

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

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ABSTRACT

Middle Eocene to Early Miocene sedimentary rocks in southwest Montana and east-central Idaho were deposited within an actively extending north-trending rift system (Cabbage Patch beds and Medicine Lodge beds) and a broad depositional basin on the eastern flank of this rift (Renova Formation). Distinct sediment sources for sandstones from different parts of this extensional system are identified using detrital zircon SHRIMP geochronology and LA-MC-ICPMS Hf isotope geochemistry. Sedimentary petrology independently shows strong compositional similarities among sandstones grouped by provenance. The Muddy-Grasshopper detachment system was the eastern boundary of the Paleogene rift and controlled sediment dispersal patterns.

Hf isotope ratios and U-Pb ages of zircons from conspicuous two-mica feldspathic sandstones of the syn-extensional Medicine Lodge beds and Cabbage Patch beds confirm that the sands were derived from a ca. 75 Ma two-mica bearing granitic source. This pluton was likely in the footwall of the Anaconda core complex to the north and west. Persistent basin-axial south-southeastward flow fed the Medicine Lodge beds. Two-mica sand of the Cabbage Patch beds was likely deposited by separate fluvial systems draining the Anaconda Range.

Other Medicine Lodge sands contain locally derived zircons from both the footwall and hanging wall of the Eocene-Oligocene Muddy-Grasshopper detachment fault. Nearly identical Phanerozoic detrital zircon age spectra from sandstone in the southernmost Medicine Lodge beds and the southern Renova Formation imply first- or second-cycle sediment contribution from the 80-100 Ma southern Atlanta lobe of the Idaho batholith in central Idaho. If first cycle, northeast-directed drainage with headwaters

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in central Idaho, far west of the modern continental divide, is indicated. If second cycle, grains ultimately derived from the southern Atlanta lobe could have been recycled through local Cretaceous sandstones.

Anomalous unimodal 90-110 Ma zircon populations are present in two Paleogene sandstones. The middle Cretaceous (Cenomanian) volcanic-lithic Vaughn Member of Blackleaf Formation is a possible proximate source. The ultimate source area was likely the now-eroded volcanic carapace of the Atlanta lobe of the Idaho batholith.

Feldspathic volcanic-lithic sandstone of the type area for the Renova Formation south of Whitehall, Montana contains almost exclusively 65-80 Ma grains likely derived from the Boulder batholith or Elkhorn Mountains volcanics immediately to the west. These source rocks were exposed in the latest Eocene, probably along the crest of a roll-over anticline in the hangingwall of the Anaconda detachment fault.

INTRODUCTION

Basin-fill deposits in extensional settings can be critical for constraining timing and magnitude of deformational events (Leeder and Gawthorpe, 1987; Gans et al., 1989; Janecke, 1994, 2007; Constenius, 1996; McCann and Saintot, 2003; Janecke et al., 2005). Much of our understanding of extensional tectonics in the North American Cordillera has been achieved through stratigraphic, geochronologic, and structural studies of stratigraphic packages deposited in the Basin and Range province and analogous extensional terranes (e.g. Gans et al., 1989; Constenius, 1996; Ingersoll, 2003). The relationship between regional tectonics and contemporaneous sedimentation is often complex, especially in regions characterized by spatial and temporal variability of tectonic and depositional settings. Well-exposed Cenozoic successions of basin-fill sedimentary rocks in southwestern Montana and east-central Idaho offer insight into the tectonic and paleogeographic history of the region.

The tectonic significance, paleogeography, and depositional settings of extensive Cenozoic sedimentary deposits of east-central Idaho and southwest Montana (Fig. 1) have long been subjects of controversy (c.f. Fields et al., 1985; Hanneman and Wideman, 1991; Rasmussen, 2003; Fritz et al., 2007). Eocene to Miocene basins in southwest Montana and east-central Idaho formed across several underlying tectonic provinces. The area has been dissected by at least three stages of extension following Sevier and Laramide contraction (Janecke, 1992, 2007; Sears and Thomas, 2007). Eocene-Oligocene extension in the region is attributed to post-contraction gravitational collapse of the over-thickened Sevier fold-and-thrust belt (Janecke, 1994; Constenius, 1996; Foster and Fanning, 1997). The bulk of extension and syn-extensional deposition occurred in western Montana and east-central Idaho along a north-south trending belt; the "Paleogene rift system" (Janecke, 1994) (Fig. 1) within the former fold-and-thrust belt. Diverse, syn-extensional depositional settings formed within this rift zone (Janecke, 1994; Janecke et al., 2005). Deposition also occurred in a broad flu-

vial and lacustrine basin on the eastern flank of the Paleogene rift (the Renova basin) (Janecke, 1994; Thomas, 1995; Fritz et al., 2007) in the relict broken foreland of Laramide contraction. The Renova basin was surrounded by the Challis and Absaroka volcanic plateaus (Fritz et al., 2007).

Two major unconformity-bounded sequences record the two main pulses of NE-SW extension and associated continental sedimentation: (1) the Middle Eocene to Early Miocene Renova Formation in southwestern Montana and its age equivalents in the rift zone to the west and southwest (Fields et al., 1985; Janecke, 1994) and (2) the Middle Miocene to Pliocene Sixmile Creek Formation (Fields et al., 1985; Fritz et al., 2007). The two units are generally separated by a regional unconformity, often with angular relationships (Fields et al., 1985; Hanneman and Wideman, 1991). The Renova Formation and the Sixmile Creek Formation comprise the Bozeman Group in southwest Montana. The Renova Formation and its equivalents record a spatially extensive and volumetrically significant period of fluvial and lacustrine deposition. Most strata unconformably overlie pre-basin rocks, local volcanics, or older gravels (Fields et al., 1985; Janecke, 1994; Janecke et al., 1999).

Renova age equivalents (i.e. Medicine Lodge beds, Cabbage Patch beds, etc.) (Figs. 1 and 2) in Montana and Idaho are fundamental to understanding the regional depositional history (M'Gonigle and Dalrymple, 1993; Janecke et al., 2005). The paleogeography across the rift zone has been controversial with some workers envisioning little structural disruption of drainage systems in the area of the Paleogene rift zone (Thomas, 1995; Sears and Ryan, 2003; Fritz et al., 2007). Other workers have argued for nearly complete separation between depositional systems in the rift and the Renova basin farther to the east (Janecke et al., 1999, 2005; Janecke, 2007). We use the provenance and architecture of the fluvial systems that deposited these Paleogene sedimentary rocks to better constrain the tectonic and topographic evolution of the rift system and surrounding area.

The Middle Miocene to Pliocene Sixmile Creek Formation and its equivalents unconformably overlie the

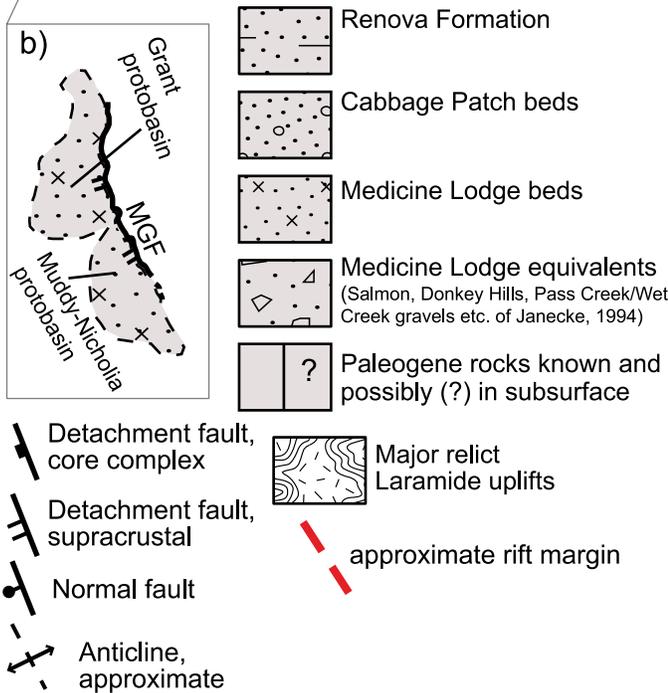
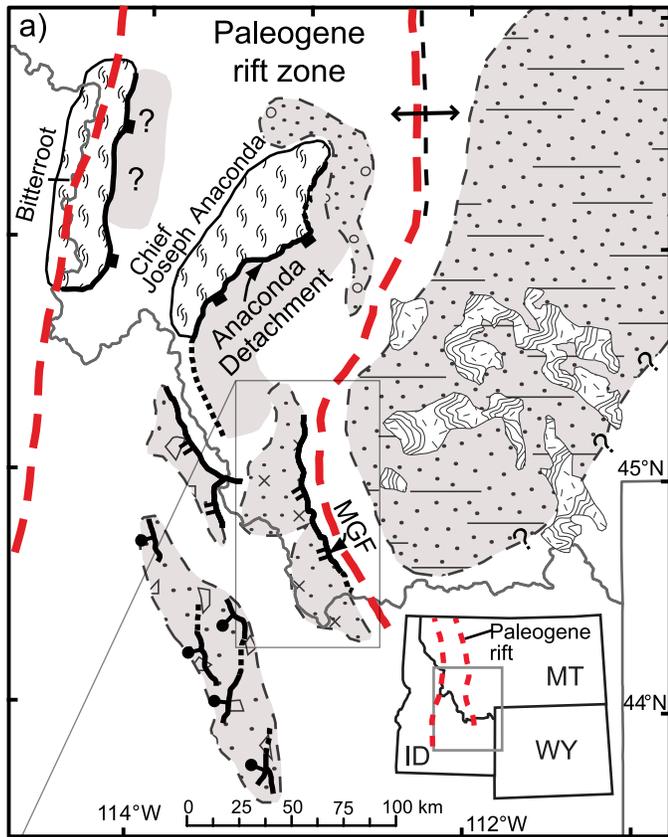


Figure 1. a) Paleogeographic map of general distribution and proposed nomenclature of Eocene-Oligocene sedimentary rocks and major Eocene-Oligocene extensional features. Paleogene rift boundaries on inset after Janecke, 1994. MGF = Muddy Grasshopper Fault. Geology compiled from Fields et al., 1985; Janecke, 1994; Foster and Fanning, 1997; Janecke and Blankenau, 2003; Bolay-Koenig and Erslev, 2003; O'Neill et al., 2004; Janecke et al., 2005. Note state borders for orientation. b) Nomenclature of basin segments in which Medicine Lodge beds were deposited (after Janecke et al., 2005).

