Cenozoic Evolution of the Montana Cordillera: Evidence From Paleovalleys

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ABSTRACT

Four phases in the tectonic evolution of the Montana Cordillera are recorded by remnants of paleovalleys and their lithologically distinctive gravel deposits. (1) Strike-parallel paleovalleys and alluvial plains marked the culmination of overthrusting in the Rocky Mountain fold-thrust belt in Late Cretaceous-early Eocene time, and fed the Beaverhead-Harebell-Piñon mega-fan of the Wyoming foreland basin. (2) Upon cessation of thrusting, the Cordillera experienced widespread erosional denudation, volcanism, and extension, with emergence of metamorphic core complexes and gravitational collapse of a regional rift system by middle Eocene time. A large, north-draining paleovalley appears to have followed the axis of a major Eocene-early Miocene rift system from central Idaho north to the Rocky Mountain trench. (3) A significant period of tectonism coincided with the outbreak of the middle Miocene Columbia River flood basalt, and a radiating system of new graben valleys diverted flow from the Eocene-early Miocene rift system in southwest Montana. (4) By late Miocene, extensional faults on the shoulder of the Yellowstone hotspot cross-cut middle Miocene paleovalleys and shunted streams into new graben valleys in southwest Montana. Many extensional faults in southwestern Montana are still active. However, widely-preserved paleovalley strath-terraces suggest that central-western Montana, near Missoula, has been tectonically stable since middle Miocene time.

INTRODUCTION

Paleovalleys are components of regional unconformities that provide important constraints on the tectonic evolution of orogenic systems. Some paleovalleys represent canyons cut through deformed strata. Others comprise linear rift-valleys filled with lakes, streams, or alluvium. Locally preserved fluvial and alluvial gravel may directly link source regions to depositional basins, providing timelines for the synergetic uplift, denudation, and subsidence of different parts of an orogenic system. Well-preserved paleovalley networks can provide a direct reference datum for the tectonic stability of individual drainage basins and divides.

Remnants of paleovalleys in western Montana and Idaho record four main tectonic phases in the Cenozoic evolution of the Montana Cordillera. In this paper, we map changes in regional drainage in western Montana that occurred during Cenozoic time, and discuss tectonic implications of the evolving paleodrainage patterns. Figure 1 shows the region of our investigation. Our interpretations are based mostly on the distribution of lithologically distinctive, stream-rounded pebbles and cobbles preserved in dated paleovalley conglomerates. Particularly distinctive clast lithologies that can be uniquely matched to bedrock source regions include Mesoproterozoic and Ordovician quartzites, Devonian black chert, Cretaceous andesite, and Eocene volcanics. This overview is intended to

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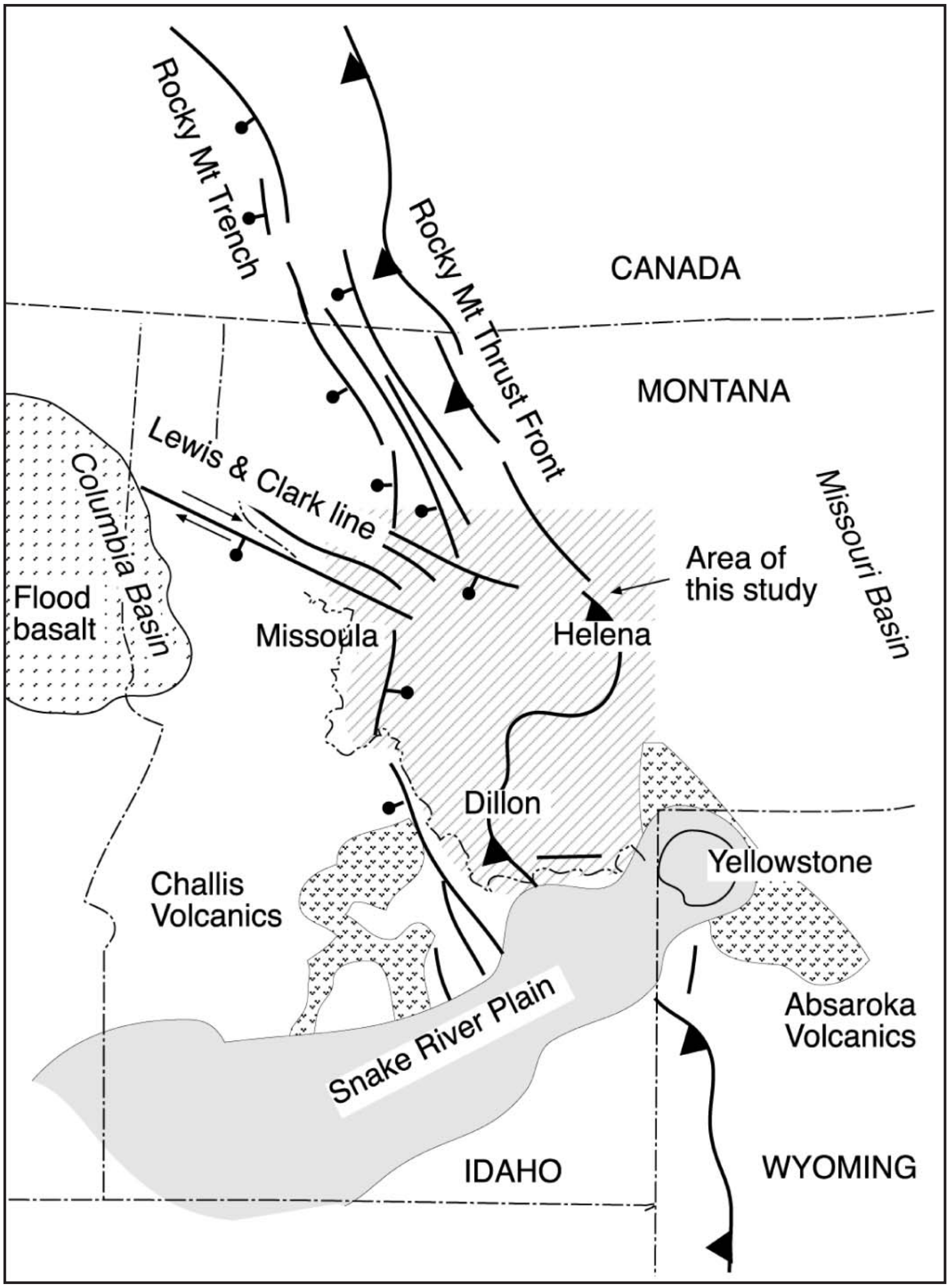

Figure 1: Generalized map of western Montana and adjacent areas showing location of maps in Figs. 2-4.

stimulate more detailed mapping and investigation of paleovalley deposits in western Montana.

