Cenozoic Extensional Basin Development and Sedimentation in SW Montana

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Abstract

Cenozoic extensional basin development in southwest Montana consists of a minimum of three primary phases of extension. Phase 1 (48-20 Ma) was a time of active extensional basin development and terrestrial deposition in a 100-km wide, north-trending "rift zone" in western Montana (*Janecke*, 2007). The "rift zone" is interpreted to have developed from the gravitational collapse of compressional structures formed during Cretaceous and Paleogene time. To the east of the "rift" was a tectonically tranquil, supradetachment basin (*i.e*., Renova Basin) that contained remnant topography formed during Cretaceous to early Paleogene compression and volcanism. Areas of sediment transport from the "rift" to the supradetachment basin are shown by provenance data gathered from fluvial deposits in the Renova Formation.

Phase 2 (17-4 Ma) extension was a period of NE-trending basin development and fluvial and debris flow deposition. The initiation of extension coincides temporally with the outbreak of the Yellowstone volcano, and has been interpreted as having formed by thermal doming and radial extension around the outbreak point (*Sears* et al., 2009). This event preserved the Renova Basin deposits in southeast-tilted half-grabens, which are now in angular discordance with the overlying fluvial and debris-flow deposits of the Sixmile Creek Formation. Provenance studies show that streams flowed to the northeast off of the Yellowstone thermal bulges, and that the gradient increased over time as the thermal bulge progressed to the northeast (*Landon & Thomas*, 1999). Distinctive duriclast gravels were derived from primary sources in central Idaho and/or reworked from the Late Cretaceous Beaverhead conglomerate.

The NE-trending structures were terminated around 4.0 Ma as Phase 3 (4.0 Ma-present) northwest-trending extensional topography developed in association with crustal adjustments along the northern margin of the Yellowstone volcano. Most of the current seismicity occurs on the NW-trending faults, as shown by a 5.6 magnitude earthquake that occurred on July 25th, 2005 north of Dillon, Montana. Future work includes provenance studies of the Sixmile Creek gravels and tephras to determine if crustal bulging and collapse related to the passage of the Yellowstone volcano influenced the sediment sources available to the NE-trending grabens in southwest Montana.

Slide 1: The center photo shows multiple tephras in the Sixmile Creek Formation at Timber Hill, southeast of Dillon, Montana.

Slide 2: A satellite photo showing the approximate location of the study area. Northwest-trending extensional topography is obvious, and if you look carefully, you can also see an older, northeast-trending extensional topography, especially to the east of Dillon, Montana.

Slide 3: The Cenozoic stratigraphy of southwest Montana. The photos to the right of the column display the typical lithologies found in these formations, including the three members of the Sixmile Creek Formation (from the base: Sweetwater, Anderson Ranch and Big Hole Gravel Members).

Slide 4: A summary of the three primary phases of Cenozoic basin development in southwest Montana. Phase 1 (48-20 Ma) was a time of active extensional basin development (i.e., "rift zone") and sedimentation in western Montana. To the east of this "rift zone", a tectonically tranquil, supradetachment basin developed with minimal remnant topography from Cretaceous compression and early Cenozoic volcanism. The Renova Formation and its equivalents were deposited in both the "rift zone" and the supradetachment basin at this time. It has been argued that the gravitational collapse of older compressional structures caused the extension.

Phase 2 (17-4 Ma) was a period of NE-trending extensional basin development and fluvial/debris flow deposition. The initiation of extension coincides temporally with the outbreak of the Yellowstone volcano. The Sixmile Creek Formation was mostly deposited by northeast-flowing fluvial systems that transported gravel and tephra derived from source areas to the southwest, possible as far away as central Idaho.

Phase 3 (4 Ma-present) was a period of NW-trending extensional basin development that terminated most of the NE-trending fluvial systems and diverted them into NW-trending grabens. These faults are currently active and produced a magnitude 5.6 earthquake north of Dillon on July 25, 2005. The photo in the lower right corner shows the NW-trending, Blacktail Fault south of Dillon, Montana.

Slide 5: A paleogeographic map of Phase 1 (48-20 Ma) extension in southwest Montana. The map shows the location of the Paleogene "rift zone" and the adjacent supradetachment basin (locally called the "Renova Basin"). The topography shown within the supradetachment basin is remnant topography from Mesozoic and early Cenozoic compression and volcanism. The photo to the right shows the Anaconda detachment fault and metamorphic core complex within the "rift zone." This fault was active early in this phase of extension and the basin fill sediments record the unroofing history of the core complex.

Slide 6: A paleoflow map of drainages within the Paleogene "rift zone" as determined by provenance work, including detrital zircon analyses. The data suggest that a primary source of distinctive two-mica sandstones (photo on the right) was the Chief Joseph Pluton to the west, and that some streams may have breached the “rift shoulder” and deposited these sediments in the supradetachment basin. On-going work is helping to further refine our understanding of the provenance of the Renova Formation and its equivalents.

Slide 7: A paleogeographic map of Phase 2 (17-4 Ma) extension in southwest Montana. The map shows the location of the Neogene grabens and the paleoflows of the fluvial systems based on extensive provenance work in the Sixmile Creek Formation. The photo to the right shows one of many fluvially deposited tephras in the Sixmile Creek Formation. These tephras were derived from the eruption of the Yellowstone volcano, and were deposited by floodwaters that covered much of the floodplain as shown by their occurrence on paleosols (as shown in the photo to the right). Based on measurements of the cross bedding in these tephras, the floodwaters were up to 9.0 meters deep and repeatedly flooded the basins. Ash found on debris-flow fan deposits in the Sixmile Creek Formation indicates that the thickness of air-fall ash in the area did not exceed 10 cm.

Slide 8: A paleoflow map of the NE-trending drainages, and some of the mountain ranges that currently exist within the path of these paleodrainages. Duriclast gravels (center photo) in the Sixmile Creek Formation contain distinctive black chert cobbles (Milligen chert) that suggest that the headwaters of these streams were in central Idaho. Extensive provenance work shows that these streams flowed to the northeast and were relatively linear (i.e., low variance around the paleoflow vector mean). Grain-size reductions show a downstream reduction in grain size (graph on the right), and temporal changes in grain size show an up-section increase in size, possibly reflecting an increased gradient due to the encroaching Yellowstone thermal bulge over time.

Slide 9: An alternative model for the origin of the sediment in the Sixmile Creek Formation. Detrital zircon work by Stroup and others (2008) has been interpreted as showing that the gravels were derived from the “rift shoulder” rather than central Idaho, as suggested by Sears and others (2009). According to Stroup and others (2008), the Cretaceous Beaverhead Conglomerate (photo on the right), which was possibly exposed along the rift shoulder, was the primary source of the gravels. Sears and others (2009) acknowledge that some of the gravels in the Sixmile Creek Formation were likely derived through the reworking of the Beaverhead Conglomerate, but also believe that the headwaters of these streams extended further to the south into central Idaho.

Slide 10: A satellite photo showing the Phase 3 (4 Ma-present) NW-trending faults cutting the NE-trending Ruby Graben. The dark rock under the arrow in the Ruby Graben is a 6.0 Ma basalt flow called the Timber Hill Basalt that came from the Heise Volcanic Field in Idaho. The inset photo shows the modern extensional topography with an impressive amount of relief formed in the last 4.0 million years! The map to the right shows some of the other NW-trending faults that cut the Phase 2, NE-trending Beaverhead and Ruby Grabens.

Slide 11: Field relationships between the three phases of basin formation at Timber Hill, southeast of Dillon, Montana. The photo on the left shows the Sixmile Creek Formation resting on Archean metamorphic rocks, and capped by the 6.0 Ma Timber Hill Basalt. The Sweetwater Fault, a NW-trending, listric normal fault, cuts the sequence and offsets the basalt by about 700 feet. The Renova Formation is not visible at this locale, because it has been removed by pre-Sixmile Creek Formation erosion, but it occurs elsewhere in the area in angular discordance with the overlying Sixmile Creek Formation. The photo to the right shows an aerial view of the Sweetwater Fault and the mesas formed by the Timber Hill Basalt.

Slide 12: The NW-trending "Frying Pan Fault" (dashed line), which produced a 5.6 magnitude earthquake on July 25th, 2005. It ruptured at 3.0 miles depth, and the epicenter (red circle) was located 9 miles north of Dillon, Montana. The damage in Dillon was relatively minor, although numerous chimneys were damaged (photo on the right) and some historical buildings suffered minor structural damage. This fault is uplifting and tilting the Pioneer Mountains (the topography to the left in the photo) to the southwest, while it is asymmetrically dropping the divide basin (the valley to the right of the Pioneer Mountains) down to the southwest. This is the typical geometry of the NW-trending normal faults in the region.

Slide 13: A hypothesized relationship between the outbreak of the Yellowstone volcano and the formation of the NE-trending extensional topography in southwest Montana around 17 Ma. The map shows other extensional features that are oriented around the outbreak point of the Yellowstone volcano around 17 Ma. There is no doubt that the track of the Yellowstone volcano affected sedimentation in the NE-trending grabens in southwest Montana, and it possibly played a role in the formation of the NW-trending topography at 4.0 Ma.

Slide 14: A map that shows the potential for future work testing the influence of the passage of the Yellowstone volcano on the source areas for sediment deposited in the Beaverhead and Ruby Grabens from 17 to 4 Ma. As the Yellowstone thermal bulge progressed from the southwest to the northeast, it is possible that old sediment sources were cut off while new ones were created. Detailed provenance work should be able to work this out, and possibly test the merits of the alternative hypothesis proposed by Stroup and others (2008), shown in Slide 9.