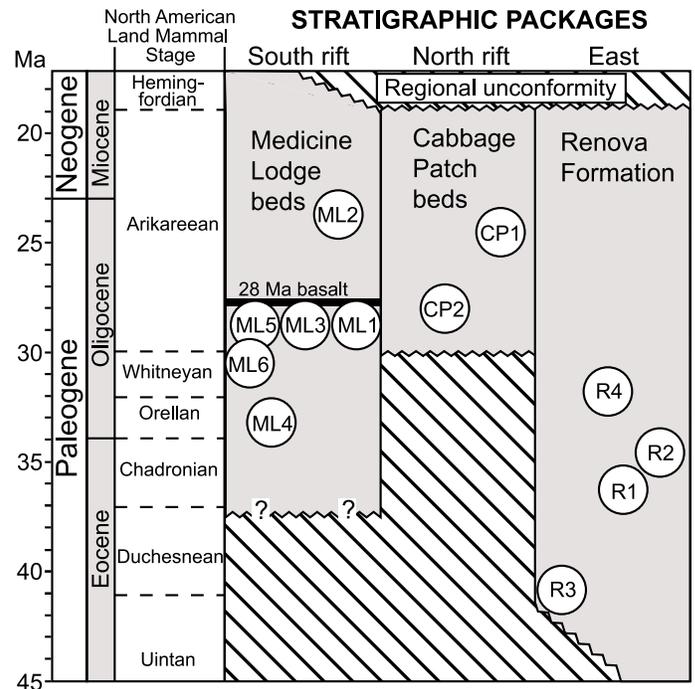


Figure 2. Generalized correlation chart of stratigraphic packages in southwest Montana (modified from Fields et al., 1985). Circles represent general stratigraphic positions of samples. See table 1 for sample description and age constraints. Timescale from Gradstein et al. (2004). Land mammal ages from Woodburne (2004).

Renova Formation and its equivalents and were deposited following a depositional hiatus of uncertain and variable duration (Fields et al., 1985; M'Gonigle, 1994). This hiatus is usually attributed to tectonic disturbance coincident with initiation of Miocene Basin-and-Range extensional faulting in southwest Montana and the outbreak of the Yellowstone Hotspot (e.g. Burbank and Barnosky, 1990; Sears and Thomas, 2007). Within the Paleogene rift zone, however, the unconformity (sequence boundary) reflects the end of Eocene to early Miocene extension and negligible younger tilting has been defined (VanDenburg, 1997). The provenance of the Sixmile Creek Formation is addressed by Stroup et al. (2008).

Work presented here integrates sandstone petrology, detrital zircon geochronology, and Hf isotope data with stratigraphic and structural data to constrain the provenance of Eocene-Oligocene sandstones in Idaho and Montana and test hypotheses of basin architecture, paleoflow patterns, and tectonic setting. The working paleogeographic model tested here is presented in Figure 1. Specifically, we test if provenance of rocks within the rift is different than provenance of rocks east of the rift, which would support the hypothesis that the rift existed as a topographic feature in the Paleogene.

STRATIGRAPHY AND GEOLOGIC SETTING

Middle Eocene to Early Miocene basin fill

Middle Eocene to Early Miocene rocks of the Renova Formation in southwest Montana and age equivalents in Montana and east-central Idaho span a depositional area of over 200 km by 200 km (Fig. 2). These sedimentary rocks are diverse and range from coarse conglomerates to tuffaceous mudstones (Fields et al., 1985; Hanneman and Wideman, 1991; M'Gonigle, 1994; Janecke et al., 1999, 2005; Fritz et al., 2007). Renova-age equivalents in Idaho and near the Idaho-Montana border are rift-fill deposits and are coarser grained, thicker, and more variable than strata of the type Renova Formation (M'Gonigle and Dalrymple, 1993; Janecke, 1994; Janecke and Blankenau, 2003).

The Renova Formation was named by Kuenzi and Fields (1971) during early work in the Jefferson River Valley. The name has since been extended to include many correlative units throughout southwest Montana (Fields et al., 1985). The term 'Renova equivalent' was originally used where correlations were tentative because of distance or lack of detailed work (Fields et al., 1985). In the Jefferson River basin and surrounding area, the Renova Formation has been subdivided into two units: sequences 2 and 3 (Hanneman and Wideman, 1991; Hanneman et al., 2003).

Kuenzi and Fields (1971) first suggested the type Renova Formation was deposited in isolated erosional valleys cut into a relatively subdued, stable, post-Laramide, Eocene surface (c.f. Fields et al., 1985). A consensus is now emerging that the type Renova Formation was deposited in a broad basin east of the Paleogene rift system. This basin was dominated by fluvial systems and intermittent lakes which occupied low areas between relict Laramide highlands (Fritz and Sears, 1993; Janecke, 1994; Thomas, 1995; Sears and Fritz, 1998; Sears and Ryan, 2003; Fritz et al., 2007). Modern mountain ranges have broken the continuity of the originally quiescent Renova basin, in many cases by Miocene to Pliocene normal reactivation of Laramide thrusts and reverse faults (Sears and Fritz, 1998).

We distinguish the broad tectonically stable basin east of the eastern rift flank (the Renova basin of Janecke, 1994) from the north-trending Paleogene rift system (Fig. 1) where deposition was influenced by contemporaneous normal faulting and strata are generally thicker and coarser. Within the rift system we use informal local names: "Medicine Lodge beds" for Paleogene sedimentary rocks above the Muddy-Grasshopper detachment (Fig. 1) following Scholten et al. (1955) and "Cabbage Patch beds" in the proximal hanging wall of the Anaconda detachment fault after Konizeski and Donohoe (1958). We restrict the use of Renova Formation to strata east of the rift zone (c.f. Janecke et al., 2005; Janecke, 2007). Fritz et al. (2007) suggested that all Middle Eocene to Early Miocene rocks in the region were deposited in a quiescent basin between the Challis and Absaroka volcanic fields and named it the "Dillon-Renova basin". This is an oversim-

plification as the Dillon-Renova basin of Fritz et al. (2007) includes portions of the Paleogene rift system of Janecke (1994), which was developed on top of Challis volcanic rock.

West and southwest of the Renova basin, rift-fill sediments were deposited on the hanging wall of the Eocene to Oligocene Muddy-Grasshopper detachment fault, which marks the eastern margin of the rift system south of Dillon, Montana (M'Gonigle and Dalrymple, 1993; Janecke et al., 1999), and on the hanging wall of the Anaconda metamorphic core complex (O'Neill et al., 2004) (Fig. 1). In east-central Idaho, rift-fill gravels were deposited in the Salmon, Donkey Hills, Pass Creek-Wet Creek, and Arco Pass areas (see Janecke, 1994, and Fig. 1).

Basin-fill lithologies are finer in the eastern rift than in the western rift (compare Janecke, 1994 and Janecke and Blankenau, 2004; and Janecke et al., 2005) and more closely resemble the type Renova Formation. Sandstones with distinctive two-mica composition within the Medicine Lodge beds and Cabbage Patch beds serve as an important facies for basin reconstruction and were deposited by southeastward flowing rivers (Thomas, 1995). In the original model of two-mica sandstone dispersion (Thomas, 1995), a megafan shed off the Anaconda Range spread across the rift and onto its footwall, in a distribution seemingly at odds with evidence for Eocene-Oligocene normal faulting in the area (Janecke, 2007).

DETRITAL ZIRCON GEOCHRONOLOGY

This study uses data from 15 detrital zircon samples: 12 from Eocene-Oligocene sandstones, two from modern stream sediment, and one from a volcanic-lithic Cretaceous sandstone (Table 1) to gain insight into structural and topographic controls on Paleogene depositional systems. Data from sample BW (the Big Wood River) were presented in Link et al. (2005). All other data and analytical procedures are presented in Link et al. (2008). Sample locations are shown in Figure 3. For the sake of clarity, samples are given abbreviations related to their stratigraphic and geographic positions (Table 1, Figs. 2 and 3).

Sampling strategy and analytical techniques

Well-exposed stratigraphic sections of Eocene-Oligocene sedimentary rocks were targeted for sampling where previous work had constrained the stratigraphic position, land mammal age, absolute age, or relative age with respect to radiometrically dated horizons. Fine- to medium-grained sediments were targeted, but where this was not possible coarse-grained material was sampled. Two-mica feldspathic sandstones described by Thomas (1995) were a special focus and comprise five samples.