LATE CRETACEOUS TO EARLY EOCENE

The architecture of the Rocky Mountain fold-thrust belt and a large volcanic plateau at the eastern edge of the Cordilleran magmatic arc appear to have controlled Late Cretaceous to early Eocene paleodrainage in western Montana (Fig. 2). The Lewis and Clark line divided the Montana fold-thrust belt into two main domains, each dominated by thick thrust slabs of Mesoproterozoic Belt Supergroup (Sears, 1988). The Lewis-Eldorado-Hoadley thrust slab lay to the northeast of the Lewis and Clark line, while the Sapphire-Grasshopper-Ermont-Tendoy thrust slab lay to the southwest. The Elkhorn Mountains volcanics, volcanic facies of the Two Medicine Formation, and

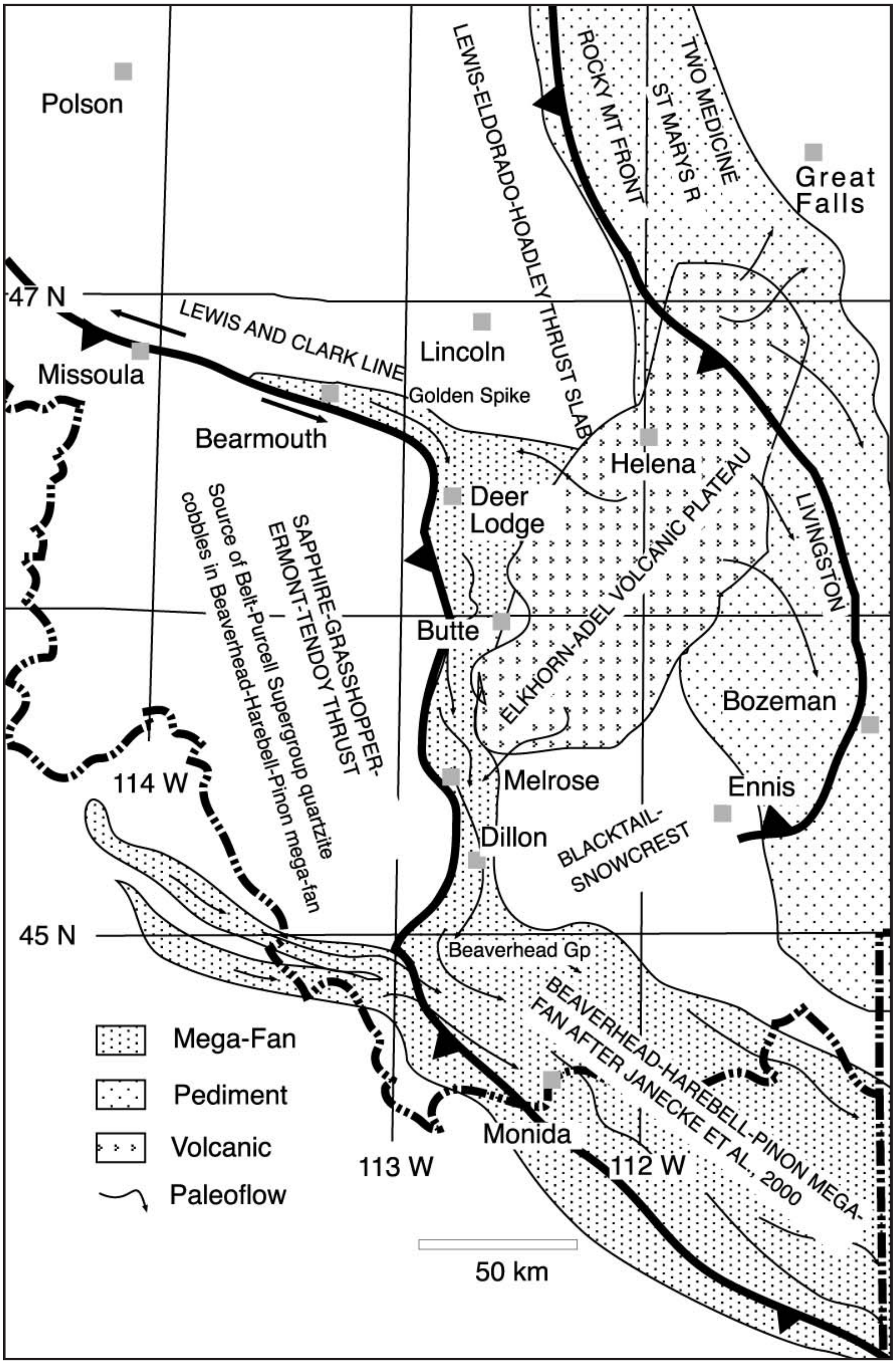

Figure 2: Late Paleocene paleogeographic map of southwestern Montana and adjacent Idaho. Large paleovalley along leading edge of Sapphire-Grasshopper-Ermont-Tendoy thrust system joined paleovalleys in southwest Montana, and delivered Belt-Purcell Supergroup clasts to the Beaverhead-Pinon-Harebell mega-fan in the Wyoming foreland (see Janecke et al., 2000). Elkhorn-Adel volcanic plateau shed volcanic debris flows into the Two Medicine, Livingston, and Golden Spike formations, and the Beaverhead Group.