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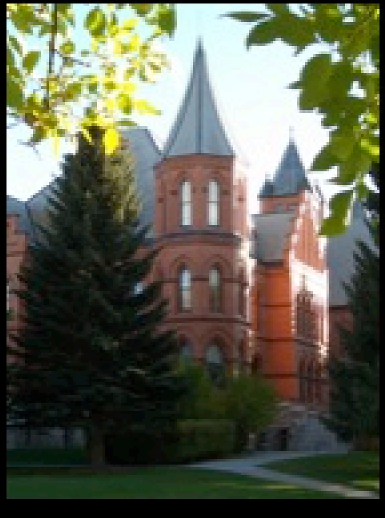
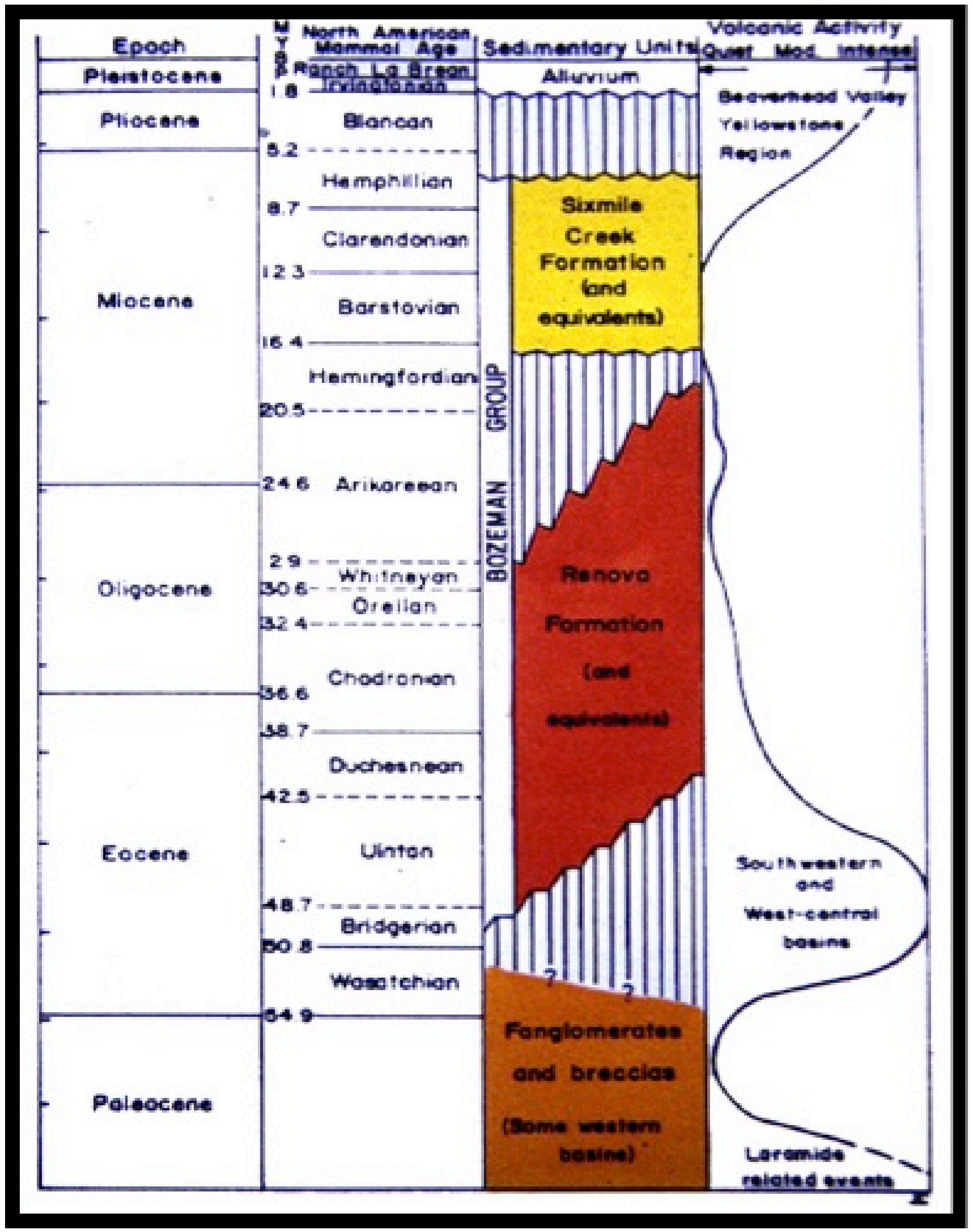