In general, the youngest rim or zone of about 60 randomly selected detrital zircon grains was analyzed with a sensitive high-resolution ion microprobe (SHRIMP) and a U-Pb age was obtained using standard techniques (see Williams, 1998 and Link et al., 2008). Complete analytical data are

TABLE 1: EAST-CENTRAL IDAHO AND SOUTHWEST MONTANA DETRITAL ZIRCON SAMPLES WITH LOCATIONS

Name	Fig.	Unit	Location	Age	Age Source	Youngest		Description	UTM			Sample Number	†Data Source
						Detrital	Age		Zone	Easting	Northing		
BW	7a	Modern Alluvium	Big Wood River, ID	Modern	N/A	45.5 ± 1.1		medium lithic feldspathic sand	11	721812	4811445	201PL97	1,2
MC	4a	Modern Alluvium	Mussigbrod Creek, MT	Modern	N/A	50.9 ± 1.1		medium-coarse 2-mica feldspathic sand	12	297053	5073936	3PL04	1
CP1	4b	Cabbage Patch beds	Flint Creek basin, MT	Late Oligocene (Arikareean, <29.5 Ma)	Portner (2005); Nichols et al. (2001)	72.5 ± 1.4		medium-coarse 2-mica feldspathic sandstone	12	344038	5161207	RAP1127.1	1
CP2	4c	Cabbage Patch beds	Divide, MT	Oligocene (Arikareean)	Fields et al. (1985)	60.6 ± 0.8		medium-coarse 2-mica feldspathic sandstone	12	364801	5068272	2PL04	1
ML1	8c	Medicine Lodge beds	Mill Point, MT	Late Oligocene (Arikareean, >28 Ma)	Nichols et al. (2001); Janecke et al. (2005)	*32.1 ± 0.6		fine-coarse volcanic-lithic sandstone	12	338579	5010753	24PL02	1
ML2	6a	Medicine Lodge beds	Bannock State Park, MT	Late Eocene - Early Miocene (<24 Ma?)	Janecke et al. (2005)	*24.2 ± 0.6		fine-coarse volcanic-lithic sandstone	12	341848	5003122	25PL02	1
ML3	4d	Medicine Lodge beds	Bannock Road, MT	Oligocene (Arikareean, >28 Ma)	Janecke et al. (2005)	*34.7 ± 0.7		medium 2-mica feldspathic sandstone	12	338316	4996850	26PL02	1
ML4	6b	Medicine Lodge beds	Bachelor Mountain, MT	Eocene-Oligocene (>28 Ma)	Janecke et al. (2005)	1123 ± 16		medium quartz sandstone	12	330875	4990140	27PL02	1
ML5	4e	Medicine Lodge beds	Red Butte, MT	Early Oligocene (>28 Ma)	Janecke et al. (2005)	*28.6 ± 0.7		medium to coarse 2-mica feldspathic sandstone	12	323368	4988336	29PL02	1
ML6	7b	Medicine Lodge beds	Nicholia Creek basin, MT	Early Oligocene (<34 Ma)	Janecke et al. (1999); this study, youngest 3 grain population	*29.6 ± 1.6		medium-coarse volcanic-lithic feldspathic sandstone	12	350322	4932735	41MH03	1,3
R1	9a	Renova Formation	South of Whitehall, MT	Late Eocene? (Chadronian)	Kuenzi and Fields (1971)	61.8 ± 4.8		medium-coarse feldspathic lithic-volcanic sandstone	12	414148	5072370	5CS06	1
R2	9b	Renova Formation	South of Whitehall, MT	Late Eocene? (Chadronian)	Kuenzi and Fields (1971)	*25.0 ± 1.1		medium feldspathic lithic-volcanic sandstone	12	414046	5072680	7CS06	1
R3	8b	Renova Formation	Mantle Ranch, MT	Late Eocene (late Uintan or Early Duchesnean)	Fields et al. (1985); A.R. Tabrum written comm. (2003)	83.1 ± 1.9		fine-coarse volcanic-lithic sandstone	12	370789	5030890	17PL02	1,4
R4	7c	Renova Formation	Sweetwater Creek, MT	Early Oligocene (<34 Ma)	this study, youngest 3 grain population	*33.4 ± 0.6		fine-medium volcanic-lithic feldspathic sandstone	12	403622	4991980	22CS07	1
VN	8a	Vaughn Member of the Blackleaf Formation	Drummond, MT	Cretaceous (Cenomanian, <95 Ma)	Zartman et al. (1995); this study, youngest 3 grain population	*94.4 ± 2.5		medium-coarse lithic-volcanic feldspathic sandstone	12	337767	5168294	26CS07	1

*Possible maximum depositional age

†Data Sources: 1=Link et al. (2008); 2=Link et al. (2005); 3=Hodges (2006); 4=McHugh (2003)

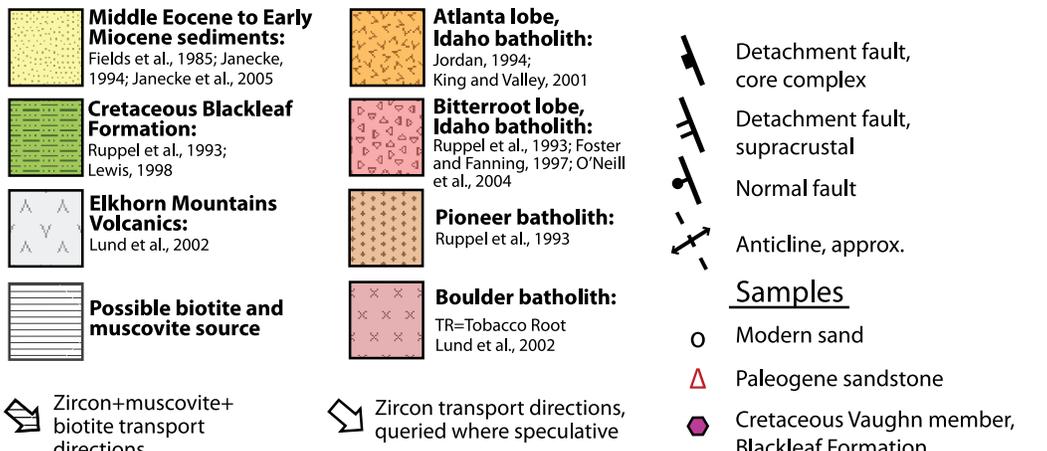
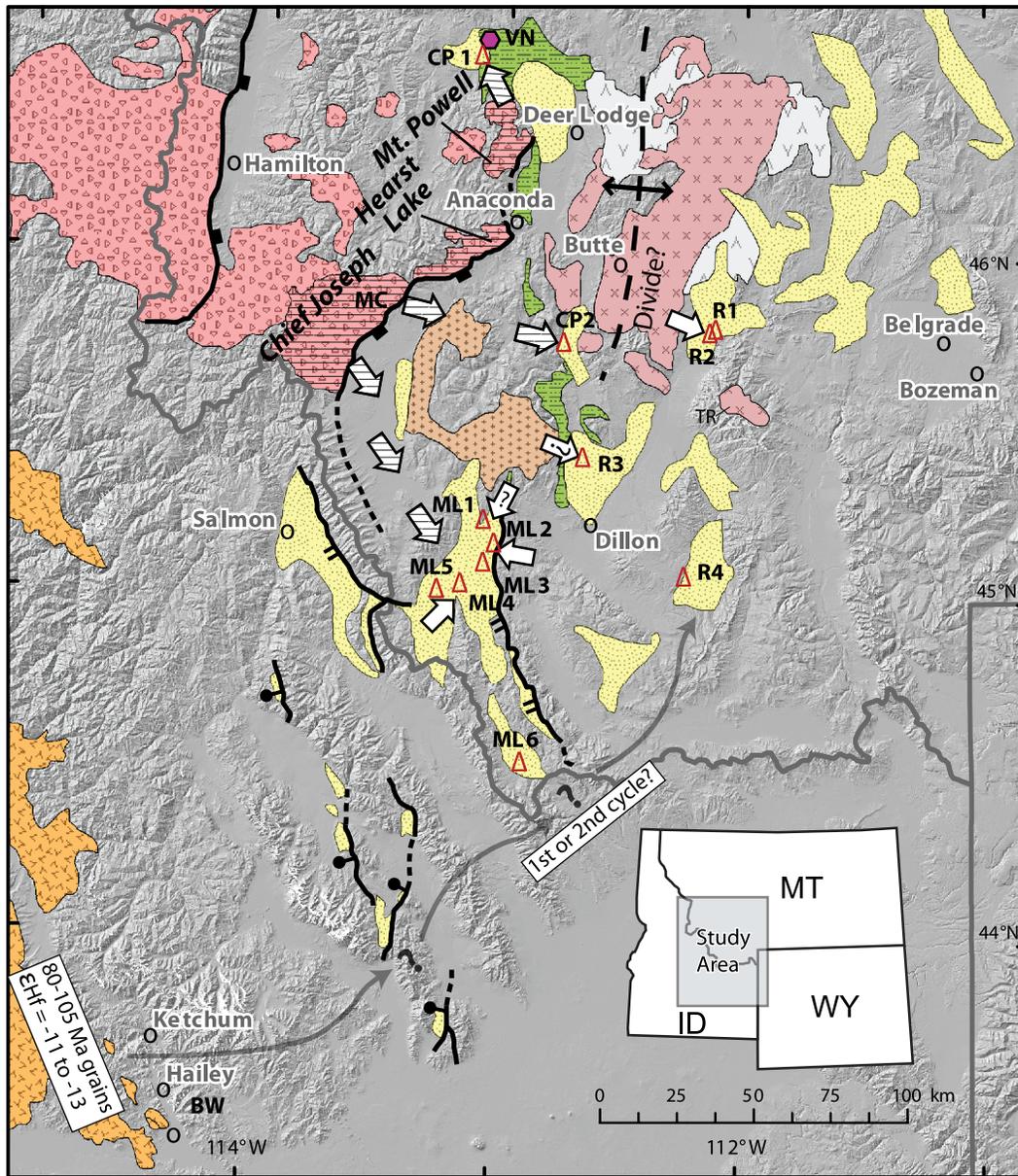


