass (Morgan and McIntosh, 2005). Evidently, at about 4 Ma, the Yellowstone hotspot crosscut and beheaded a major Sixmile Creek Formation paleovalley with headwaters to the south of the Snake River Plain (Sears, 2014).

FUTURE WORK

The Sixmile Creek Formation as defined by Kuenzi and Fields (1971) includes the Neogene section above the middle Miocene unconformity, described overall as generally coarser-grained than the underlying Renova Formation. Despite this broad designation,



few attempts have been made to define stratigraphic units and relationships within the Sixmile Creek Formation. However, in the thermal bulge area around the Yellowstone hotspot, three distinct, interleaving members were defined: the Sweetwater Creek, Anderson Ranch, and Big Hole River members (Fritz and Sears, 1993). Elsewhere, a few other local members have been defined, but for the most part the Sixmile Creek Formation remains a single unit in other areas with poorly defined internal stratigraphy. Extensive additional detailed work in the Sixmile Creek is needed to help establish regional stratigraphic relationships, depositional and tectonic history, and to determine if the designation "Sixmile Creek Formation" should apply throughout its current mapped extent.

Even within the area of the thermal bulge where distinct members of the Sixmile Creek Formation have been defined, they are difficult to map, because their temporal and spatial variability can dramatically change over the distance of one section or less across a topographic map—a reflection of the complexities of terrestrial depositional systems. Several geological field camps in the Dillon area over the years have attempted to map the members, with poor results and confusion for students. Additional work on each of these members is very much needed to refine the criteria by which they are recognized. The basic stratigraphic framework, provenance, and tectonic implications of these members have been collected, analyzed, and interpreted (Fritz and Sears, 1993; Landon and Thomas, 1999a,b; Nielsen and Thomas, 2004; Parker, 2016), but there is a need to look more carefully at the physical and biological processes of deposition, especially in terms of the tectonic setting within the margin of a continental hot spot. For example, preliminary work on fluvially deposited tephra (ash) of the Anderson Ranch Member by Robert C. Thomas (unpublished data) suggests these deposits were initiated as debris flows that evolved downgradient into fluvial deposition. The particle density in such clean ash deposits appears to greatly impact sediment transport and produce unusual sedimentary structures not seen in siliciclastic-dominated fluvial systems. Work on the

Figure 16. Summary diagram of evolution of southwest Montana and deposition of the Sixmile Creek Formation in context of Yellowstone hotspot. (A) Middle Miocene: radial grabens form on the large dome centered upon the outbreak area of the hotspot in southeast Idaho. Drainages develop off the dome, following grabens into southwest Montana. Debris flows of the Sweetwater Creek member, some of them very large, spill into grabens from uplifted horsts. (B) Late Miocene: silicic tephra (gray circle) of the Anderson Ranch member derived from caldera eruptions along the track of the Yellowstone hotspot (x's) is deposited into the grabens, fluvially reworked, and interbedded with far-traveled gravel of the Big Hole River member, which is deposited by streams between eruptions. (C) Late Miocene: northwest-striking faulting on the flanks of hotspot domes along the eastern Snake River Plain cross-cut older northeast-trending horsts and grabens, capturing segments of rivers in northwest-trending grabens. The arrow shows the trend of successive volcanic fields along the path of the Yellowstone hotspot. Modified from Sears and others (2009).

rates of deposition using the existing chronostratigraphic data and additional detrital zircon data would also be worth pursuing. The widespread use of detrital zircon dating has profound applications for determining details of paleotopography for the Sixmile Creek Formation throughout its extent, and further examination of paleoclimate indicators could provide significant data to better understand sedimentological processes, soil formation, rare evaporite deposits (Thomas, unpublished data), and of course add to global climate models for this period of Earth history.

Many coarse-grained units that rest on the Renova Formation or older rock have been mapped or have the potential to be mapped as the Sixmile Creek Formation. It is likely that past mapping has erroneously identified Late Cretaceous Beaverhead and other conglomeratic units as the Sixmile Creek Formation and vice versa. It is also likely that Pleistocene and Holocene coarse-grained deposits have been erroneously identified as Sixmile Creek Formation. There is a need to look at all deposits mapped as Sixmile Creek Formation once again to verify the accuracy of the mapping, and to define units and variations within the formation that may lead to redefining, renaming, or remapping it across western Montana.

North of the Lewis and Clark Tectonic Zone, the Sixmile Creek Formation is not shown on geologic maps, although this part of Montana is part of the Basin and Range Province. Why are middle Miocene coarse-grained deposits absent above the Renova Formation equivalents in the Kishenehn Basin of northwestern Montana? Are Sixmile Creek equivalents present in the subsurface of other valleys north of the Lewis and Clark Tectonic Zone? If not, why are these deposits missing in this region? There is much to do for those who are looking!