The University of Montana Western

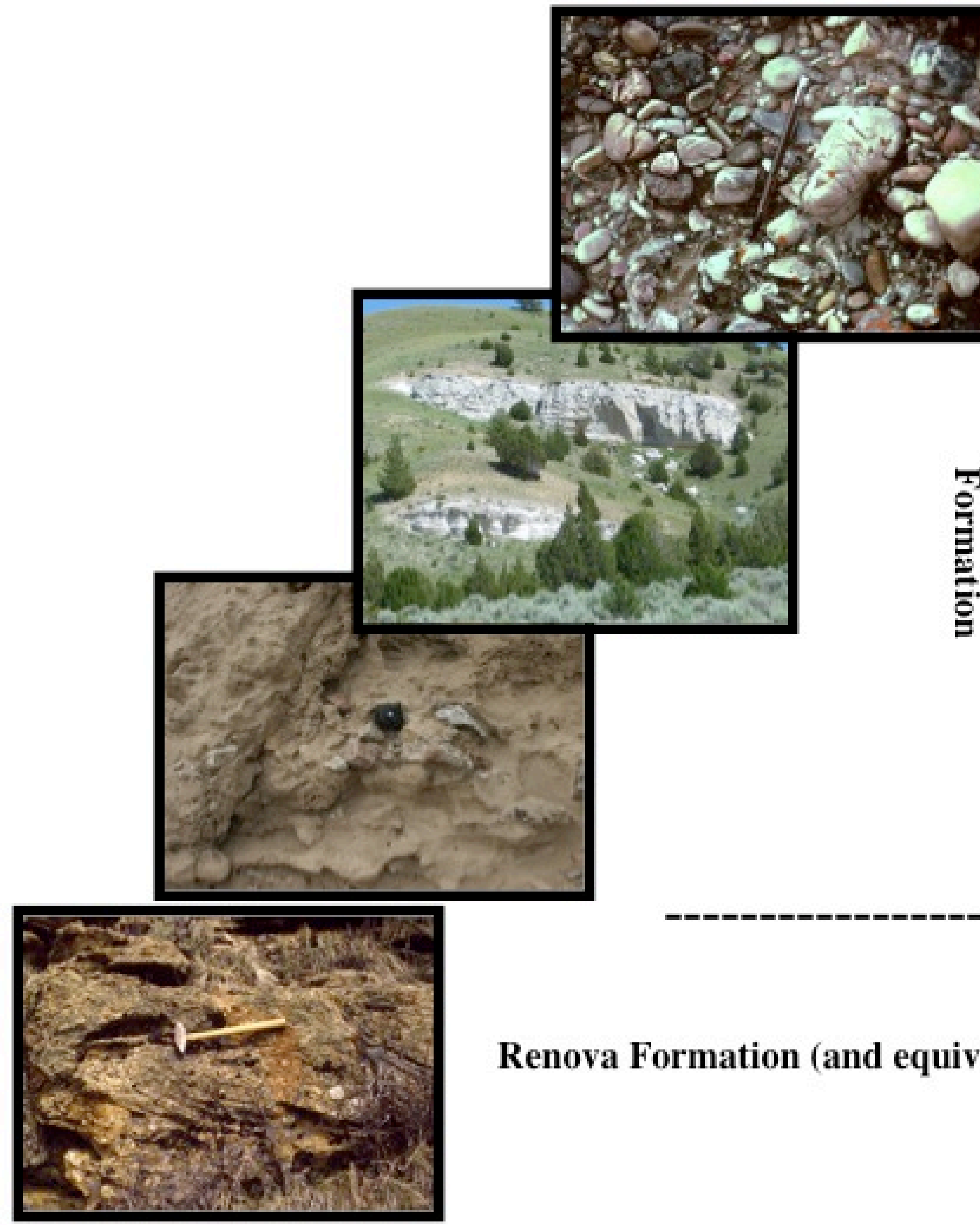
Location map of the study area

Google Earth, 2008

Cenozoic stratigraphy of southwest Montana



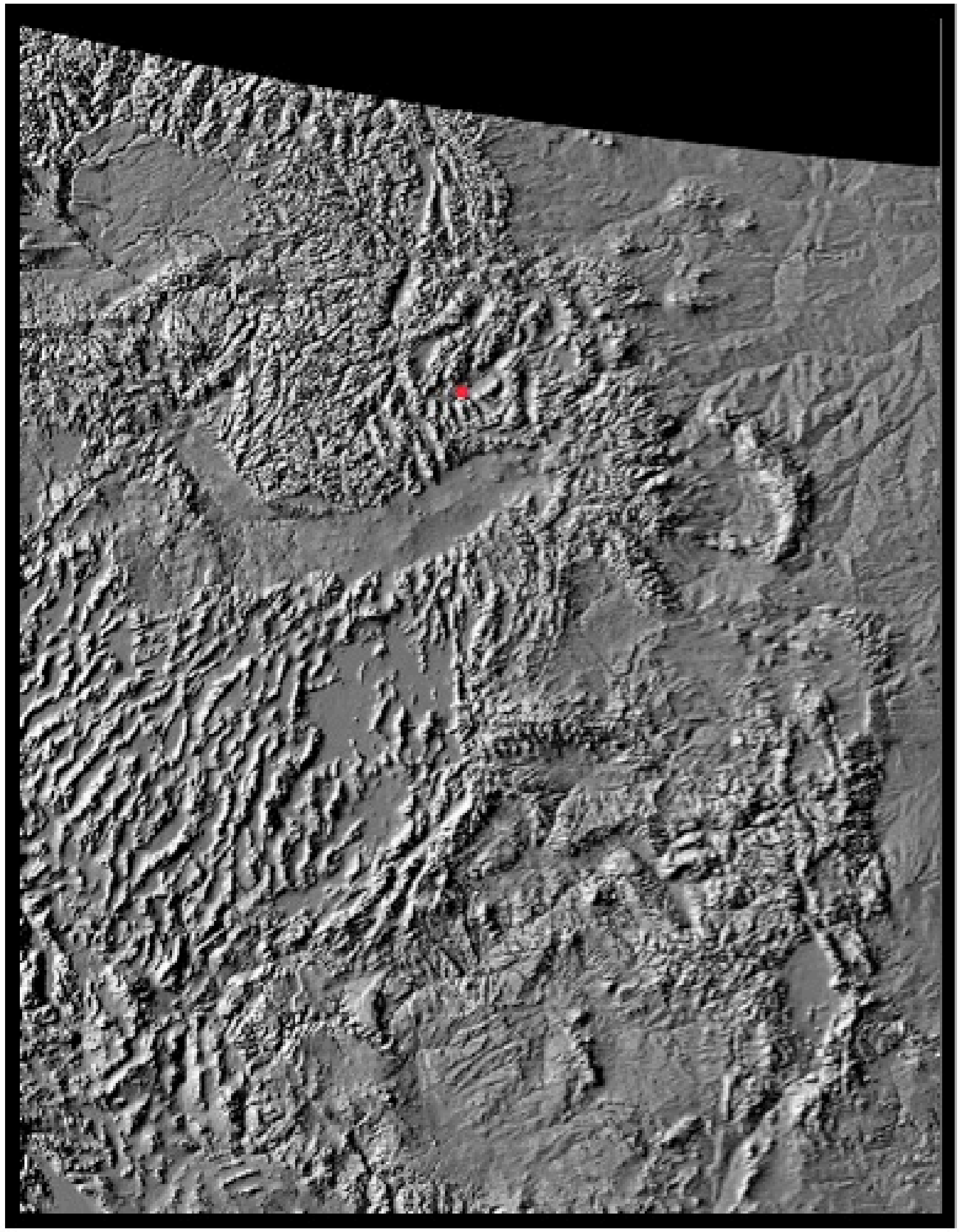
Modified from Fields et al., 1985



Sixmile Creek Formation

Renova Formation (and equivalents)

Summary of Cenozoic extensional basin development



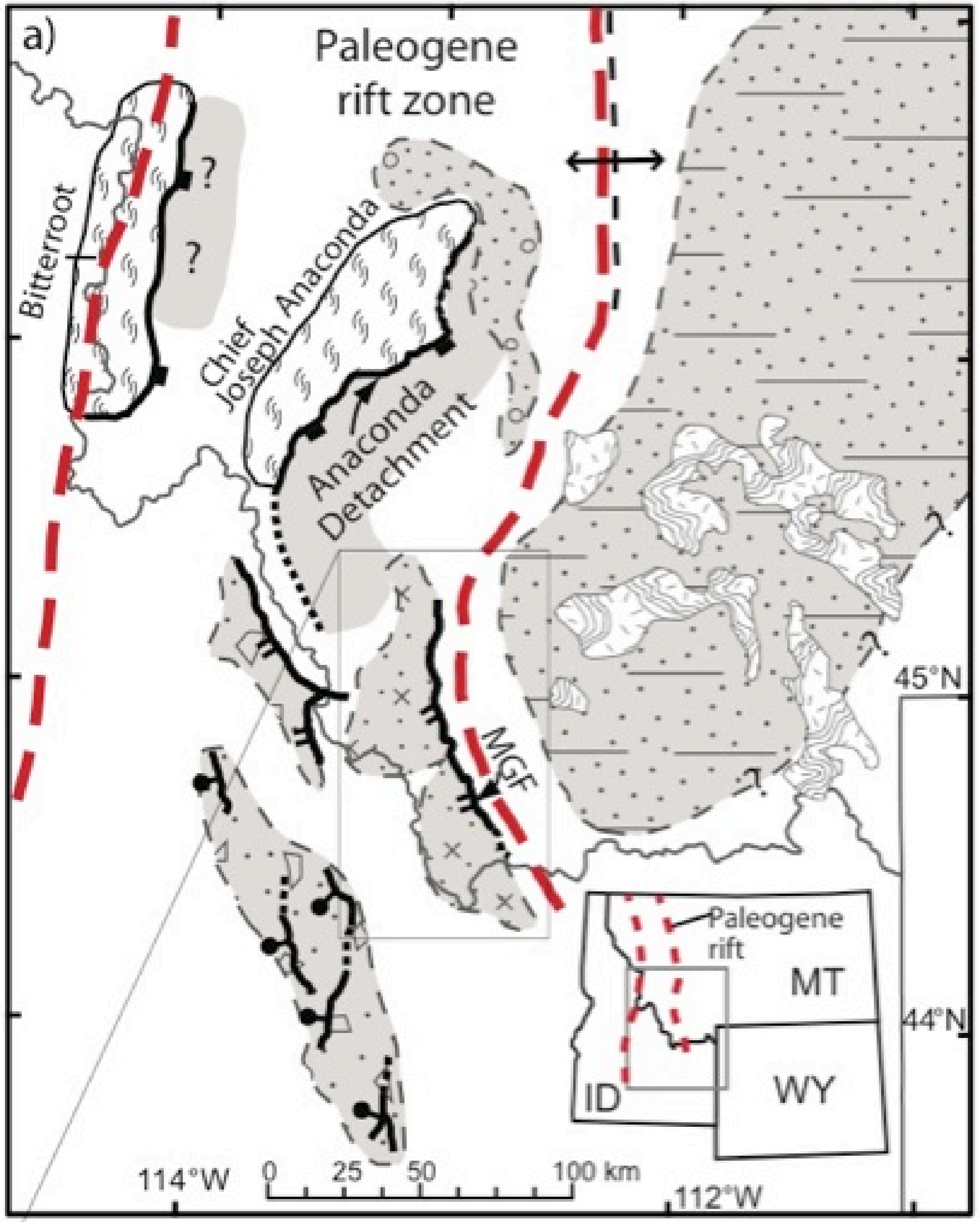
Regional extensional topography (Raven Maps, 2008)

Three primary phases of basin development

- Phase 1: Gravitational collapse "rift zone" basins in the west with a tectonically tranquil supradetachment basin to the east (48 - 20 Ma)
- Phase 2: NE-trending extensional basins possibly associated with the outbreak of the Yellowstone hot spot (17 - 4 Ma)
- Phase 3: NW-trending extensional basins (4 Ma - present)

4.0 Ma, NW-trending Blacktail fault south of Dillon, Montana (Thomas, 2004)

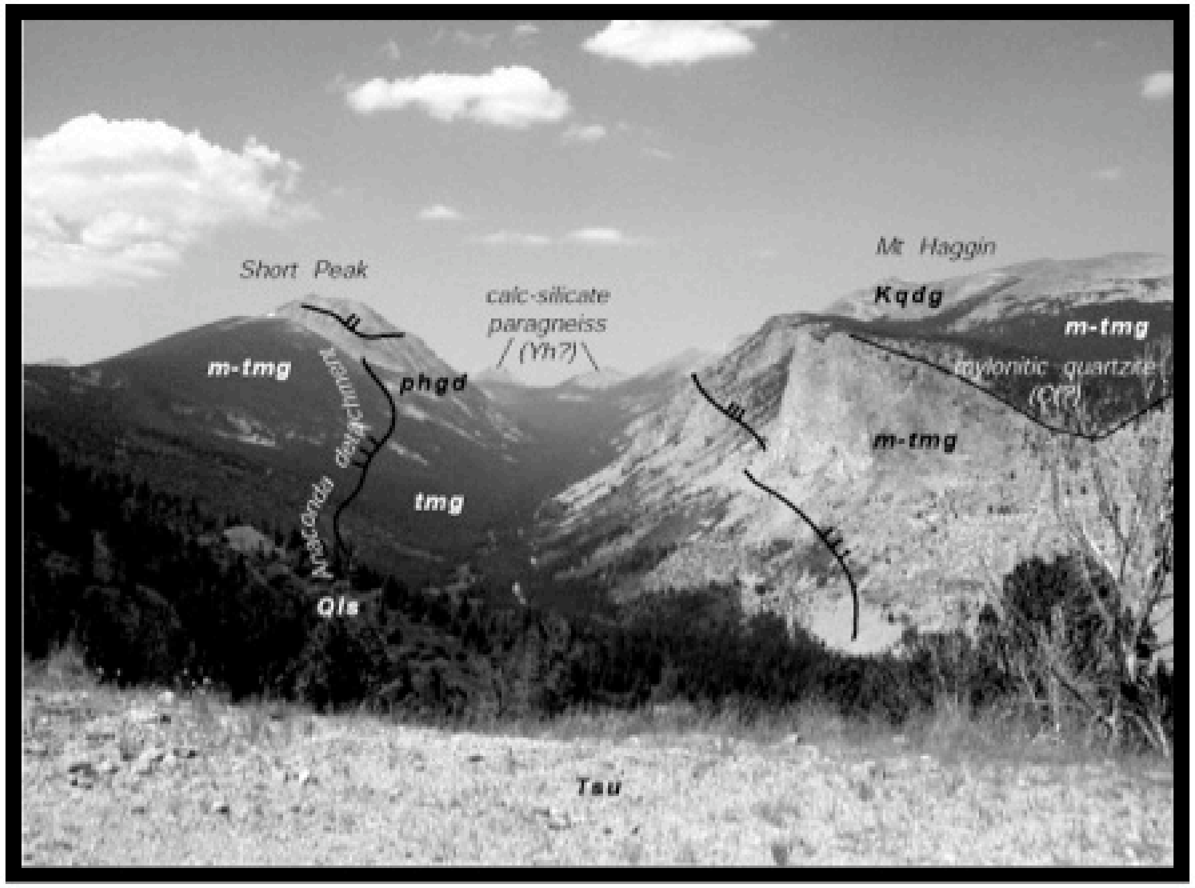
Phase 1: Eocene to early Miocene (48 to 20 Ma)