Adel Mountains volcanics appear to represent parts of a large volcanic plateau that were later segmented by thrusting (Hamilton and Meyers, 1967; Viele and Harris, 1965; Harlan et al., 1991; Sears, 2001). Archean basement forms the cores of foreland uplifts southeast of the Lewis and Clark line in the Blacktail-Snowcrest arch (Perry et al., 1988).

Detritus derived from the lithologically distinctive and durable Belt Supergroup and from the Elkhorn-Adel volcanic plateau outline a broad drainage system in the region. Remnants of syntectonic conglomerate, including the Golden Spike Formation, Beaverhead Group, and possible equivalents, appear to define a large fluvial-alluvial system along the east margin of the Sapphire-Grasshopper-Ermont-Tendoy thrust system (Ruppel et al., 1981). As documented by Gwinn and Mutch (1965) and Waddell (1997), the Golden Spike conglomerate includes stream-rounded cobbles of distinctive Belt Supergroup quartzite derived from the Sapphire plate to the west, as well as volcanic cobbles derived from the Elkhorn Mountains volcanics to the east. Mapping by Sears et al. (2000a) extended the known distribution of the Golden Spike conglomerate eastward by several km near Deer Lodge. Small pre-Eocene conglomerate remnants near Bearmouth and Deer Lodge may further define the extent of the paleovalley. The unconformity at the base of the Golden Spike Formation cuts structures of the Lewis and Clark line, but is also folded by them, indicating at least two major periods of tectonic movement.

The Beaverhead Group is a major stratigraphic unit that has been mapped from north of Melrose to south of Monida (Nichols et al., 1985). Like the Golden Spike Formation to the north, it rests with angular unconformity on thrust-faulted and folded strata as young as Late Cretaceous, but is also cut by thrusts and is folded. It contains fluvial facies with stream-rounded cobbles of Belt quartzite and Paleozoic lithologies, as well as alluvial facies with angular Paleozoic limestone clasts. The distribution of facies outlines a south- to southeast-trending paleovalley that may have comprised a continuation of the Golden Spike paleovalley. The Sapphire-Grasshopper-Ermont-Tendoy thrust system formed the west flank of the Beaverhead paleovalley, and the Elkhorn-Adel volcanic plateau, Blacktail-Snowcrest arch, and associated structures defined the east side. Andesite agglomerate from the volcanic plateau mixed with fluvial gravel in the Beaverhead Group (Gonnerman, 1992). Alluvial fans from the Blacktail-Snowcrest arch fed into the Lima conglomerate of the Beaverhead Group (Nichols et al., 1985).

In southwest Montana, the Golden Spike-Beaverhead paleovalley appears to have been joined by paleovalleys from central Idaho that have been defined by Janecke et al. (2000), and may have spread southeastward into the Beaverhead-Harebell-Pinon mega-fan in the Wyoming foreland basin (Janecke et al., 2000). This paleodrainage system appears to have delivered cobbles of distinctive Belt Supergroup to Wyoming across the future position of the eastern Snake River Plain (Fritz and Sears, 1993; Janecke et al., 2000). The most distinctive cobble lithologies are red and pink, feldspathic, cross-laminated quartzites and siltites that contain red mud chips – a typical lithology of the upper Belt Supergroup (cf. Winston, 1986).

In contrast to the Golden Spike-Beaverhead paleovalley, the Two Medicine, St. Mary's River, and Livingston formations appear to have accumulated on broad pediments that sloped into the Cretaceous Interior Seaway along the east margin of the Rocky Mountains (Viele and Harris, 1965; Price and Mountjoy, 1970; Mallory, 1972; Rogers et al., 1993). These dominantly fine- to medium-grained siliciclastic deposits were largely re-worked from Mesozoic and Paleozoic formations. They contain abundant volcanic detritus from the Elkhorn-Adel volcanic plateau (cf. Schmidt, 1978), but generally lack Belt Supergroup clasts, suggesting that they were separated from the Golden Spike-Beaverhead paleovalley by a drainage divide.

Continuing movement of the Rocky Mountain thrust system deformed the deposits of the Golden Spike-Beaverhead paleovalley, and broke up the Elkhorn-Adel volcanic plateau. Paleovalley deposits of the Golden Spike Formation and Elkhorn Mountains volcanics were sheared along the Lewis and Clark line (Sears et al., 2000b). In southwest Montana, syndepositional thrusts deform the Beaverhead Group (Nichols et al., 1985).

EOCENE TO MIDDLE MIOCENE

The tectonic regime in western Montana abruptly changed before middle Eocene time with the cessation of thrusting and the onset of regional extension, possibly as the result of gravitational collapse of the overthickened Cordilleran orogenic wedge (Coney and Harms, 1984; Constenius, 1996). Listric extensional faults commonly reactivated thrust decollements (Constenius, 1996).

A major rift system evolved along the axis of the Cordillera in central Idaho and western Montana (Janecke, 1994; Janecke et al., 1997) (Fig. 3). This broad rift system cross-cut the late Cretaceous-Paleocene paleodrainage pattern in central Idaho (Janecke et al., 2000). Lakes and rivers formed in several half-graben valleys within the rift system (Mudge et al., 1982; Constenius, 1982, 1996). On the Montana-Idaho boundary, the Bitterroot metamorphic core complex and its mylonitic border emerged from 50 Ma to 44 Ma (Foster and Fanning, 1997; Hodges and Applegate, 1993). The Bitterroot Valley formed as a half-graben on the east flank of the Bitterroot core complex (Hyndman, 1980).

Janecke (1994) determined that uplift along the margins of the rift system unroofed distinctive bedrock lithologies from beneath a thick regional covering of Eocene Challis volcanics that formerly covered most of central Idaho (Armstrong, 1978). Janecke (1994) hypothesized that fluvial drainage transported sediment along the axis of the rift system from central Idaho to the Bitterroot Valley of western Montana. Our independent observations in Montana are consistent with Janecke's (1994) hypothesis.