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REFERENCES CITED

Anders, M.H., Geissman, J.W., Piety, L.A., and Sullivan, J.T., 1989, Parabolic distribution of circum-eastern Snake River Plain seismicity and latest Quaternary faulting: Migratory pattern and association with the Yellowstone hotspot: Journal of Geophysical Research, v. 94, p. 1589–1621, doi: https://doi.org/10.1029/JB094iB02p01589

Anderson, A.L., 1947, Drainage diversion in the northern Rocky Mountains of east-central Idaho: Journal of Geology, v. 55, p. 61–75, doi: https://doi.org/10.1086/625402

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3563, doi: https://doi.org/10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2

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

Beranek, L.P., Link, P.K., and Fanning, C.M., 2006, Miocene to Holocene landscape evolution of the western Snake River Plain region, Idaho: Using the SHRIMP detrital zircon record to track eastward migration of the Yellowstone hotspot: Geological Society of America Bulletin, v. 118, p. 1027–1050, doi: https://doi.org/10.1130/B25896.1

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%3C1093:TMOBMI%3E2.3.CO;2

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

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

Christiansen, R.L., 2001, The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana: U.S. Geological Survey Professional Paper 729-G, 145 p.

Collier, A.J., 1917, Age of the high gravels of the northern Great Plains, Montana: Washington Academy of Sciences Journal, Geological Society of Washington, 314th Meeting, Washington, D.C., p. 194–195.

Collier, A.J., and Thom, W.T., 1918, The Flaxville gravel and its relation to other terrace gravels in the northern Great Plains: U.S. Geological Survey Professional Paper 108-J, p. 179–184.

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.

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 Petroleum Geologists, p. 9–36.

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%3C0427:TOTYHW%3E2.3.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. p. 91–110.

Garson, Y.N., Sears, J.W., Fritz, W.J., and Wampler, J.M., 1992, Tectonic significance of an outlier of Huckleberry Ridge Tuff in the upper Ruby Basin of SW Montana: Geological Society of America, Abstracts with Programs, v. 24, no. 6, p. 13.

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

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/B31655.2.

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, 117 p.

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.

Hooper, P.R., Camp, V.E., Reidel, S.P., and Ross, M.E., 2007, The origin of the Columbia River flood basalt province: Plume versus nonplume models, *in* Foulger, G.M., and Jurdy, D.M., eds., Plates, plumes, and planetary processes: Geological Society of America Special Paper 430, p. 635–668, doi: https://doi.org/ 10.1130/2007.2430(30)

Howard, A.D., 1960, Cenozoic history of northeastern Montana and northwestern North Dakota with emphasis on the Pleistocene: U.S. Geological Survey Professional Paper 326, 108 p., doi: https://doi.org/10.3133/pp326

Hurlow, H.A., 1995, Structural style of Pliocene–Quaternary extension between the Red Rock and Blacktail Faults, southwestern Montana, *in* Mogk, D.W., ed., Field guide to geologic excursions in southwest Montana: Northwest Geology, v. 24, p. 221–228.

Iddings, J.P., and Weed, W.H., 1894, Livingston folio, Montana: U.S. Geological Survey Geologic Atlas of the United States Folio, GF-1, 4 p., scale 1:250,000.

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(1994)106%3C1083:SAPOAE%3E2.3.CO;2

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%3C439:LLTOGA%3E2.0.CO;2

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, doi: https://doi.org/10.1130/0016-7606(1969)80[315:MTUNBA]2.0.CO;2

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, doi: https://doi.org/10.1130/0016-7606(1971)82[3373:TSSAGH]2.0.CO;2

Landon, S.C., and Thomas, R.C., 1999a, Provenance of gravel deposits in the mid-Miocene Ruby graben, southwest Montana: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 292.

Landon, S.C., and Thomas, R.C., 1999b, Geohistory of the mid-Miocene Ruby graben in southwest Montana: Geological Society of America Abstracts with Programs, v. 31, p. A-300.

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

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.

Lonn, J.D., Skipp, E., Ruppel, E.T., Perry, W.W., Jr., Sears, J.W., Janecke, S.U., Bartholomew, M.J., Stickney, M.C., Fritz, W.J., Hurlow, H.A., and Thomas, R.C., 2000, Geologic map of the Lima 30′ x 60′ quadrangle, southwest Montana, scale 1:100,000.

McLeod, P.J., 1987, The depositional history of the Deer Lodge Basin, western Montana: Missoula, University of Montana, M.S. thesis, 61 p.

Meneley, W.A., Christiansen, E.A., and Kupsch, W.O., 1957, Preglacial Missouri River in Saskatchewan: Journal of Geology, v. 65, p. 441–447, doi: https://doi.org/10.1086/626445

Morgan, L.A, and McIntosh, W.C., 2005, Timing and development of the Heise volcanic field, Snake River Plain, Idaho, western USA: Geological Society of America Bulletin, v. 117, p. 288–306, doi: https://doi.org/10.1130/B25519.1

Nielsen, K., and Thomas, R.C., 2004, Paleoenvironmental reconstruction of the mid-Miocene Beaverhead graben in southwest Montana: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 546.

Pardee, J.T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America Bulletin, v. 61, p. 359–406, doi: https://doi.org/10.1130/0016-7606(1950)61[359:LCBFIW]2.0.CO;2

Parker, S.D., 2016, Tectonic alteration of a major Neogene river drainage of the Basin and Range: Missoula, University of Montana, M.S. thesis, 115 p.