Location of the "rift zone" and Renova Basin (Stroup and others, 2008)

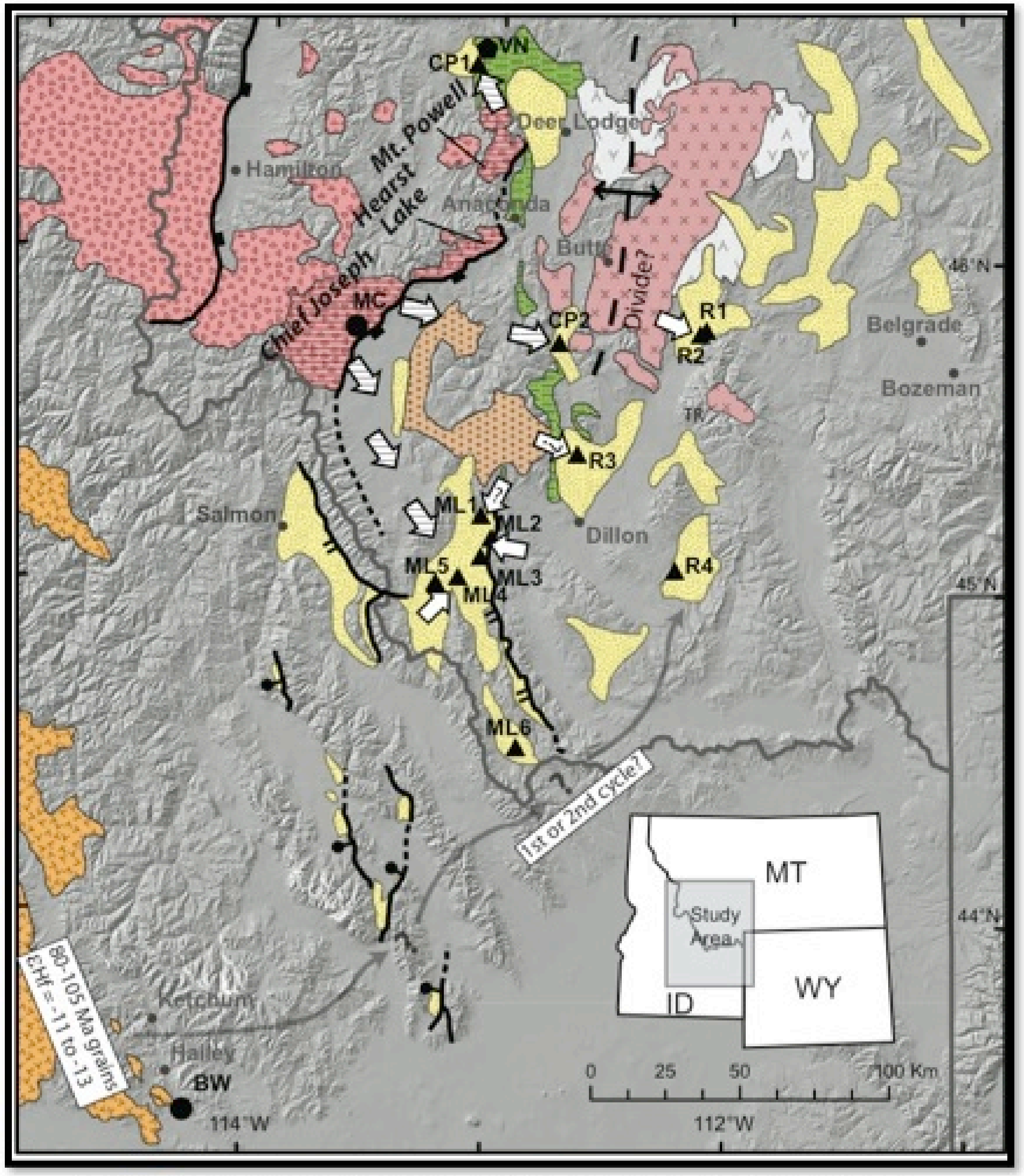
"Rift zone" and Renova Basin

- Zone of extension ("rift") with many basins west of Dillon, MT
- Supradetachment basin (Renova Basin) east of the "rift"
- Renova Basin was tranquil with deposition around remnant topography from Cretaceous and Paleogene compression
- Streams episodically breached the "rift shoulder"



Anaconda detachment fault within the "rift zone" (Kalakay and others, 2003)

Provenance study of the "Phase 1" basins



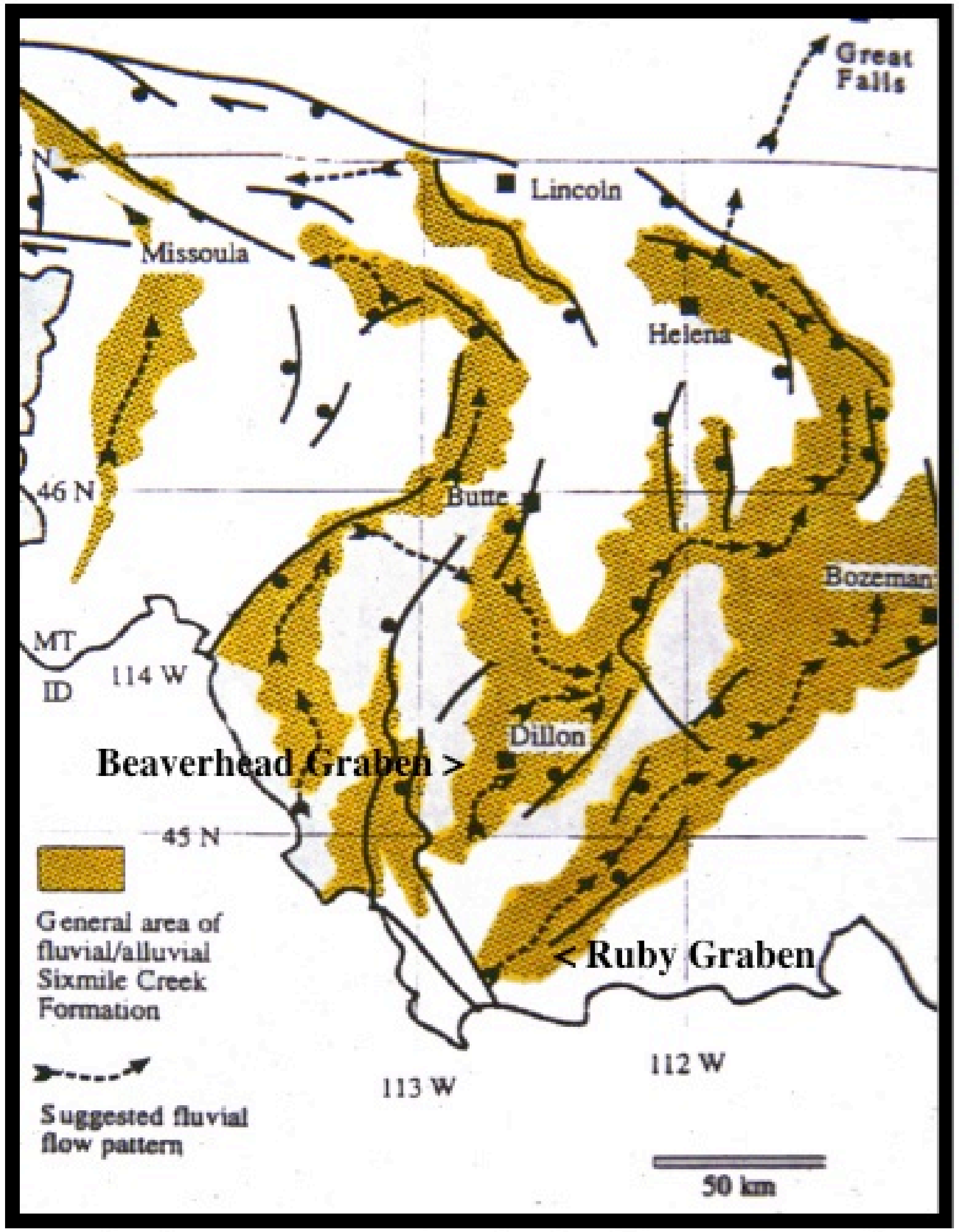
Paleoflow interpretations in the "rift" area (Stroup and others, 2008)

Sediment sources and topography

- Two-mica granitic sandstones suggest drainage across the "rift"
- Chief Joseph Pluton the likely source of the sands (75 Ma zircons)
- Detrital zircons suggest the "rift shoulder" (shown by easternmost dashed line on the map to the left) was breached by streams
- Ongoing provenance work is helping to define drainages in the supradetachment basin (includes groups from Alabama, Allegheny College, Idaho State, Montana, Montana Western and Utah State

Two-mica sandstone within the area of the "rift" (Thomas, 1995)

Phase 2: Mid-Miocene to Pliocene (17 to 4 Ma)