Figure 3. Map of sample location and modern distribution of key Cretaceous source areas. See Table 1 for sample ages and location details. CP = Cabbage Patch beds; R = Renova Formation; MC = Mussigbrod Creek; ML = Medicine Lodge beds; BW = Big Wood River; VN = Vaughn Member, Blackleaf Formation. Interpreted Eocene-Oligocene sediment transport directions are also shown. Modern topography in background. Faults from Janecke, 1994; Foster and Fanning, 1997; O'Neill et al., 2004; Janecke et al., 2005.

presented in Link et al. (2008). Precambrian grains that are greater than 20% discordant were not included in the probability-frequency plots presented in this paper. Ages used here are generally the $^{207}\text{Pb}/^{206}\text{Pb}$ age for grains older than ca. 800 Ma and the $^{206}\text{Pb}/^{238}\text{U}$ age for grains younger ca. 800 Ma.

Single youngest detrital zircon U-Pb ages were not used here as robust indicators of maximum depositional age. Only populations consisting of three grains or more were considered significant. Although single grain ages may be meaningful in many situations (e.g. Dickinson and Gehrels, 2008), the conservative approach taken here minimizes the risk of attaching significance to spurious ages.

Following SHRIMP analysis, Hf isotope measurements were made by G. Yaxley, with a Neptune LA-MC-ICPMS coupled to a 193 nm ArF excimer laser at the Research School of Earth Science, Australian National University. Measurements were made from the same sample spots as SHRIMP U-Pb analysis.

Interpreting provenance

Zircon is a heavy mineral resistant to chemical weathering that is a common component in siliciclastic sedimentary systems. Because zircons do not break down chemically in sedimentary systems, grains can be recycled through weathering of older sedimentary rocks (Link et al., 2005). Grains present in a sedimentary system can, therefore, be derived from very old sources, stored in sedimentary strata, and put back in the system one or more times. Second-cycle zircons may be widely distributed and give information about

the ultimate source, but not the proximate one. Conversely, first-cycle zircons are derived from weathering of igneous and metamorphic rocks.

Populations of zoned magmatic zircon grains are sourced from felsic magmatic rocks and can serve as precise provenance tracers in small (first- and second-order; Ingersoll, 1990) fluvial basins. If it can be reasonably demonstrated that zircon grains in a sedimentary system are first-cycle, start and end points for transport vectors can be inferred. This requires knowledge of the ages of possible source areas.

The geochronology of the northern Rocky Mountains is reasonably well defined, although in some areas little U-Pb geochronology has been done. Possible source areas for Paleogene sedimentary rocks sampled here are given in Table 2. A number of first-cycle source areas with unique ages are present and allow for direct interpretation of provenance. Some zircons may be first- or second-cycle, some have unknown source areas, and some have more than one possible source for key populations of grains. Despite these complexities many trends emerge and show clear patterns. Cretaceous magmatic zircon populations were particularly useful for inferring provenance because other populations have broad or numerous possible source areas.

In addition to Paleogene sandstones, modern sands from streams draining known source areas (the Big Wood River and Mussigbrod Creek) were sampled. Detrital zircon age spectra and Hf isotope ratios from these modern sands serve as analogs to compare with age spectra and Hf signatures of Paleogene sands which may have been sourced from similar areas.

TABLE 2: DETRITAL ZIRCON AGE POPULATIONS IN EOCENE-OLIGOCENE SANDSTONES OF SOUTHWEST MONTANA AND SELECTED POSSIBLE SOURCE ROCKS. MODIFIED FROM LINK ET AL. (2005) AND BERANEK ET AL. (2006).

Population	Minimum age (Ma)	Maximum age (Ma)	Source regions
Dillon Volcanics	17	59	Southwest Montana (Fritz et al., 2007)
Eocene-Oligocene Volcanics	33	38	Unknown source, possibly airfall from Great Basin
Challis and Absaroka volcanics and related intrusions	42	55	South-central Idaho and southwest Montana, north of Snake River Plain
Chief Joseph Pluton	50	58 (80?)	Point source in eastern Anaconda range, southwest Montana, likely source for 2-mica arkose (Desmarais, 1983)
Pioneer Batholith, Anaconda Batholith and Bitterroot Lobe of the Idaho Batholith	50	80	Eastern Idaho and southwestern Montana (Foster and Fanning, 1997)
Boulder Batholith, Elkhorn Volcanics, and Tobacco Root batholith	67	80	Southwest Montana (Lund et al., 2002; Mueller et al., 1996)
Atlanta Lobe of the Idaho batholith	80	100	South-central Idaho north of the Snake River Plain
Unknown Cretaceous grains	90	110	Recycled through Vaughn member of the Blackleaf Formation. (Zartman et al., 1995), First-cycle source unknown, but possibly the Atlanta lobe of the Idaho batholith
Grenville orogen	950	1300	Central Idaho and Idaho-Wyoming thrust belts; Neoproterozoic to Paleozoic miogeocline
Recycled Yavapai-Mazatzal, non-North American grains, and syn-Belt volcanics	1380	1800	Recycled through the Missoula and Lemhi Groups of the Belt Supergroup (Link et al., 2007)
Paleoproterozoic basement	1800	2500	Primary grains, exposed basement west of the Wyoming province (Kellogg et al., 2003; Foster et al., 2006)
Wyoming province	2500	2800	Primary grains from exposed basement

Using the Gazzi-Dickinson method, detrital modes of all sandstones, except sample BW, were determined by point counting of thin sections. Point count data from sample CP1 (RAPIII27.1) are from Portner (2005). A minimum of 500 grains were counted from each sample. The Gazzi-Dickinson method minimizes the effect of grain size on calculation of detrital modes (Ingersoll et al., 1984). Sandstone compositions are summarized in Figure 4.

Hafnium isotopes: Independent provenance indicators

Hafnium isotope analysis of zircon has recently emerged as a powerful independent provenance indicator tool when analyses are performed on grains of known age (Kinney and Maas, 2003; Xia et al., 2005; Goodge and Vervoort, 2006; Augustsson et al., 2006; Flowerdew et al., 2007). U-Pb analysis by ion microprobe (SHRIMP) is the crucial first step to characterize grain ages. Ion-microprobe analyses have minimal sample consumption; the SHRIMP pits are on the order of 1 micron in depth. Therefore, several SHRIMP analysis can be made per grain prior to the final Lu-Hf isotope laser ablation analysis of the same area within the zircon grain.

$^{176}\text{Hf}/^{177}\text{Hf}$ ratios were measured from several 50-125 Ma grains within key populations via laser ablation and serve as an independent provenance indicator (Appendix I). Where U-Pb ages of populations overlap, Hf isotope signatures can

distinguish these populations. Hf isotope model ages reflect the time elapsed since the source of the parental magma separated from the mantle (Kemp et al., 2006); i.e. they provide an estimate for the crustal residence time.

At present, Hf isotope geochemistry of source rocks in the region is not defined, although work is in progress and is producing consistent results (Gaschnig et al., 2007a, Gaschnig et al., 2007b, this study). As new geochronologic and Hf isotope data from source areas become available, detrital zircon Hf isotope geochemistry in conjunction with U-Pb geochronology will be increasingly useful in provenance studies.

PROVENANCE OF PALEOGENE SANDSTONES

Provenance of Medicine Lodge beds of the Grant protobasin

Strata of the Medicine Lodge beds adjacent to the northern segments of the Muddy-Grasshopper detachment fault were interpreted by Janecke et al. (2005) to have been deposited in an Eocene-Oligocene supradetachment basin (the Grant protobasin, Fig. 1b) that later broke up into several sub-basins (Janecke et al., 2005).

Sedimentologic studies and mapping suggest that the Grant protobasin contains fanglomerates derived from the west, clastics derived from the eastern footwall, and a broad axial zone of meandering stream and lacustrine deposits. Two-mica sand facies are restricted to the meandering stream deposits (Janecke et al., 2005).

MC, ML3, and ML 5. Detrital zircon age spectra of axial two-mica feldspathic facies of the Oligocene Medicine Lodge beds (ML3 and ML5) in the Grant protobasin consistently contain a dominant ca. 75 Ma peak (Fig. 5, d and e). The sandstones are feldspathic and lithic-volcanic arenites. Their composition is remarkably consistent, both north and south of the Anaconda core complex (Fig. 4). The only major plutonic source in the area with both muscovite and biotite is the peraluminous Chief Joseph pluton (eastern Bitterroot lobe of the Idaho batholith) in the Anaconda Range (Fig. 3) (Desmarais, 1983; Ruppel et al., 1993; Thomas, 1995; Janecke et al., 2005). The same dominant ca. 75 Ma peak is present in detrital zircon ages from modern two-mica sand of Mussigbrod Creek (MC, Fig. 5a), which drains the Chief Joseph pluton. Epsilon Hf values from zircon grains from ML5 overlap with those of grains from Mussigbrod Creek (Fig. 6).