Patton, W.T., 1987, Quaternary drainage and Tertiary geology of the Turner-Hogeland Plateau, north-central Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 138 p.

Peale, A.C., 1896, Three Forks folio, Montana: U.S. Geological Survey Geologic Atlas of the United States Folio, GF-24, 5 p., scale 1:250,000.

Perkins, M.E., and Nash, B.P, 2002, Explosive silicic volcanism of the Yellowstone hotspot: The ash fall record: Geological Society of America Bulletin, v. 114, p. 367–381, doi: https://doi.org/10.1130/0016-7606(2002)114%3C0367:ESVOTY%3E2.0.CO;2

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot: Volcanism, faulting, and uplift: Geological Society of America Memoir 172, p. 1–54.

Rainbird, R.H., and Ernst, R.E., 2001, The sedimentary record of mantle-plume uplift: Geological Society of America Special Paper 352, p. 227–245.

Rasmussen, D.L., 1969, Late Cenozoic geology of the Cabbage Patch area, Granite and Powell Counties, Montana: Missoula, University of Montana, Ph.D. dissertation, 188 p.

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

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, Colorado, Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 459–477.

Reed, J.C., Jr., Wheeler, J.O., and Tucholke, B.E., 2005, Geologic map of North America: Geological Society of America, DNAG Continent-Scale Map 001, scale: 1:5,000,000.

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

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.

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, doi: https://doi.org/10.3133/i486

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

Ryder, R.T., and Scholten, M.R., 1973, Syntectonic conglomerates in southwestern Montana: Their nature, origin, and tectonic significance: Geological Society of America Bulletin, v. 84, p. 773–796, doi: https://doi.org/10.1130/0016-7606(1973)84%3C773:SCISMT%3E2.0.CO;2

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, doi: https://doi.org/10.1130/0016-7606(1955)66[345:GOTLRS]2.0.CO;2

Sears, J.W., 1995, Middle Miocene rift system in SW Montana: Implications for the initial outbreak of the Yellowstone hotspot: Northwest Geology, v. 25, p. 43–46.

Sears, J.W., 2007, Middle Miocene karst and debris flows and Neotectonic faults near Clark Canyon Reservoir, southwest Montana, *in* Thomas, R.C., and Gibson, R., eds., Geologic history of southwest Montana: Northwest Geology, v. 36, p. 251–260.

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/10.1130/GSATG178A.1

Sears, J.W., 2014, Tracking a big Miocene river across the Continental Divide at Monida Pass, Montana/Idaho: Exploring the northern Rocky Mountains, *in* Shaw, C.A., and Tikoff, B., eds, Geological Society of America, Field Guide 37, Ch. 4, p. 89–99.

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: Boulder, Colorado, Geological Society of America Special Paper 323, p. 241–247.

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 Section SEPM (Society for Sedimentary Geology), p. 289–301.

Sears, J.W., and Thomas, R.C., 2007, Extraordinary middle Miocene crustal disturbance in southwestern Montana: Birth of the Yellowstone hot spot?: Northwest Geology, v. 36, p. 133–142.

Sears, J.W., Hurlow, H.A., Fritz, W.J., and Thomas, R.C., 1995, Late Cenozoic disruption of Miocene grabens on the shoulder of the Yellowstone hotspot track in southwest Montana: Field guide from Lima to Alder, Montana: Northwest Geology, v. 24, p. 201–219.

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

Seeland, D., 1985, Oligocene paleogeography of the northern Great Plains and adjacent mountains, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic systems of the Rocky Mountain region: Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 187–205.

Shane, P.A., and Sears, J.W., 1995, Miocene tephra beds in SW Montana: Geochronology, geochemistry and implications: Geological Society of America, Abstracts with Programs, v. 27, no. 4, p. 55.

Smith, M.P., 1992, The geology and geomorphology of Lobo Mesa: Evidence of middle Miocene volcanism and Quaternary tectonism in the Gravelly Range, Montana: Missoula, University of Montana, M.S. thesis, 46 p.

Stickney, M.C., 2007, Historic earthquakes and seismicity in southwestern Montana: Northwest Geology, v. 36, p. 167–186.

Storer, 1969, An upper Pliocene Neohipparion from the Flaxville gravels, northern Montana: Canadian Journal of Earth Sciences, v. 6, p. 791–794, doi: https://doi.org/10.1139/e69-076

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, v. 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.

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., 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

Vuke, S.M., 2020, The Eocene through early Miocene sedimentary record in western 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, 38 p.

Wernicke, B., and Snow, J.K., 1998, Cenozoic tectonism in the central Basin and Range: Motion of the Sierran-Great Valley Block: International Geology Review, v. 40, p. 403–410, doi: https://doi.org/10.1080/00206819809465217

Whitaker, S.T., 1980, The Flaxville Formation in the Scobey-Opheim area, northeastern Montana: Boulder, University of Colorado, M.S. thesis, 143 p.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to Present: Science, v. 292, p. 686–693, doi: https://doi.org/10.1126/science.1059412