The Bitterroot graben filled with well-sorted fluvial sand and gravel, together with silt, clay, and volcanic ash (Lonn and Sears, 1998). Channelized sand and gravel deposits of the paleovalley crop out from Hamilton north to Missoula, a map distance of 100 kilometers. Stream-rounded pebbles and cobbles of grey granite and mylonitic granitic gneiss, white quartzite, and milky vein-quartz dominate the gravel beds, with sprinklings of brown porphyritic volcanics, and rare pebbles of black chert laced with white quartz veins and translucent, pink, jasperoid quartzite (Lonn and Sears, 1998). The granitic, mylonitic, and vein-quartz pebbles were clearly derived from the Bitterroot core complex. Occurrence of mylonitic pebbles, in deposits 70 km north of the northern terminus of the Bitteroot mylonite zone near Victor, documents the northerly stream flow of the Bitterroot paleovalley. Furthermore, the pebble size and abundance of less-durable clasts decreases northward.

The veined-chert pebbles do not match any bedrock lithologies presently exposed within the Bitterroot drainage basin. They appear to have been derived from the Devonian Milligen Formation of central Idaho, which forms a particularly unique bedrock lithology of thick, black, bedded chert laced with several generations of white quartz veins (Davis, 1983), providing a durable and vividly recognizable clast type. The Milligen Formation is largely confined to the Pioneer Mountains of central Idaho (Fig.2), where it crops out beneath the Eocene Challis volcanics. The translucent, pink, jasperoid quartzite may derive from the lithologically similar Swauger quartzite of the Lehmi Range in central Idaho. The provenance link of pebbles in the Bitterroot deposits to central Idaho source rocks is consistent with Janecke's (1994) rift model.

Grey volcanic ash, coal laminae, and fossil plant fragments occur in some clay beds in the Bitterroot paleovalley deposits. A 3-m thick green clay layer caps the sand and gravel in several quarries. X-ray diffraction analysis indicates that the clay formed from the decomposition of fine volcanic ash. The upper part of the bed appears to be an ancient soil zone. In places, thin layers of glassy volcanic ash with accretionary lapilli directly overlie the clay bed.

The north-trending Bitterroot paleovalley appears to be tectonically disrupted at both its south and north ends. South of Hamilton, the paleovalley floor emerges from the subsurface and rises gently toward the south. It forms perched strath-terrace benches south to Lost Trail Pass at the Idaho border, where it appears to be truncated by faults. North of Missoula, the Lewis and Clark line truncates the paleovalley. Surface exposures and well-logs indicate that the paleovalley fill may be as thick as 1.6 km, and dips northward at 45-70 degrees in the down-dropped hanging wall of the southwest-dipping Clark Fork-Ninemile fault, a major strand of the Lewis and Clark line (Harris, 1997; Stickney et al., 2000). Sediments on the northern margin of the Missoula Valley contain gray, smectitic volcanic ash similar to volcanic ash in the Bitterroot Valley, as well as coal, sandstone, and lateritic diamict that contains both smectite and mixed-layer kaolinite/smectite (Ryan et al. 1998). Steeply plunging folds in the paleovalley sediments imply a component of strike-slip movement. Some cobbles exhibit stress fractures and pressure solution pits indicative of deformation before cementation of the conglomerate. A broad wind-gap in the uplifted footwall of the Clark Fork-Ninemile fault at Evaro Hill may represent the offset and exhumed floor of the paleovalley.

Janecke (1994) interpreted the Paleogene rift zone to cross the Lewis and Clark line and continue north along the Rocky Mountain trench system, with several subordinate half-grabens in northern Montana. Constenius (1996) discussed several half-grabens in western Montana and Wyoming. Exposures of Tertiary rocks are limited north of the Lewis and Clark line because of widespread glacial drift. Small occurrences include poorly stratified, orange-weathering diamict that passes upward into interbedded mudstone and diamict with local occurrences of sandstone, angular conglomerate, and volcanic tuff beds