The ca. 75 Ma zircon U-Pb crystallization ages are older than previously obtained ages for the Chief Joseph pluton. Earlier geochronologic work resulted in a 58 Ma monazite U-Pb lower intercept age and muscovite and biotite K-Ar cooling ages ranging from 54.8 ± 2.4 to 58.2 ± 2.1 (Desmarais, 1983). Our detrital zircon geochronology from modern sediment of Paleocene grains of this age. The dominant population is at ca. 75 Ma. This is consistent with age spectra from Oligocene two-mica sandstones in the area (Fig. 5) which lack 50-60 Ma

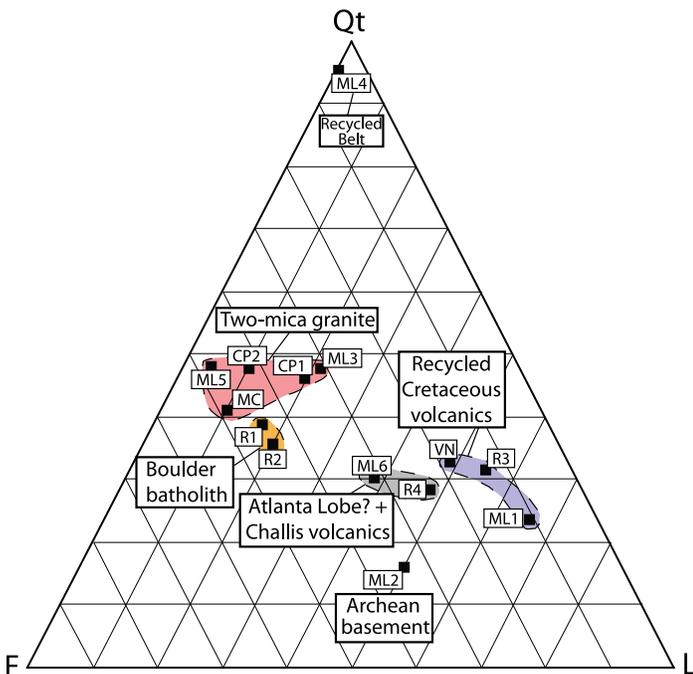


Figure 4. Standard Qt-F-L diagram with samples grouped by provenance inferred from detrital zircon U-Pb geochronology and Hf isotope geochemistry. Samples interpreted as having common sources are also compositionally similar. Detrital modes are representative of source areas.

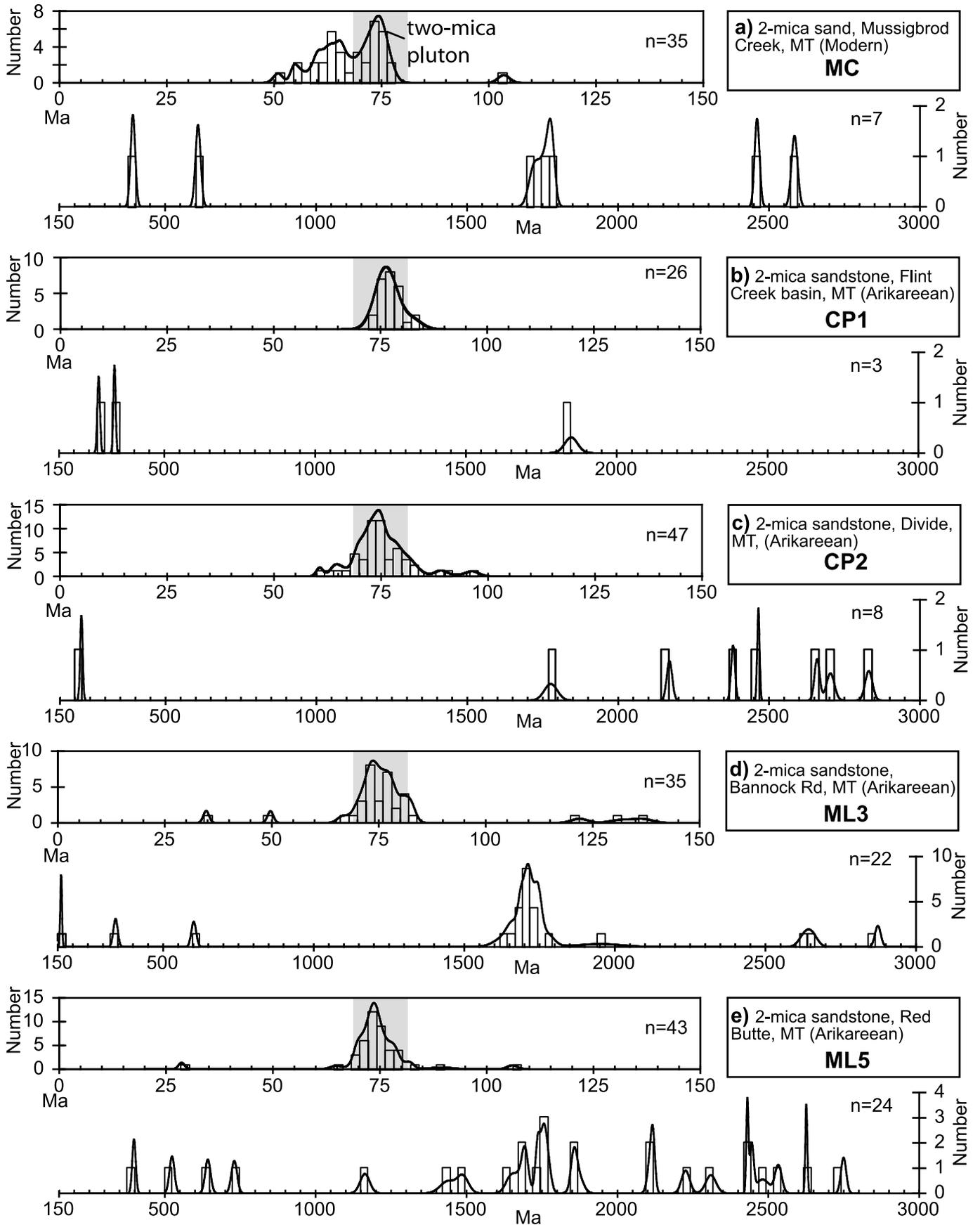


Figure 5. Detrital zircon age spectra of two-mica feldspathic sands in southwest Montana containing consistent ca. 75 Ma peaks. Note that y-axis is not fixed. Bin widths on 0-150 and 150-3000 Ma plots are 2 and 25 Ma, respectively.

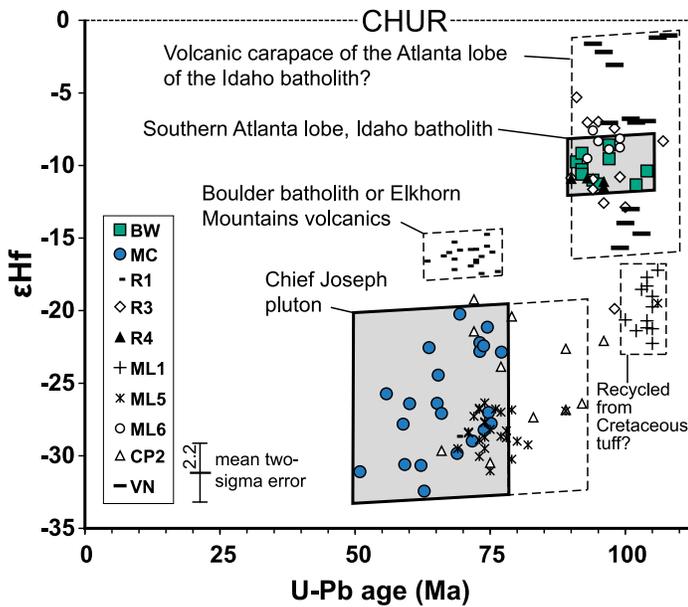


Figure 6. ϵ_{Hf} values from individual grains (calculated from $^{176}\text{Hf}/^{177}\text{Hf}$ values, see Goodge and Vervoort, 2006) plotted against individual U-Pb grain age. Solid, shaded boxes are defined by values of sediment from streams draining known source areas. Dashed lines represent predicted signatures of inferred source areas. CP = Cabbage Patch beds; R = Renova Formation, ML = Medicine Lodge beds. MC = Mussigbrod Creek; BW = Big Wood River; VN = Vaughn Member, Blackleaf Formation.

grains. High-resolution geochronology is required to verify that a large 75 Ma two-mica-bearing pluton is present in the southern Anaconda core complex, as predicted here.

Derivation of the muscovite in Paleogene sands from muscovite-rich Precambrian metamorphic basement rocks is unlikely. $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of detrital muscovite from Paleogene sandstones in Medicine Lodge beds range from 53 to 103 Ma (Janecke et al., 2005). Also, the coarse two-mica sandstones are remarkably consistent in composition (Fig. 4), composed largely of granitic material with occasional clasts of Belt Supergroup quartzite but no mica-rich metamorphic clasts. Further, Paleoproterozoic and Archean zircons are not present in all two-mica sands (Figs. 5b and c), which would require unlikely complex sorting of zircon and muscovite prior to deposition.