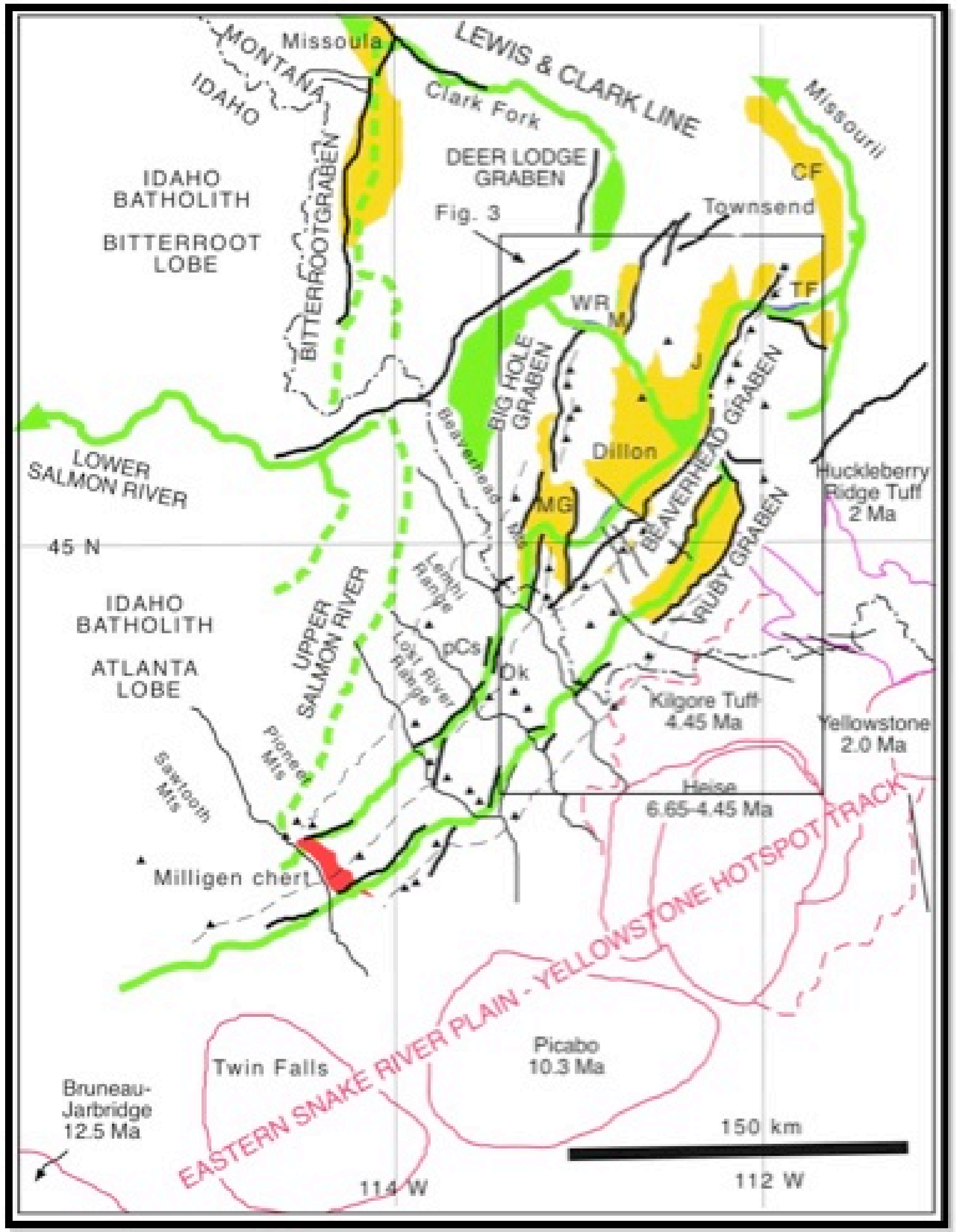
Paleoflows in Neogene grabens (Modified from Sears and others, 1995)

Beaverhead and Ruby Grabens

- Formation of NE-trending extensional topography
- Provenance data show drainage from Idaho into Montana
- Debris-flow fans show that air-fall ash was a max of 10 cm
- Drainages were choked by ash deposits (>20 m) that originated from Yellowstone hot spot eruptions and covered graben floors with flood waters up to 9 meters deep (Thomas, in preparation)

Fluvialy-deposited ash resting on a paleosol in the Ruby Graben (Thomas, 2003)

Provenance study of the "Phase 2" basins

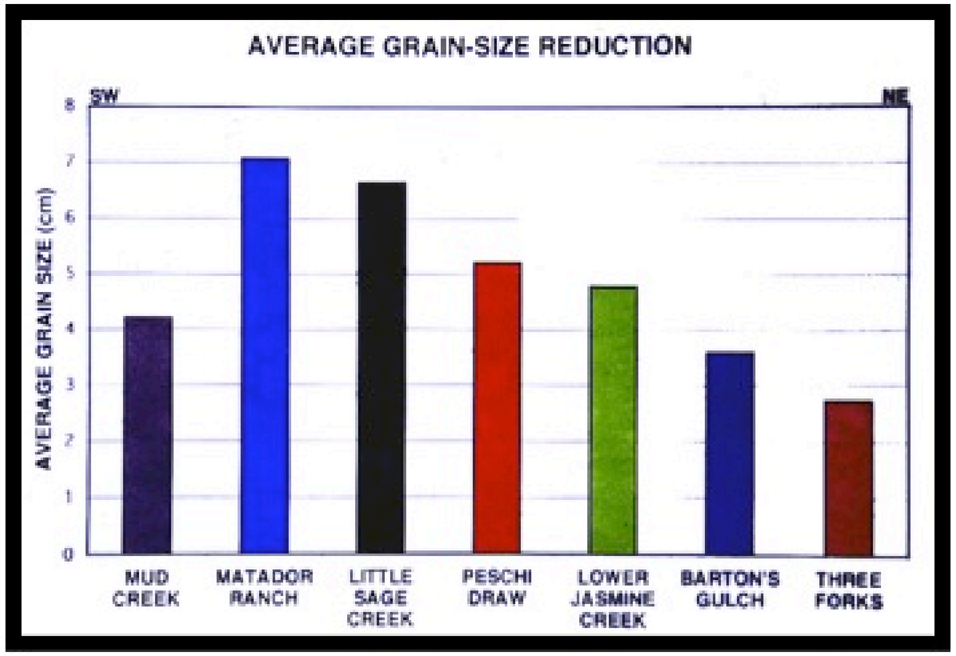


Provenance of Sixmile Creek gravels (Sears and others, 2009)

Provenance Data from Sixmile Creek Formation

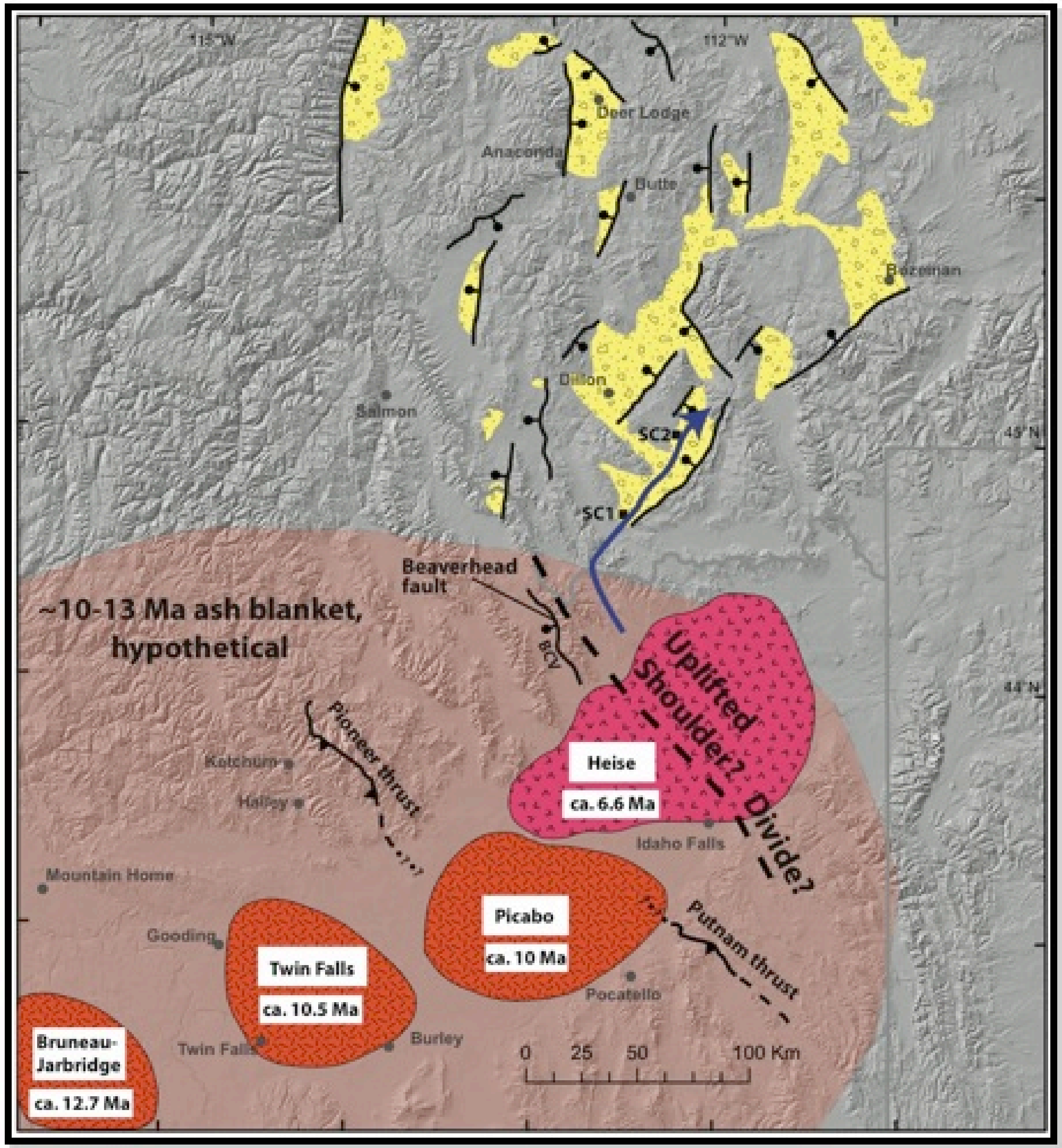
- Paleoflow vector mean for Ruby Graben is N54E with low variance
- Paleoflow vector mean for Beaverhead Graben is N62E with low variance
- Gravels contain exotic duriclasts that have sources in central Idaho
- Spatial changes in grain sizes show exponential decay from the SW to NE
- Temporal changes in grain size show an up-section coarsening, possibly from increasing gradient due to the encroaching Yellowstone thermal bulge