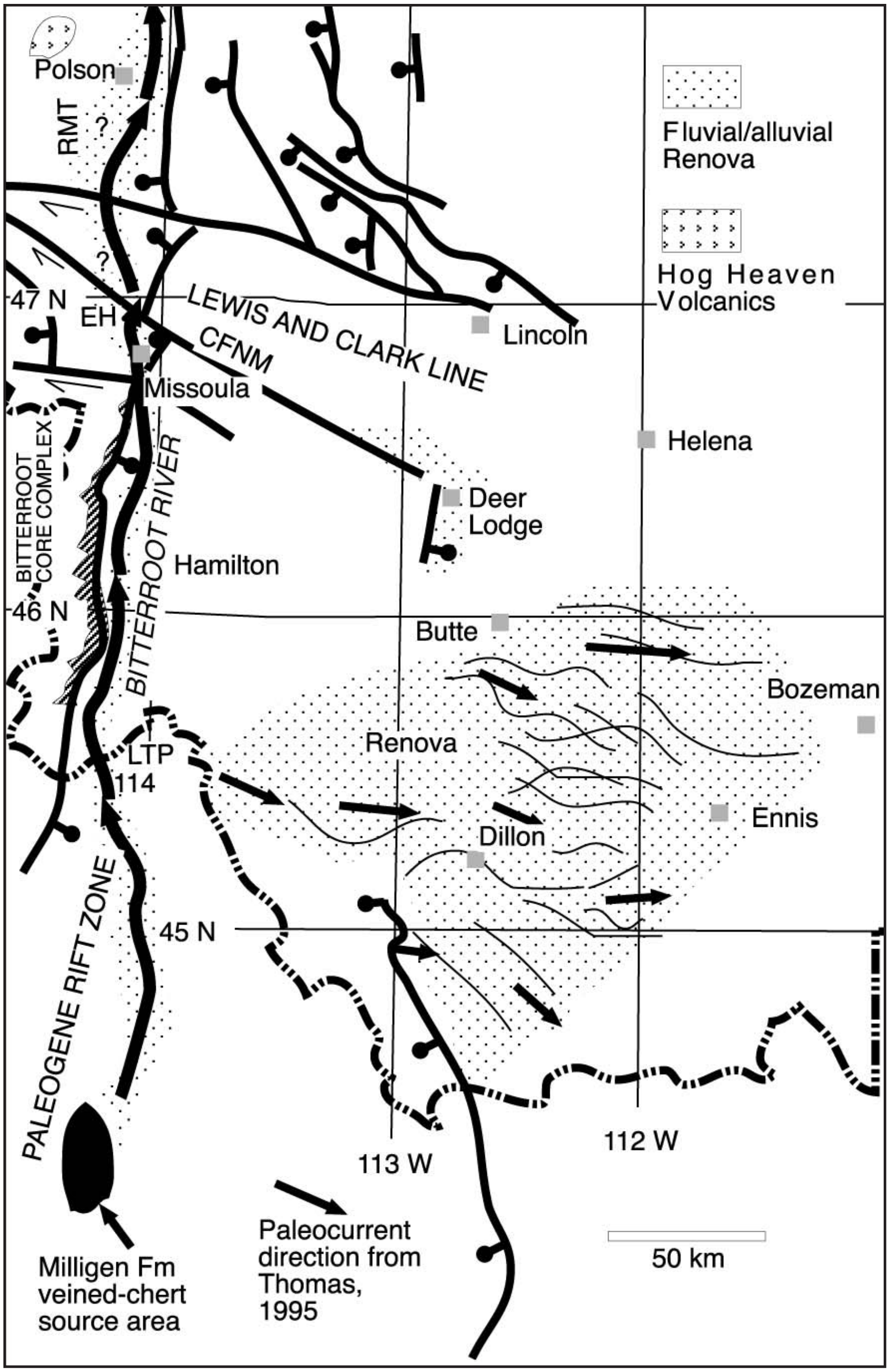

Figure 3: Middle Eocene-early Miocene paleogeographic map of southwestern Montana and adjacent Idaho. Paleovalley along the rift system (see Janecke, 1994) diverted drainage from the Milligan Formation area in central Idaho to the Bitterroot Valley and the Rocky Mountain Trench(?). East shoulder of the rift was desert braidplain transporting clasts down slope toward the east (Thomas et al., 1995). (Modified from Sears and Fritz, 1998.) CFNM, Clark Fork-Ninemile fault; LTP, Lost Trail Pass; RMT, Rocky Mountain Trench; EH, Evaro Hill.

The clay-rich matrix consists of halloysite and kaolinite/smectite (Ryan et al. 1998), an assemblage that is consistent with pronounced leaching produced by temperate to subtropical conditions, much like middle Eocene soils elsewhere in the region (Thompson et al.,1982). The tuffs are found interbedded with and atop lateritic Tertiary diamict, and range from bentonitic tuffs near the Lewis and Clark line to ash flow tuffs proximal to the 31- 36 Ma Hog Heaven volcanic field (Zehner, 1987). Recent K-Ar dates from biotite mineral separates from tuff at three localities ranged from at 35 Ma to 36 Ma (Ryan et al., 1998).

The similarity of the ages, textures, lithologies and XRD data indicates that the sediments north and south of the Lewis and Clark line could have been contiguous prior to movement of the Clark Fork-Ninemile fault. It is also worthwhile to note that, in addition to the sparse surface exposures, Tertiary sediment is widely distributed in the subsurface north of the Clark Fork-Ninemile Fault. For example, > 150 m of interbedded sandstone, coal seams, conglomerate and claystone were reported in USGS monitoring wells south of Polson. This sequence is similar to exposures of mid-Tertiary sediment near Missoula. Compositions of the subsurface sandstone and conglomerate north of the Clark Fork-Ninemile Fault are currently unknown, but future analyses should target presence/absence of Bitterroot mylonite-derived clasts north of the Clark Fork-Ninemile Fault.

The Paleogene rift system was likely complex, with several en echelon basins in southwestern Montana (Constenius, 1996). However, the uplifted east shoulder of the regional rift system appears to have formed a broad desert braidplain upon which relatively thin deposits of the late Eocene-early Miocene Renova Formation accumulated (Sears and Fritz, 1998; Janecke, 1994). Paleocurrent, grain size, and petrologic analysis of sheet sandstones within the Renova Formation indicates that siliciclastic sediment was transported eastward in broad, channelized sheets from granitic and volcanic sources exposed along the rift shoulder (Thomas, 1995). The sands mixed with airfall ash that was probably derived from the Paleogene Cascade volcanic arc.

The rift-shoulder veneer differs in facies and thickness from the rift-axis deposits. The shoulder has thin, widespread, well-layered facies with numerous paleosols and small playa lake deposits, and abundant terrestrial vertebrate remains (cf. Fields et al., 1985). By contrast, the rift axis has rapid facies changes among thick, carbonaceous lake beds, coal measures, and debris flows, including large landslide blocks, and plant fossils are more common than vertebrate fossils (cf. Janecke, 1994; Janecke et al., 2000).

In summary, the Eocene-early Miocene extensional regime appears to have formed a broad rift system that trended north and had several component half-grabens. The rift system cross-cut the Late-Cretaceous-early Eocene drainage and diverted flow from central Idaho to central-western Montana along the Bitterroot Valley. A major river may have flowed down the Paleogene rift from lakes in central Idaho, northward to the Rocky Mountain trench. Search for clasts of distinctive Bitterroot mylonitic granite in the Paleogene sediments north of the Lewis and Clark line is needed to document northward continuation of the paleovalley.

MIDDLE MIOCENE

A significant tectonic event affected a large region of western Montana during middle Miocene time (Sears and Fritz, 1998). The event is recorded by a profound angular unconformity that is bracketed between faulted and tilted early Miocene beds of the Renova Formation (ca. 20 Ma) and overlying middle Miocene beds of the basal Sixmile Creek Formation (ca. 16.5-17 Ma) throughout southwest Montana and adjacent Idaho (Fields et al., 1985). The event was synchronous with the outbreak of the Yellowstone hotspot and Columbia River flood basalts (Sears, 1995), and with a brief, wet climatic interval recorded by regionally extensive middle Miocene laterite paleosols and profound erosion (Thompson et al., 1982).