ML2 and ML4. Conglomeratic sandstone from the eastern margin of the Grant protobasin (ML2) contains mainly Paleoproterozoic and Archean zircon grains (Fig. 7a) likely derived from the Belt Supergroup and Archean basement, respectively, in the adjacent uplifted footwall of the Muddy-Grasshopper fault (Fig. 1; Fig. 3; Link et al., 2007). The Belt Supergroup occurs as clasts and boulders in the Cretaceous Beaverhead Formation in the footwall (Lowell, 1965). ML2 also contains a small population of 70-80 Ma grains ($n=5$) which may share a common source with other Medicine Lodge sandstones (ML3 and ML5), in the footwall of the Anaconda detachment. Alternatively, they may have been derived from the Cold Spring volcanics in the footwall of the Muddy-Grasshopper fault.

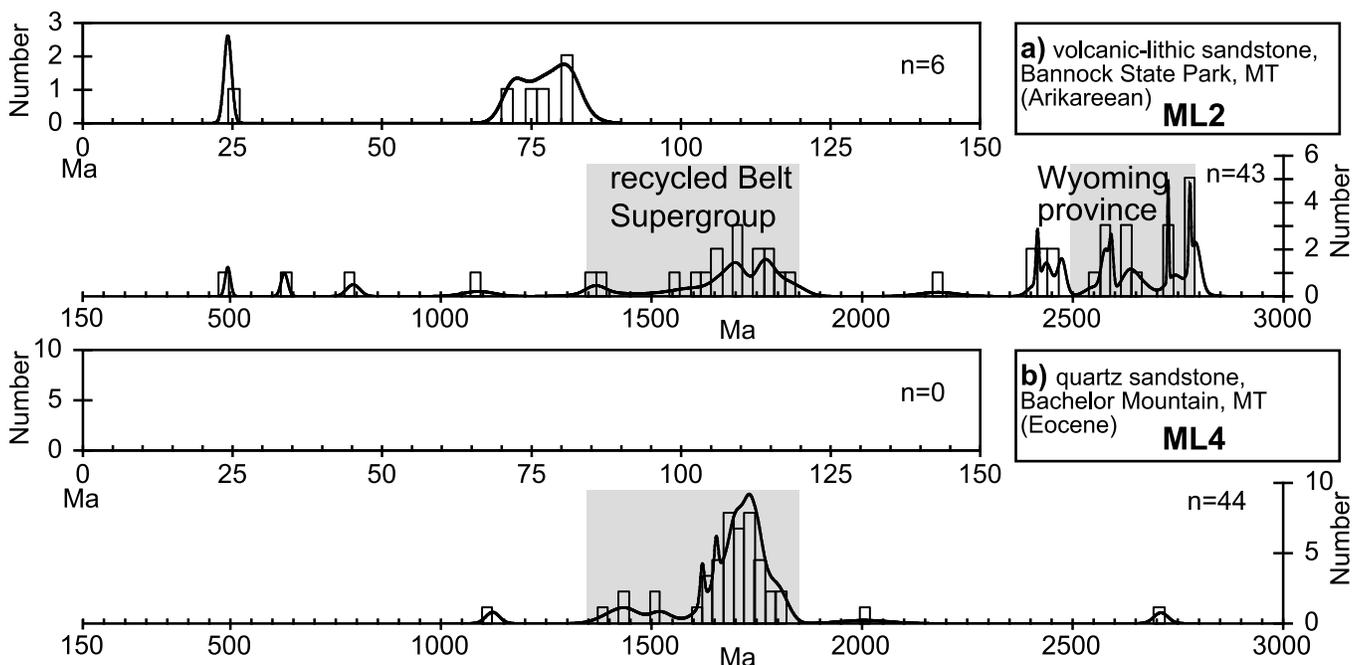


Figure 7. Detrital zircon age spectra of locally sourced Medicine Lodge sandstones. Note that y-axis is not fixed.

The six grains that are 2400 to 2500 Ma are the same age as 2450 Ma Early Paleoproterozoic gneiss in the Beaverhead Impact site and the Maiden Peak prong of the Beaverhead Range (Kellogg et al., 2003). Some of the 1650 to 1800 Ma grains in Cenozoic sandstones may have been derived directly from plutons in the Paleoproterozoic Great Falls tectonic zone or Selway terrane (Foster et al., 2006) north and west of the Archean Dillon block, respectively. The separation of Belt recycled zircons from primary Great Falls tectonic zone or Selway terrane zircons needs further study (Link et al., 2007).

Zircons in quartz arenite (Fig. 4) of the western facies, Medicine Lodge beds (Janecke et al., 2005) near Bachelor Mountain, Montana (ML4) are dominantly recycled Paleoproterozoic grains (Fig. 7b) derived proximately from the Belt Supergroup (Link et al., 2007). The absence of Archean grains in this sandstone is suggestive of derivation from uplifted Belt Supergroup in the Grasshopper thrust sheet to the west, consistent with interpretations of Janecke et al. (2005).

Provenance of Cabbage Patch beds

CP1 and CP2. Two-mica sands of Oligocene Cabbage Patch beds from the Flint Creek basin, Montana (CP1) and Divide, Montana (CP2) (Fig. 3) contain ca. 75 Ma peaks in detrital zircon age spectra which are indistinguishable from peaks in other two-mica sands sampled in this study (Fig. 5b and c). Hf signatures of CP2 are also indistinguishable from those of ML5 and MC (Fig. 6).

These data suggest two-mica sandstones of the Cabbage Patch beds were derived from a similar source as two-mica sands in the Medicine Lodge beds, most likely in the northern Anaconda core complex (Figs. 1 and 3). Their sedimentary petrology is identical (Fig. 4). Portner (2005) suggested the Hearst Lake pluton in the Anaconda Range and the Mt. Powell batholith in the Flint Creek Range (Fig. 3) as possible sources based on W-NW directed paleocurrents in two-mica sands of the Flint Creek basin (see Fig. 3, CP1 for location). Both plutons contain two-micas and yield K-Ar biotite and muscovite cooling ages of 58-63 Ma (Marvin et al., 1989) and 48-51 Ma (Wallace et al., 1992), respectively. Consistent ca. 75 Ma peaks in two-mica sands of the Cabbage Patch beds require either these plutons to be older than their cooling ages or that these sands were derived from elsewhere, perhaps the Chief Joseph pluton to the south. Pending further zircon U-Pb geochronology we can infer only that the two-mica source for the Cabbage Patch beds was in the footwall of the Anaconda detachment fault. The 67-80 Ma Boulder batholith and Elkhorn Mountains volcanics to the east also likely contributed sediment to this system (Rasmussen, 1977; Lund et al., 2002, Vuke, 2004) but could not have contributed muscovite.

Based on zircon age spectra (Fig. 5b and c), northwest directed paleocurrents, and facies assemblages in the surrounding areas, (Rasmussen, 1977; Portner, 2005) we speculate that fluvial systems shed from the Anaconda Range delivered two-mica sediment to Cabbage Patch beds.

Provenance of Medicine Lodge beds of the Muddy-Nicholia protobasin

ML6. Detrital zircon age spectra of Oligocene Medicine Lodge volcanic-lithic feldspathic sandstone in the Muddy-Nicholia protobasin (Fig. 1; Fig. 3, ML6) contain significant peaks at 33-35, 45-55, and 85-100 Ma (Fig. 8) (Hodges, 2006). The 33-35 Ma grains are probably from volcanic ash-fall or local volcanics, and a number of regional and distal sources are possible. This population provides a maximum age of deposition. The 45-55 Ma grains were derived from the aerially extensive Challis Volcanic Group, or related intrusions (Link et al., 2005). Precise provenance interpretation can not be made from these zircons alone because Challis-age rocks are abundant both locally and regionally. However, local sourcing is likely because the sandstone overlies about 1 km of boulder to pebble conglomerate derived from the Challis volcanic rocks on the west side of the basin (Skipp and Janecke, 2004).

The 85-100 Ma population is significant and unexpected; the only known first-cycle source of this age in the region is the southern Atlanta lobe of the Idaho batholith in south-central Idaho (Fig. 3), over 150 km to the southwest. Hf signatures of zircons from ML6 tightly overlap those in the Big Wood River (BW, Fig. 6) which currently drains the southeastern Atlanta lobe (Link et al., 2005). Second-order recycling of these grains through the proximal Cretaceous Beaverhead Group is possible, but a wide variety of Precambrian-age zircon grains would also be expected because the Belt Supergroup was a major source for the Beaverhead Group (Ryder and Scholten, 1973; Janecke et al., 2000).

We identified a population of zircons in immature, volcanic-lithic, feldspathic sandstone of the Cretaceous (Cenomanian) Vaughn Member of the Blackleaf Formation (VN) (Zartman et al., 1995) with ages of 90-105 Ma (Fig. 9a) that overlap ages of the Atlanta lobe of the Idaho batholith. Hf signatures from VN overlap those of BW, but are highly variable in contrast to the tight group made by BW and ML6 (Fig. 6). The most parsimonious explanation for the similarity in U-Pb age and Hf isotopic ratios from the Cretaceous grains in ML6 and the southern Atlanta lobe is first-cycle derivation. It is also possible that these grains were recycled through Cretaceous sandstones. This uncertainty remains.