Duriclast gravels



Grain-size reductions from the southwest to the northeast in the Ruby Graben (Landon and Thomas, 1999)

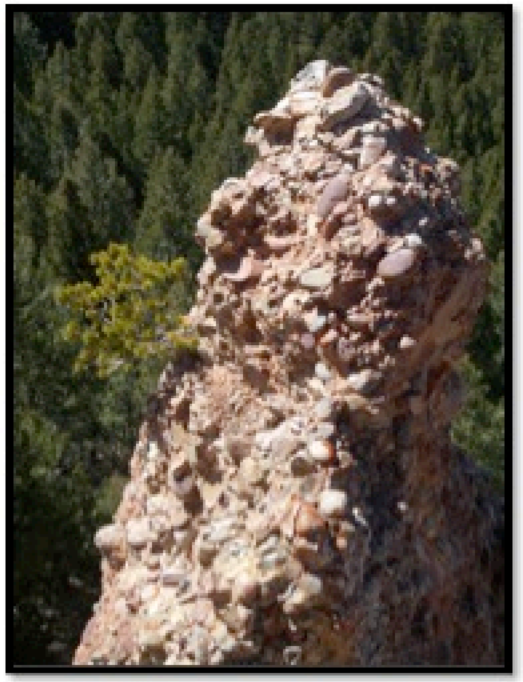
Provenance of “Phase 2” sediments: Alternative hypothesis



Map showing alternative source of Sixmile Creek sediments (Stroup and others, 2008)

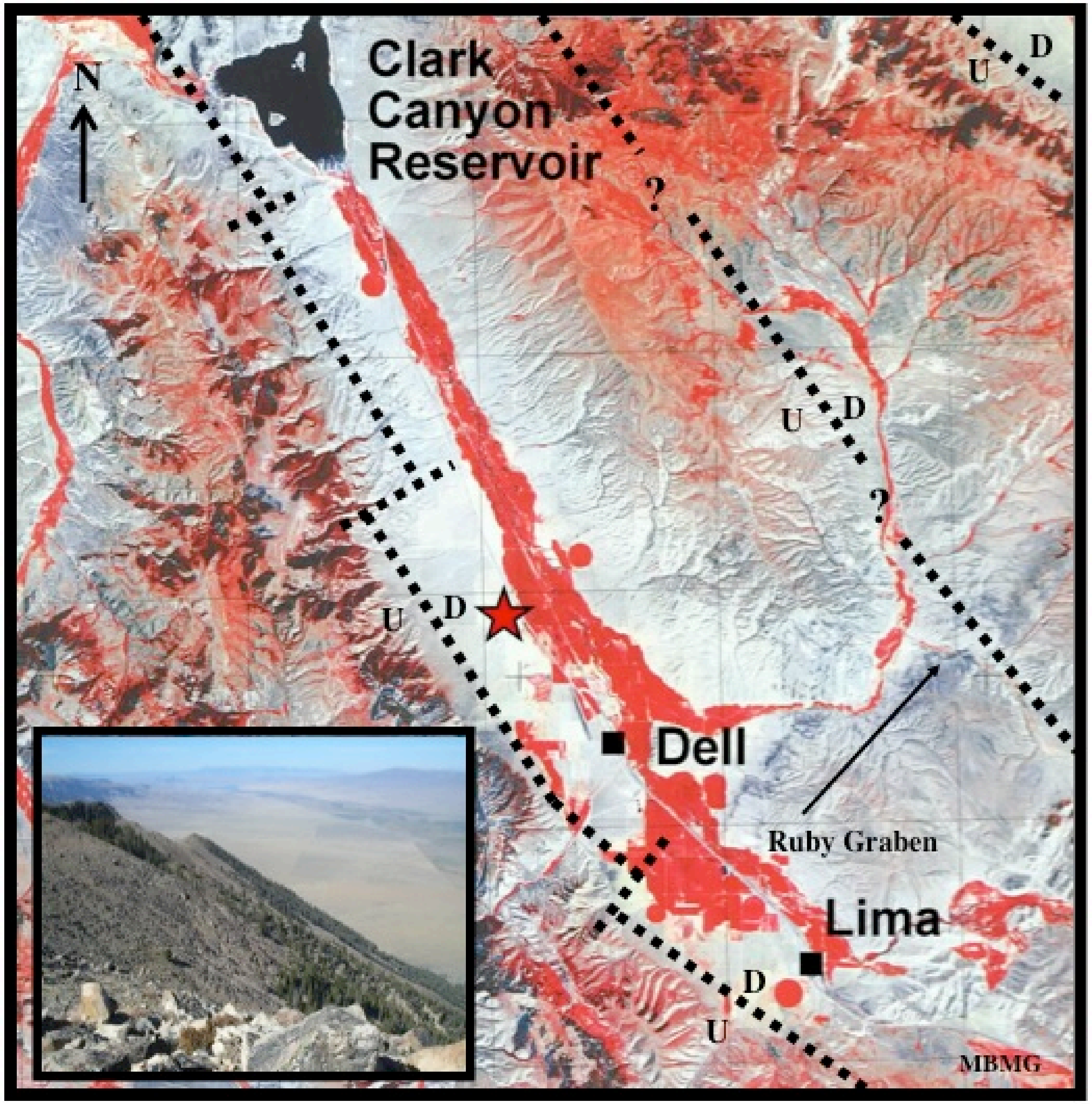
Detrital zircon analyses of Sixmile Creek Formation

- The sediments came from the “rift shoulder” not central Idaho
- Absence of zircons of Challis Volcanics (50-45 Ma) in the Sixmile Creek Formation suggests that the sediments could not have come from central Idaho where these rocks are exposed today
- Exotic “duriclasts” were recycled out of the Cretaceous, Beaverhead Conglomerate rather than primary sources in central Idaho



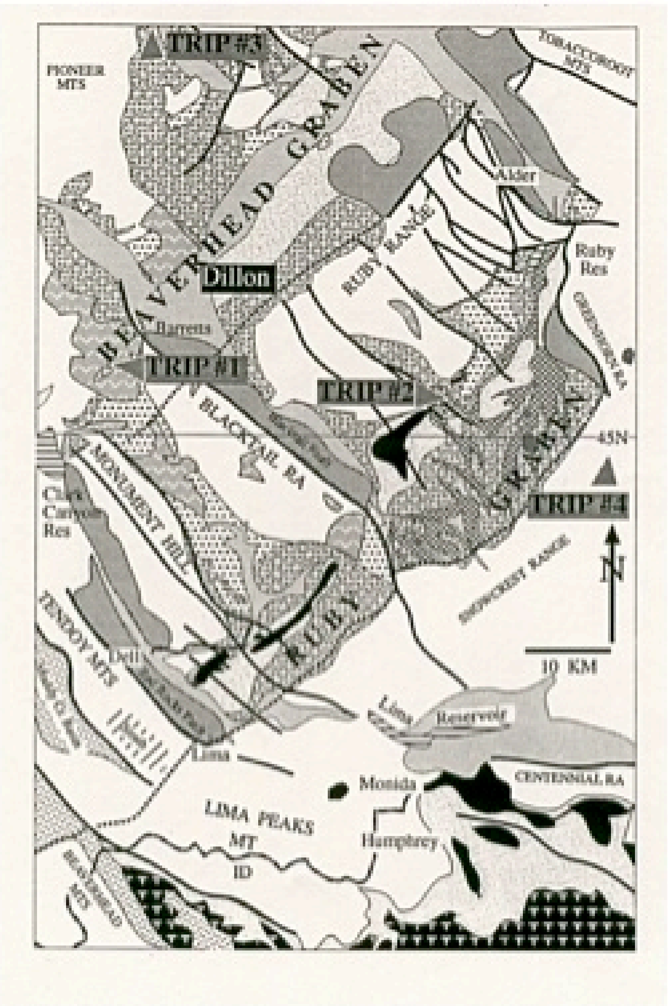
Beaverhead Conglomerate (Thomas, 2008)

Phase 3: Pliocene to present (4 Ma to today)