Several middle Miocene grabens crossed southwest Montana and linked into the Lewis and Clark line, which acted as a right-lateral transform fault zone (Sears and Fritz, 1998) (Fig. 4). The middle Miocene fault system appears to have diverted stream flow from the Paleogene rift system. During the middle Miocene wet period, the grabens contained large rivers with broad valley floors, and deep lakes.

Following the erosional interval, the middle Miocene-Pliocene Sixmile Creek Formation accumulated in the grabens (Fig. 5). Massive diamict deposits with a matrix of fluidized Renova mudstone and mega-clasts of local bedrock are characteristic of the Sweetwater Creek Member of the Sixmile Creek Formation (Fritz and Sears, 1993). These represent denudation of the uplifted shoulders of the grabens. The Big Hole River Member of the Sixmile Creek Formation is a fluvial conglomerate distributed along the axes of the grabens (Fritz and Sears, 1993). Distinctive pebbles that have been traced along the axes of the Ruby and Beaverhead grabens from Lima to Ennis include black chert laced with quartz veins, vitreous pink Proterozoic quartzite, vitreous white and black Ordovician quartzite, and Carboniferous chert-pebble conglomerate. These all match bedrock lithologies found in central Idaho in the Lemhi Range and Pioneer Mountains, but these lithologies are absent in the modern Beaverhead drainage basin, except in the Beaverhead conglomerate. Some of the pebbles may

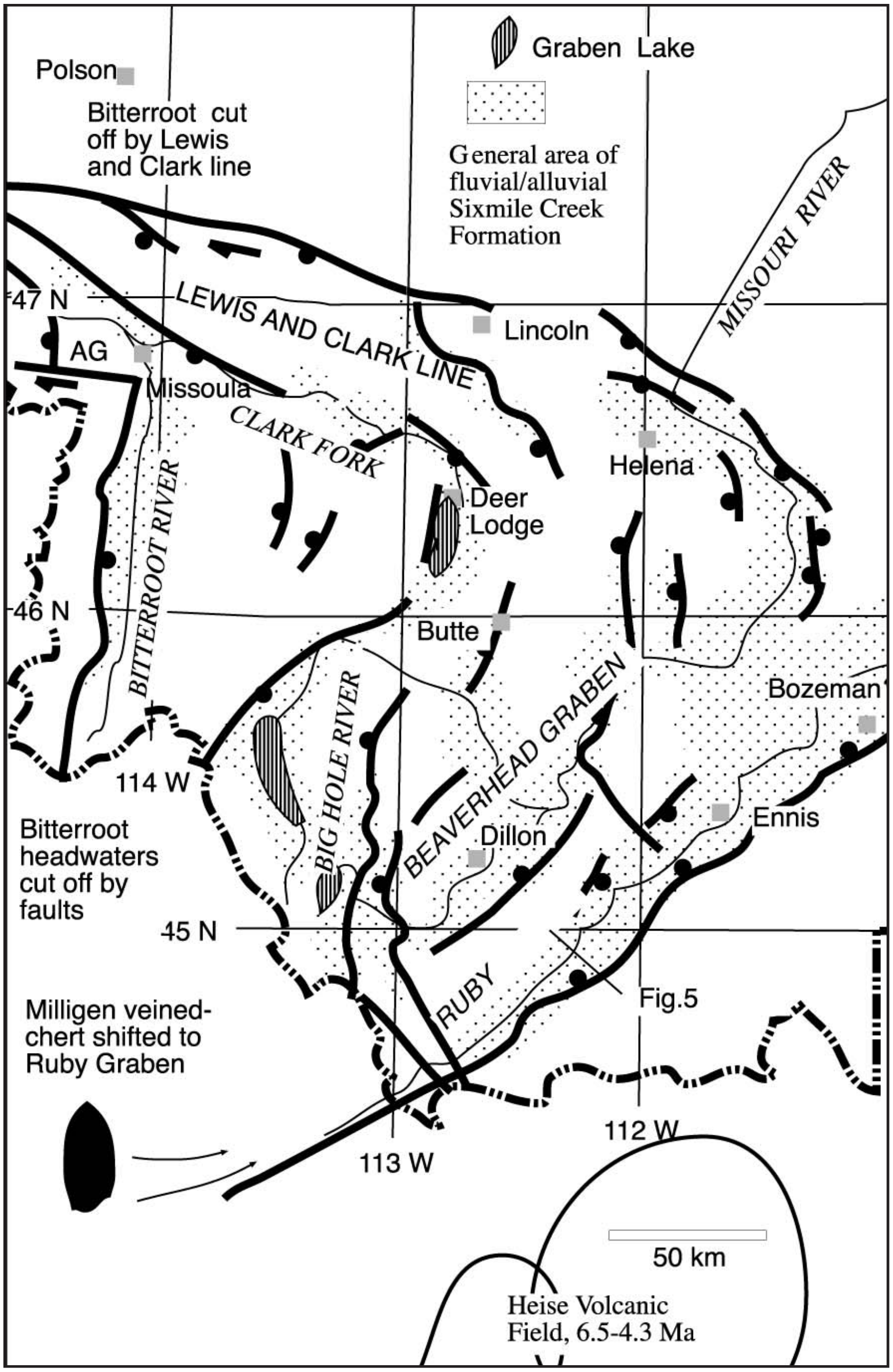

Figure 4: Middle Miocene paleogeographic map of southwestern Montana and adjacent Idaho. New grabens radiated across southwest Montana and adjacent Idaho and diverted stream flow from the Milligan Formation area of central Idaho to SW Montana. Grabens linked into the Lewis and Clark line which acted as right-lateral transform. Faulting along the Lewis and Clark line diverted stream flow along Bitterroot Valley into new canyons of the Clark Fork River. Deep lakes formed in Deer Lodge and Big Hole grabens (vertical ruling) (Modified from Sears and Fritz, 1998.) AG, Alberton Gorge

have been reworked from the Beaverhead Group, but the paleovalley deposits seem far to voluminous to have all been derived from re-cycled Beaverhead, which is confined to one or two ranges in southwest Montana. The Anderson Ranch Member of the Sixmile Creek Formation includes several thick tephra beds ranging in FT age from 6-11.3 Ma (Shane and Sears, 1995), as well as the 6-Ma Timber Hill basalt flow (Fritz and Sears, 1993; Lonn et al., 2000). The tephra beds appear to have been derived from eruptions of the Yellowstone hotspot, and were reworked into the fluvial deposits. Some stream-worn