Provenance of the Renova Formation

R4. Detrital zircon age spectra of volcanic-lithic sandstone of the basal Renova Formation (R4) near Sweetwater Creek, Montana contain the same peaks as ML6 with the addition of a late Paleoproterozoic peak (Fig. 8c), most likely recycled from Belt Supergroup zircons (Link et al., 2007). Hf signatures and U-Pb ages from Cretaceous grains of this sandstone are also identical to those defined by BW for the southern Atlanta lobe of the Idaho batholith. Although the ages of ML6 and R4 are poorly constrained and may be several

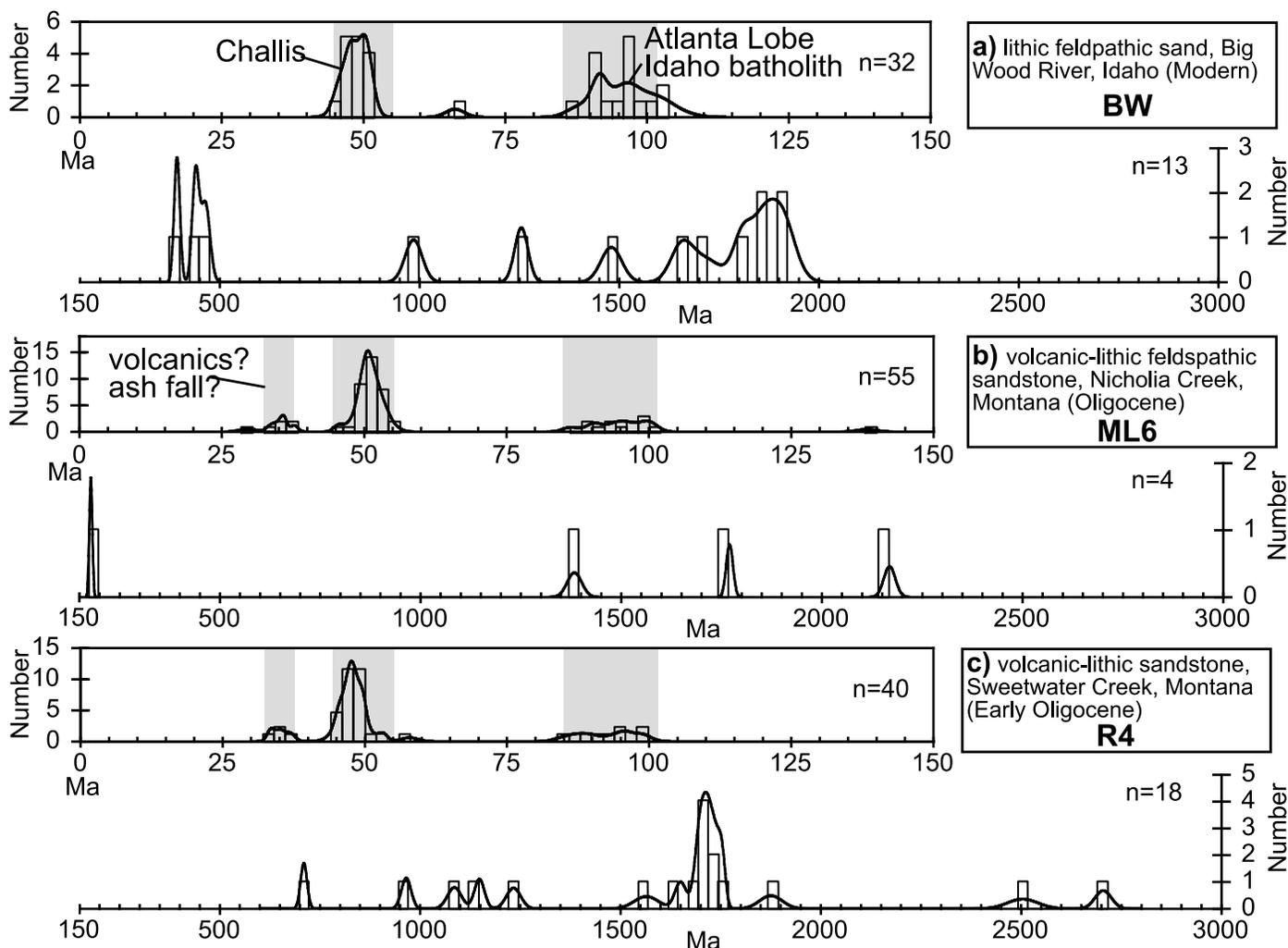


Figure 8. Detrital zircon age spectra of modern sediment from the Big Wood River, ID compared with sandstones of the Medicine Lodge beds and Renova Formation. Note that y-axis is not fixed.

million years different, we infer that Renova sandstone R4 received sediment from a similar ultimate source as Medicine Lodge sandstone ML6, if not from the same drainage system.

R1 and R2. Feldspathic volcanic-lithic sandstones (R1 and R2) from the type section of the Renova Formation (Kuenzi and Fields, 1971) contain almost exclusively Cretaceous zircons (Fig. 10). It is likely that the source of these grains was the Boulder batholith or the associated Elkhorn Mountains volcanics, which have overlapping ages of ca. 67-80 Ma (Lund et al., 2002).

The Tobacco Root batholith in the Tobacco Root Mountains to the southeast is also ca. 75 Ma (Mueller et al., 1996) but intrudes Archean rocks which compose the mountain range. If this were the source, some component of Archean zircons would be expected.

The presence of a 25 Ma grain in R2 is puzzling. As defined by Kuenzi and Fields (1971), rocks of the section sampled are Chadronian (~34-37 Ma) in age. This may be a spurious age.

Anomalous 90-100 Ma grains

Zircon age spectra of volcanic-lithic sandstones R3 and ML1 contain sharp peaks at 95 and 105 Ma, respectively, with no known local first-cycle source (Fig. 9b and c). Zircons of similar ages were found in this study (Fig. 9a) and by Zartman et al. (1995) in a volcanic-lithic feldspathic sandstone (VN) and porcellanites, respectively, of the Vaughn Member, Blackleaf Formation. Although sample VN was taken from an exposure of the Blackleaf Formation over 100 km north of R3 and ML1, the Vaughn Member crops out directly east of the Montana Pioneer Mountains and local provenance is reasonable (Fig. 3).

Cretaceous grains in the Blackleaf Formation, which are indistinguishable in age from the depositional age of the Vaughn Member, were probably derived from a coeval magmatic arc to the west, likely the volcanic carapace of the Atlanta lobe of the Idaho batholith. The epsilon Hf values of these grains (Fig. 6) are much more variable than those of Cretaceous zircons in the Big Wood River, which only drains the southeastern corner of the Atlanta lobe. The uni-

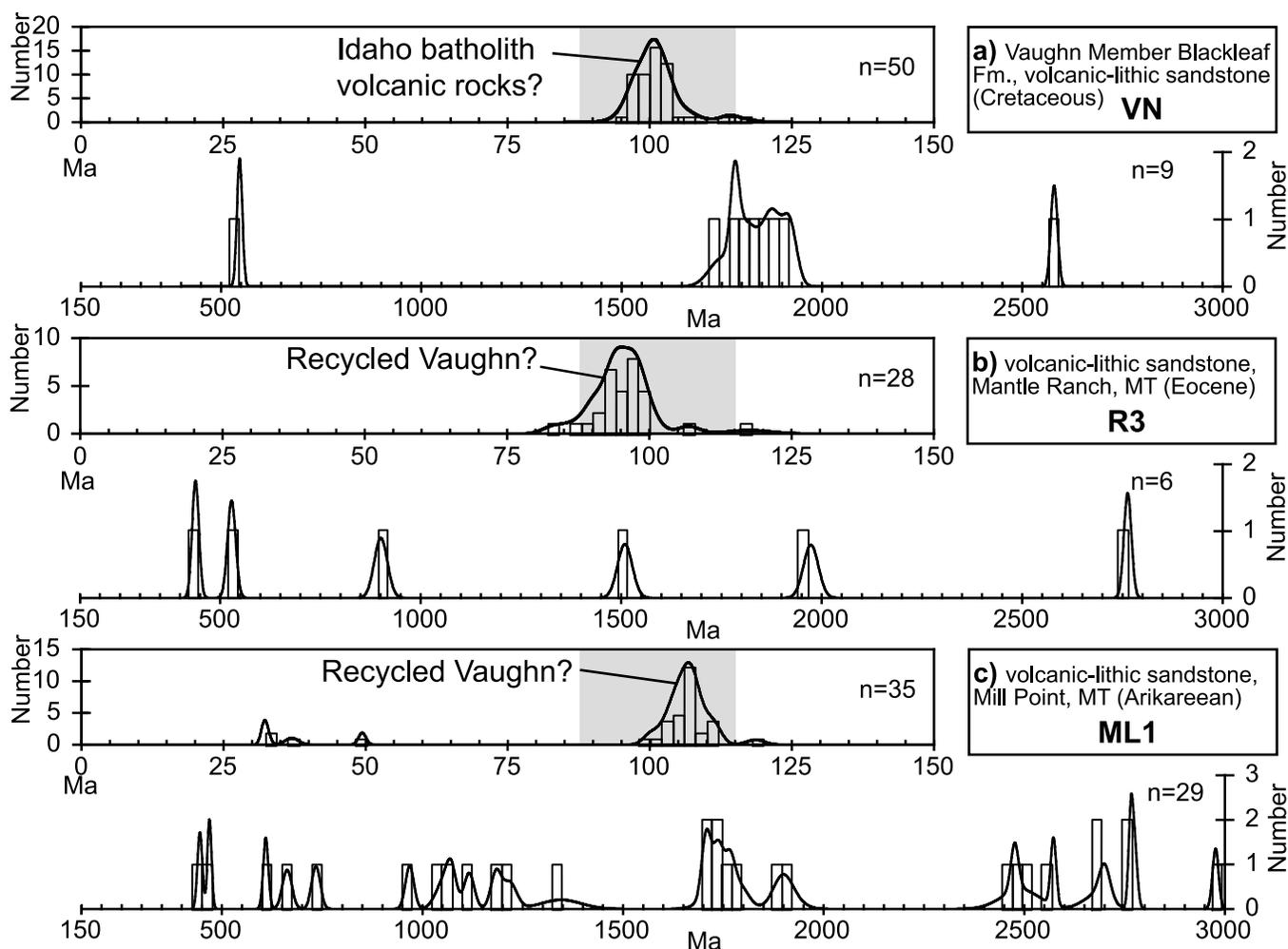


Figure 9. Detrital-zircon age spectra of Montana sandstones containing anomalously old Cretaceous peaks. Note that y-axis is not fixed.

modal Cretaceous population in ML1 may have been recycled through volcanic-rich sandstone of Vaughn Member not sampled here, and which is slightly older than the reference sample VN.