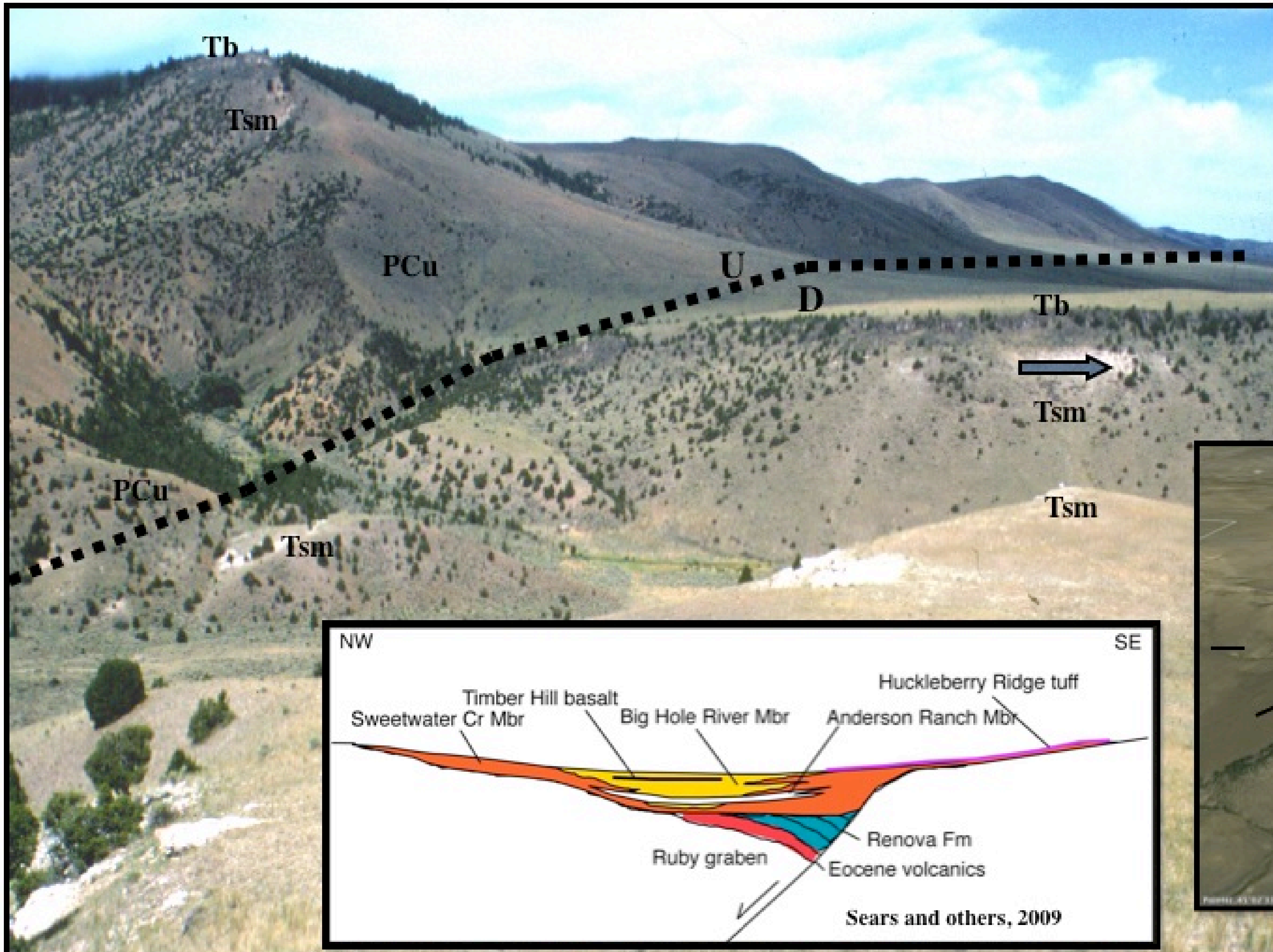
Modern drainage system

- NW-trending normal faults cut the NE topography
- Streams diverted into NW-trending drainages
- Deposition of valley-fill sediments in the new grabens



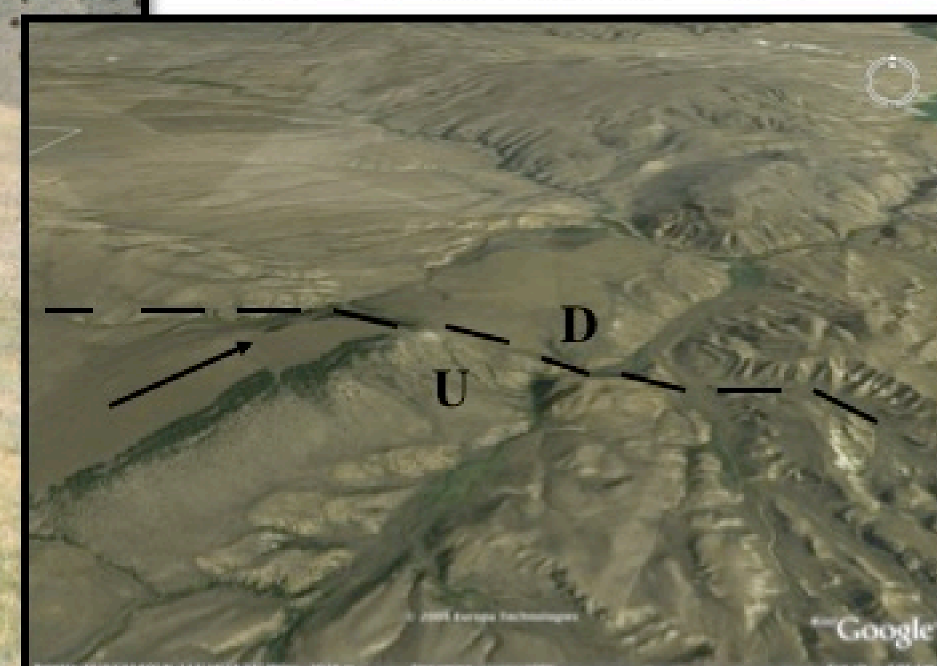
Map showing NW-trending normal faults cutting "Phase 2" grabens (Thomas and others, 1995)

An example of the three phases at Timber Hill near Dillon, MT

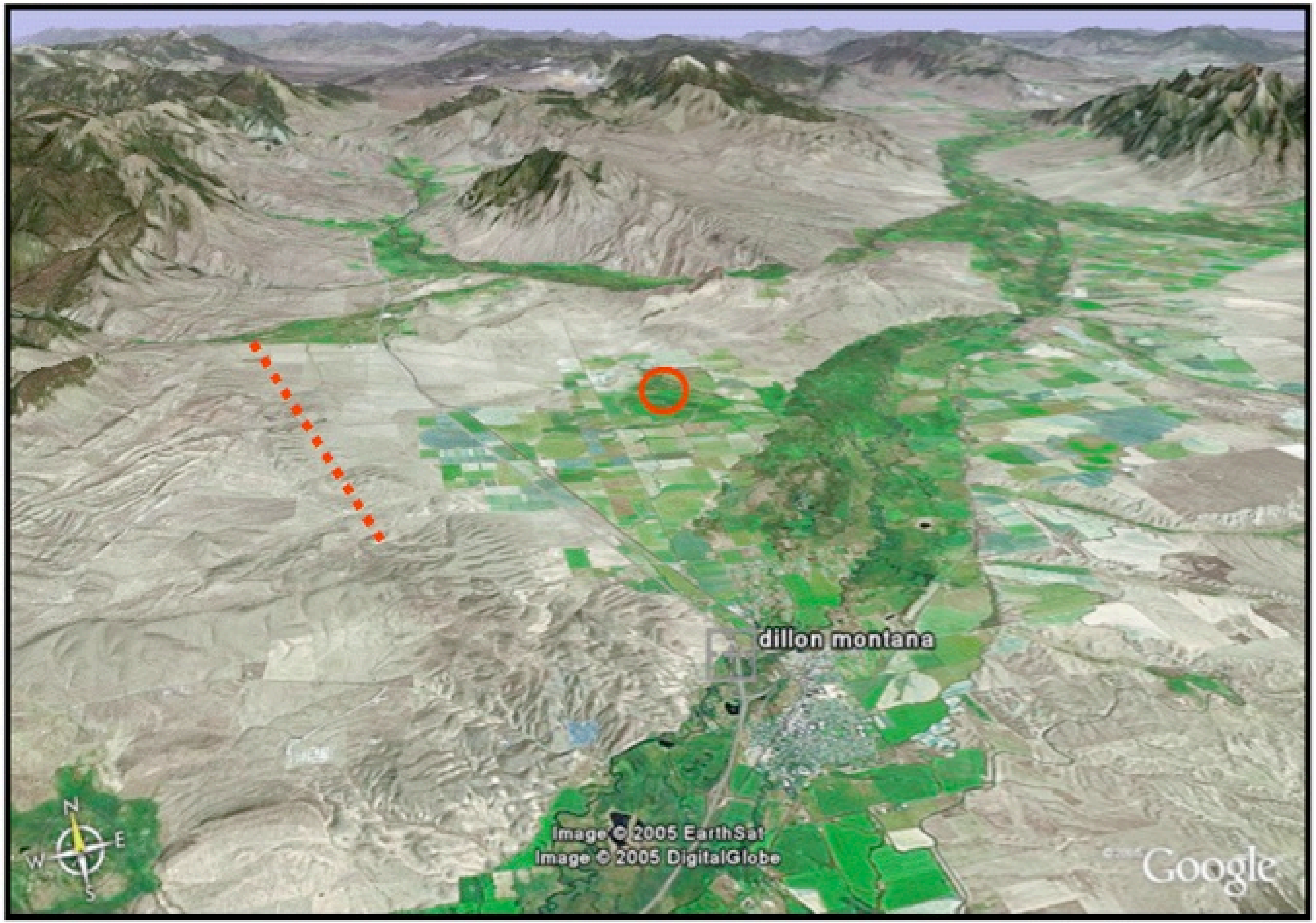


Timber Hill History

- 50-55 Ma - Eruption of Eocene volcanics
- 48-20 Ma - Deposition of Renova Fm. over eroded Cretaceous-Eocene surface
- 17-4 Ma - NE-trending Ruby Graben filled with fluvial & debris-flow sediment
- 6.0 Ma - Basalt flow from Heise Volcanic Field deposited in the Ruby Graben
- 4.0 Ma to present - Everything cut by NW-trending, Sweetwater Fault