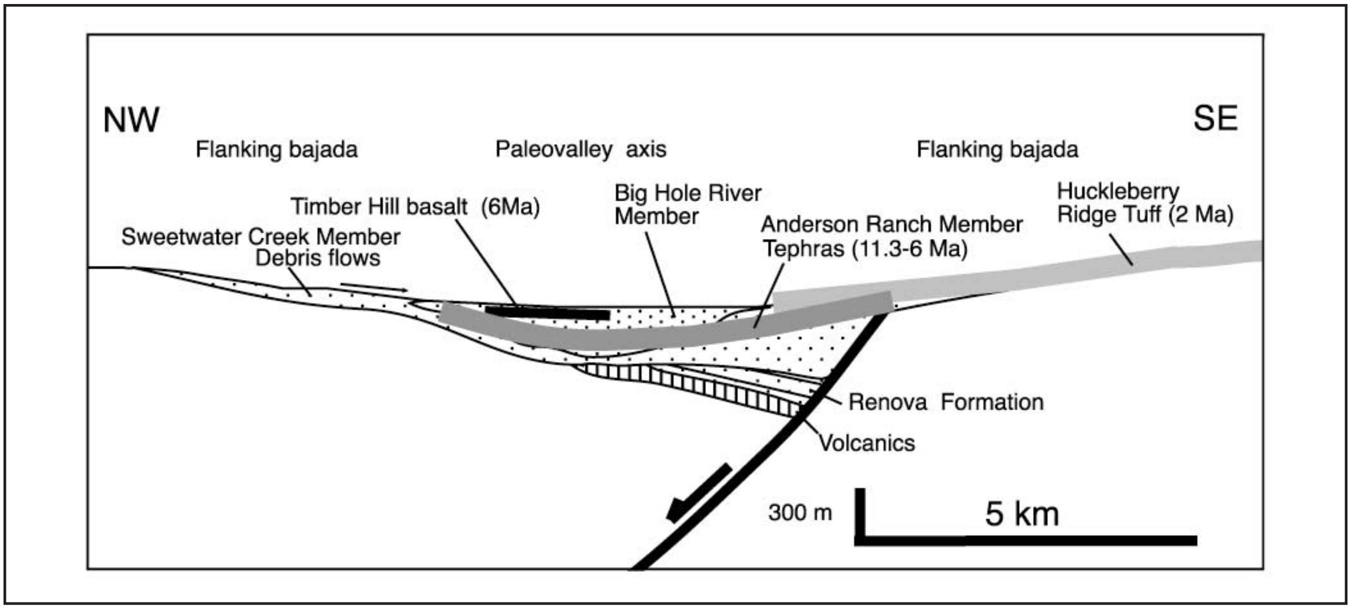

Figure 5: Schematic cross-section of Ruby graben in late Pliocene time. The Sixmile Creek Formation accumulated fluvial and alluvial gravel, tephra, and basalt prior to late Neogene cross-faulting and Quaternary erosion (Modified from Thomas et al., 1995).

lapilli >2 cm in diameter probably originally fell within 50 km of the 10 Ma location of the hotspot in central Idaho, and were then fluvially transported >100 km down the Ruby graben (Sears et al., 1995).

The Deer Lodge and Big Hole grabens were very deep, and filled with middle Miocene lakes. 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 sediments (McLeod, 1987). The lower 1 km comprises down-faulted Renova Formation and Eocene volcanics, and the remainder comprises flat-lying lakebeds 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 Big Hole lake appears to have flowed out through a canyon cut through the Pioneer Mountains and joined the Beaverhead graben. The Deer Lodge lake appears to have flowed out along the Lewis and Clark line and cut a broad canyon along the Clark Fork river from Garrison to Missoula. As the outflow canyon deepened, the lake-bed filled with fine sediment, likely stripped from the uplifted Renova 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). A strath-terrace cut on tilted early Miocene strata is overlain by flat-lying fluvial conglomerates of the Sixmile Creek Formation containing 16 Ma Barstovian fossils (Rasmussen, 1969). The strath-terrace has been traced along the Clark Fork River from Deer Lodge to Missoula (Alt and Hyndman, 1986). Near Missoula, it cuts the tilted Bitterroot River paleovalley deposits 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). We suggest that faulting along the Lewis and Clark line diverted the flow of the ancestral Bitterroot River into the modern course of the Clark Fork River. New canyons downstream of Missoula, such as Alberton Gorge, cut through bedrock ridges uplifted between grabens along the Lewis and Clark line.

LATE NEOGENE

The drainage systems that were initiated during middle Miocene time are generally those still active today, except in seismically active areas of southwest Montana. The seismic activity is part of the Intermountain seismic and Centennial tectonic belts (Stickney et al., 2000). Part of the activity includes regional crustal adjustment to the Yellowstone hotspot (Anders, et al., 1989).

The middle Miocene Ruby graben had aggraded 2-300 m of valley fill, including fluvial and alluvial sediments, fluvially reworked tephra from Yellowstone hotspot eruptions, and the >50 km long Timber Hill basalt flow, before it was segmented by cross-faults that diverted the drainage into new graben valleys (Fritz and Sears, 1993). The youngest dated materials in the Ruby graben that predate the cross-faulting are the 6 Ma Timber Hill basalt flow and underlying 6 Ma tuff of Walcott (Shane and Sears, 1995). 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 alluvial fans in the present drainage basins (Garson et al., 1992). Quaternary erosion deeply incised the alluvial fans after eruption of the Huckleberry Ridge tuff. In southwestern Montana, the cross-faults shunted drainage from the axis of the Ruby graben northwestward toward the Beaverhead graben (Fig. 6). In central Idaho, cross-faults beheaded the Ruby graben drainage and isolated the distinctive Milligen veined-chert and other source areas from southwestern Montana. Faulting diverted the Big Hole River from a middle Miocene graben into a Neogene graben to the west. The Big Hole River then flowed back toward the east and cut a new canyon across its own gravel fill (Sears et al., 1995). The continental divide appears to have shifted south 20 kilometers as faulting added Silver Bow Creek to the Clark Fork drainage basin.