Recent earthquake activity on the NW-trending faults



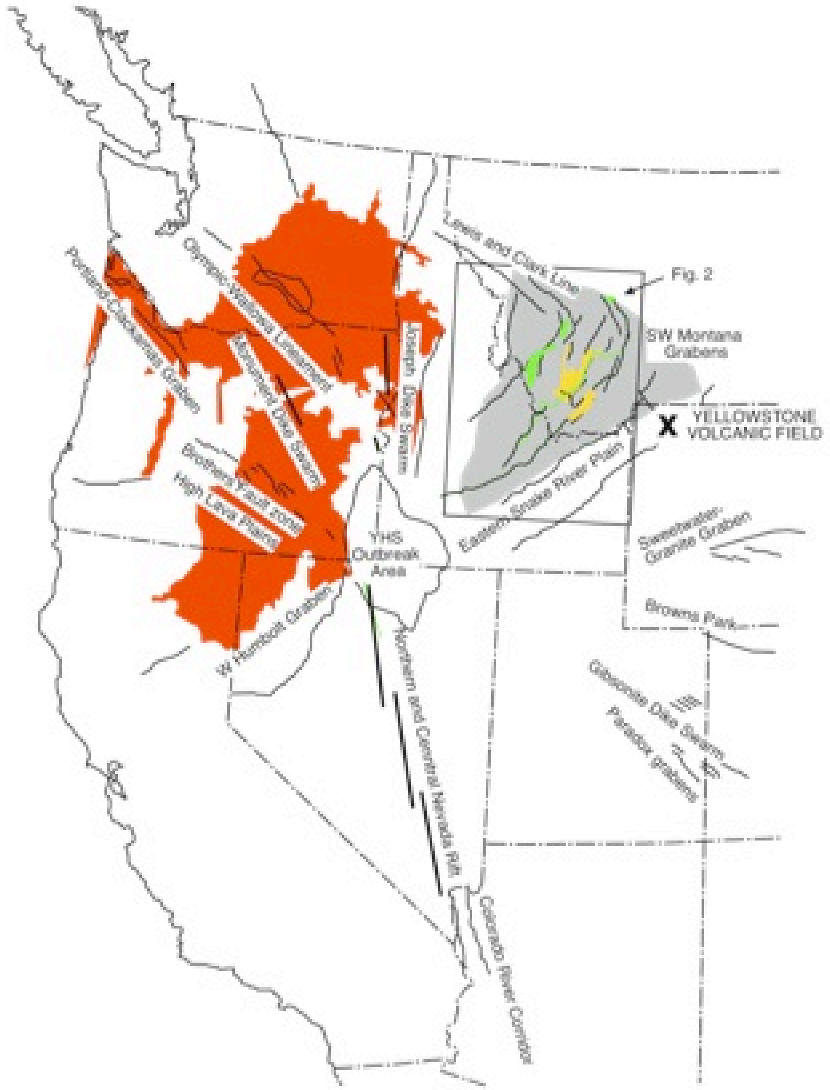
Courtesy of Mike Stickney, MBMG

"Frying Pan Fault"

- **NW-trending normal fault**
- **Ruptured on July 25, 2005**
- **Depth - 3 mi / magnitude 5.6**

Damage from the July 25th, 2005 quake in Dillon

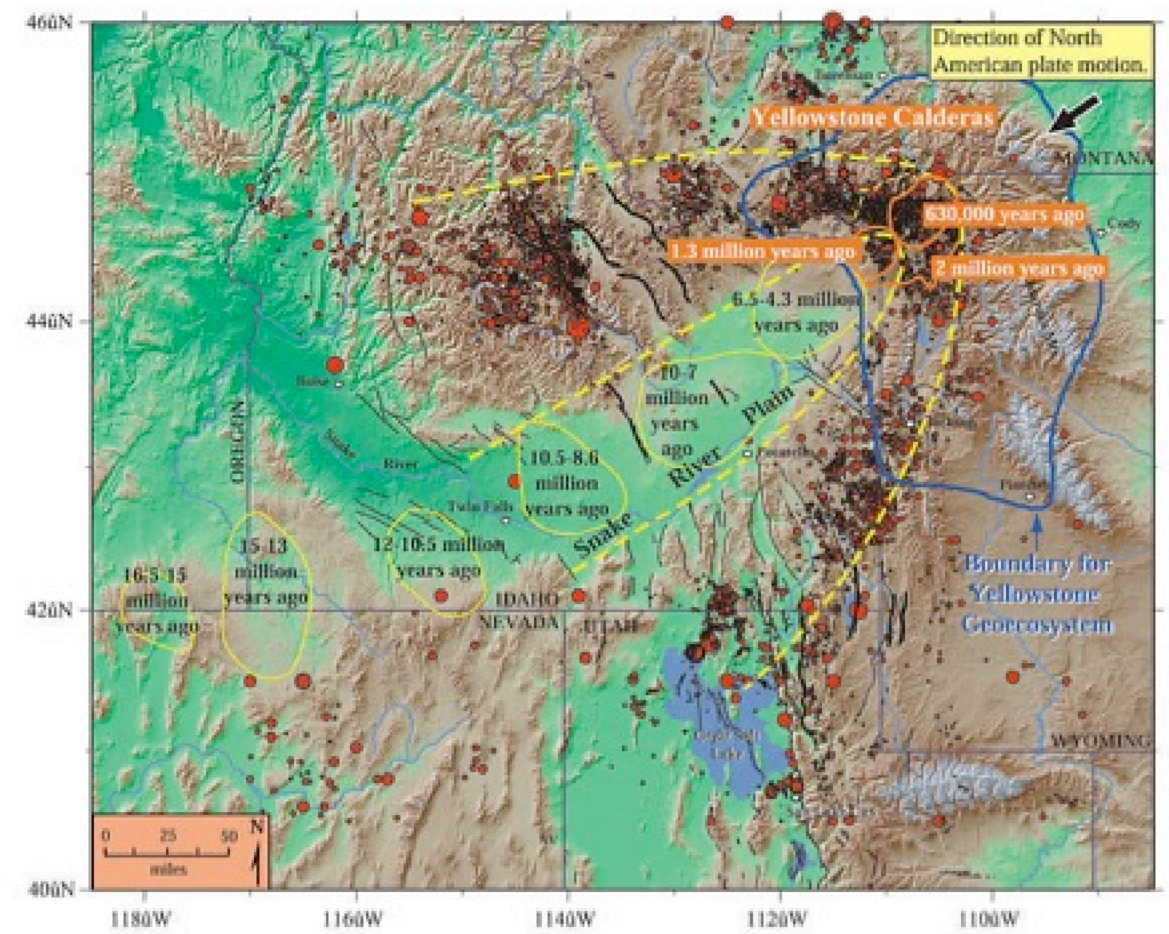
What is the influence of the Yellowstone hot spot?



Hypothesized formation of NE-trending grabens in southwest Montana due to the outbreak of the Yellowstone hot spot around 17 Ma (Sears and others, 2009)

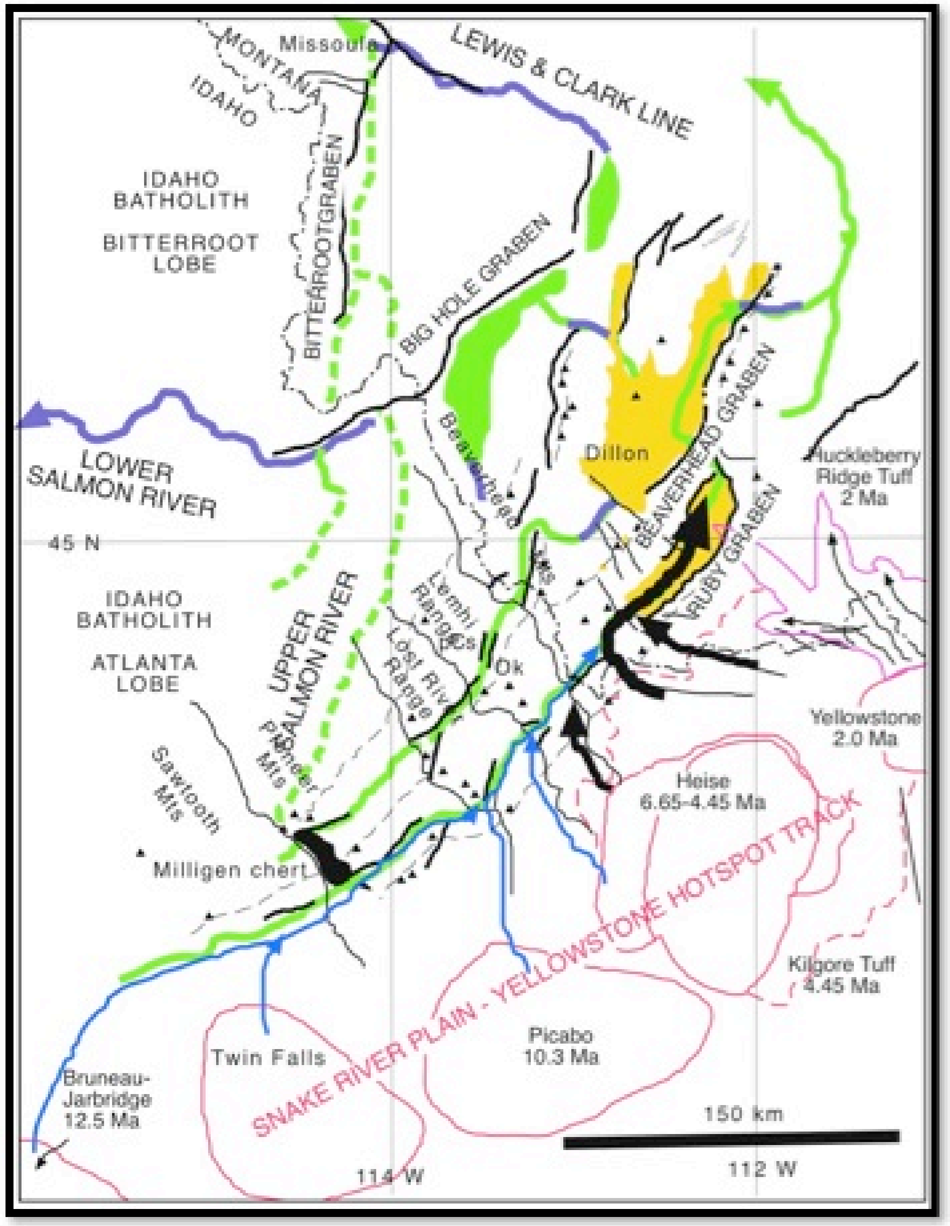
The Yellowstone hot spot

- **May have initiated the NE-trending topography at 17 Ma**
- **Influenced sedimentation in the NE-trending grabens from 17-4 Ma**
- **Plays an unresolved role in the NW-trending topography and active seismicity from 4.0 Ma to present**



Smith and Siegel, 2000

Future work



Hypothesized changes in source areas contributing sediment to the Ruby and Beaverhead Grabens associated with progression of the Yellowstone hot spot track to the northeast (Sears and others, 2009)

Testing Source Areas

Can we use the Ruby and Beaverhead Graben sediments to track the sequential doming and subsequent collapse of hot spot calderas?

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