The modern course of the Clark Fork River cuts through the lacustrine and alluvial deposits of the Deer Lodge graben , then follows the middle Miocene outflow channel to Missoula. The modern stream bed is typically about 70 m below the middle Miocene paleovalley strath-terrace, which is preserved as a prominent bench along the course of the river, locally with remnants of Miocene stream gravel. The modern valley floor is typically underlain by ~15 m of Quaternary gravel, which provides an excellent aquifer. Miocene strath-terraces also occur in the Bitterroot and other tributary valleys, showing that the drainage basin has been relatively stable throughout the region. Local variation of as much as 30 m in the relief between the Miocene and modern stream beds may reflect minor late Neogene tectonic activity.

CONCLUSIONS

Remants of paleovalleys in western Montana provide evidence for changing tectonic regimes throughout Cenozoic time. Unique bedrock lithologies were exhumed from beneath thick Eocene Challis volcanics upon Paleogene extensional faulting in central Idaho. These relatively small source areas shed distinctive pebbles and cobbles that indicate that north-flowing paleodrainage, established in Paleogene, was shunted to the northeast during middle Miocene tectonism. Late Neogene tectonism on the shoulder of the Yellowstone hotspot subsequently isolated the central Idaho source areas from drainage basins in southwest Montana and disrupted paleovalley deposits.

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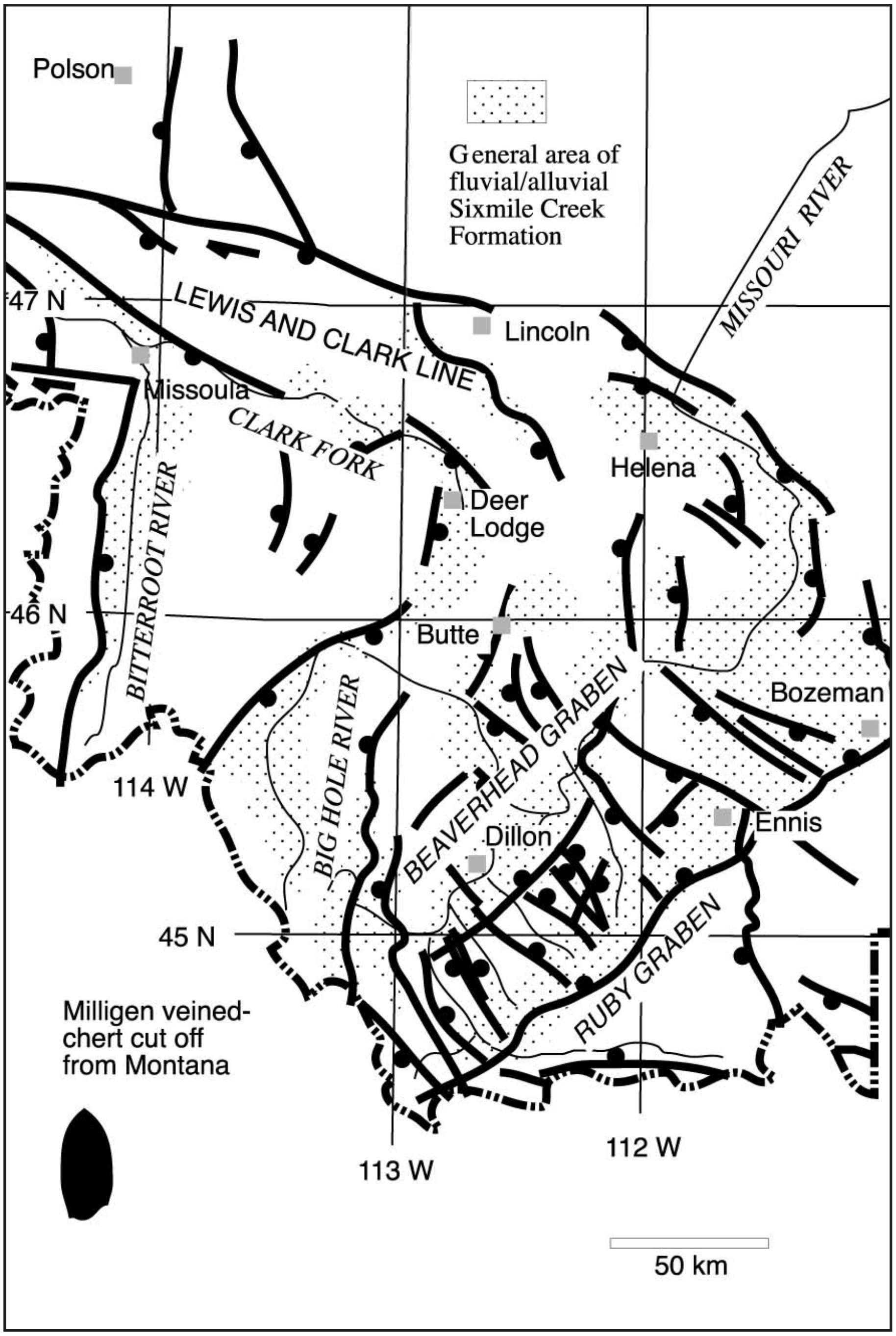

Figure 6: Late Neogene faults overprint middle Miocene faults in southwest Montana in the shoulder zone of the Yellowstone hotspot. New grabens shift drainage from Ruby graben to the Beaverhead graben. Milligan veined-chert was cut off from the Montana drainage.

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