Sample R3 was collected from the basal Renova Formation north of Dillon, Montana and is the oldest sample (early Duchesnian or late Uintan, A.R. Tabrum, written comm., 2003) included in this study. The unimodal ca. 95 Ma zircon age peak from this sample is suggestive of local derivation. Zartman et al. (1995) reported 93-95 Ma zircon ages from tuffs of the Vaughn Member of the Blackleaf Formation from the eastern Pioneer Mountains, near R3, and this a possible source. Zircons from R3 are similar to zircons from the southern Atlanta lobe of the Idaho batholith in age and epsilon Hf values. We suggest these grains were ultimately derived from volcanism of the Atlanta lobe of the Idaho batholith and recycled through the Cretaceous Vaughn Member.

Sedimentary petrology

Detrital modes of sandstones, calculated from point counts of thin sections, support independent interpretations

of distinct provenances for different sample groups. Samples grouped by their inferred source areas show strong compositional similarities (Fig. 4). These results corroborate provenance interpretations made from detrital zircon U-Pb ages and Hf isotope geochemistry and verify that in these second-order fluvial basin systems with proximal magmatic and volcanic debris, sedimentary petrology is sensitive to the same changes in provenance as transport of detrital zircons as heavy minerals.

DISCUSSION AND CONCLUSIONS

Deposition of Eocene to Oligocene sedimentary rocks in southwest Montana and east-central Idaho took place in active half-graben basins and supradetachment basins of a Paleogene rift system and in the tectonically quiet “Renova basin” on the eastern rift shoulder. The eastern rift margin is the west-dipping Muddy-Grasshopper detachment fault south of Dillon, MT and a large double rollover anticline to the north in the Butte area where extension within the rift is accommodated on east-dipping detachments of the Bitterroot and Anaconda metamorphic core complexes.

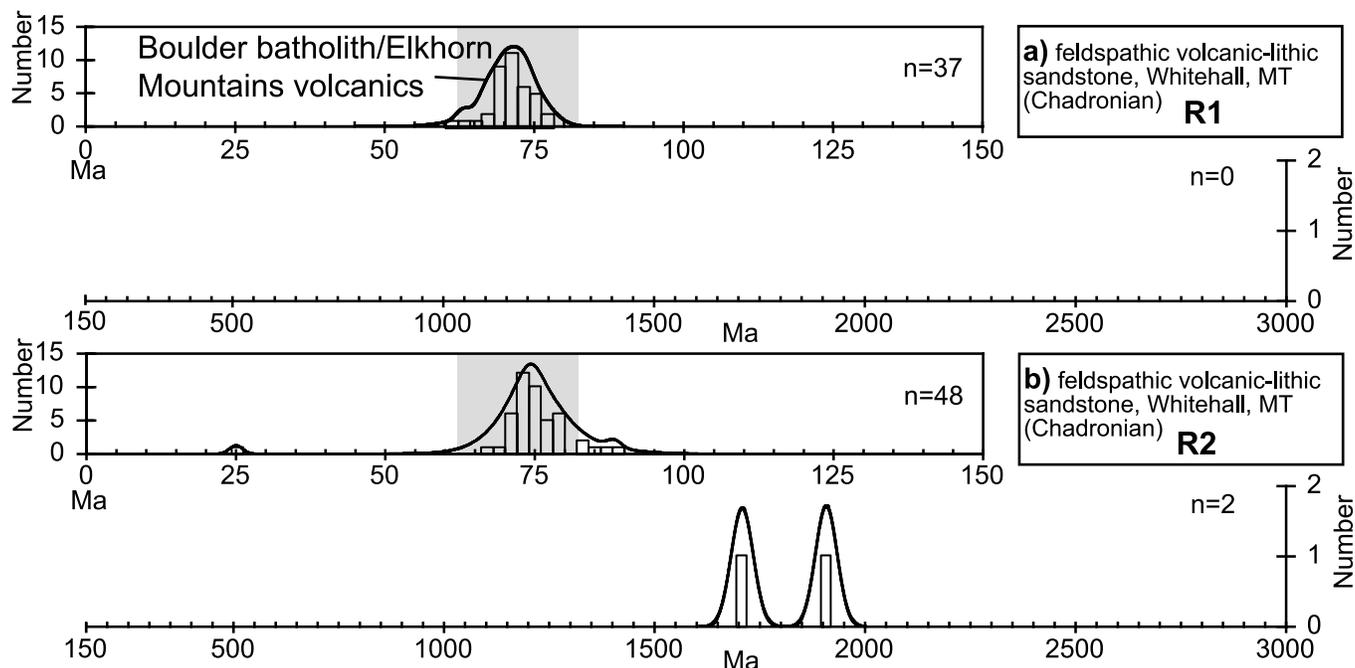


Figure 10. Similar detrital zircon age spectra from sandstone in the Renova Formation type section.

Sandstones from within the rift, with the exception of ML6 and possibly ML1, have a distinct provenance from samples of the Renova Formation. This implies that the topography of the Paleogene rift system influenced sediment dispersal patterns (Fig. 3).

Oligocene sedimentary rocks of the Medicine Lodge beds in the Grant protobasin were derived from granites to the north and northwest and, locally, the Belt Supergroup, Archean basement, and either tuffaceous Cretaceous sandstone or an unknown ca. 107 Ma source. Detrital zircon signatures from basin axial two-mica feldspathic sandstone suggest derivation from a ca. 75 Ma, two-mica bearing pluton. The best candidate is the Chief Joseph pluton to the north-northwest (Thomas, 1995). Presence of two-mica sands at multiple stratigraphic levels in the Medicine Lodge beds record persistent southward drainage along the axis of the Grant protobasin within the Paleogene rift system.

No two-mica sand was sampled or observed east of the rift shoulder. We infer that a divide approximated by the rift shoulder separated depositional systems in the Renova basin from those in the Paleogene rift system. Whether this disconnect was persistent or intermittent throughout deposition is not clear.

Intra-rift drainage in southwest Montana was controlled by west-dipping listric faults of the Muddy-Grasshopper fault system (Janecke et al., 1999, 2005) in the south and east-dipping detachments of the Anaconda and Bitterroot metamorphic core complexes in the north (Fig. 1a) (Marvin et al., 1989; Wallace et al., 1992; Foster and Fanning, 1997; O'Neill et al., 2004). The Anaconda detachment fault uplifted the Chief Joseph and associated smaller plutons in its footwall

(Desmaris, 1983; O'Neill et al., 2004). Distinctive two-mica plutons were a significant source of sediment in much of SW Montana even after the apparent end of slip along the Anaconda detachment fault (O'Neill et al., 2004). This continued sediment contribution may be the result of protracted slip into the Oligocene yet to be documented.

The Arikarean Cabbage Patch beds, deposited in the Divide, Deer Lodge, and Flint Creek areas north of the Grant protobasin, also contain two-mica sands (Vuke, 2004; Portner, 2005). We speculate that the Cabbage Patch two-mica sands were fed by large fan and fluvial systems draining highlands in the footwall of the Anaconda detachment; this was probably a distinct system from the south-southeast-flowing drainage feeding the Medicine Lodge beds of the Grant protobasin.

We interpret that Oligocene Medicine Lodge sandstone of the Muddy-Nicholia protobasin (ML6) and Oligocene Renova Formation sandstone (R4) were sourced in part from central Idaho. Both contain zircon populations apparently derived from the southern Atlanta lobe of the Idaho batholith. Cretaceous grains (85-100 Ma) have ages and Hf isotope signatures indistinguishable from zircons in modern Big Wood River alluvium which drains the southern Atlanta lobe of the Idaho batholith (Link et al., 2005). The orderly and repeated age spectra of ML6 and R4 suggest they tapped the same source without mixing of diverse Cretaceous magmatic zircons. This requires a drainage with headwaters far west of the modern continental divide, that cut across the trend of the Paleogene rift system, spilling across the rift zone possibly near the southern tip of the Muddy-Grasshopper detachment (Fig. 1, Fig. 3). Such rift-transverse paleoflow is unexpected and no field evidence has been reported for such a drainage.

Sedimentology and detrital zircon geochronology of additional sandstones of the Renova Formation and Medicine Lodge beds is necessary to test this hypothesis.

A second possibility is that Cretaceous zircons in ML6 and R4 were derived, second cycle, from local Cretaceous backarc sandstones. This predicts that Cretaceous sandstones in the area have 80-100 Ma zircon populations with similar Hf isotope ratios as populations in the southern Atlanta lobe.

None of the zircon age signatures present in the axial deposits of the Grant protobasin (e.g. ca. 75 Ma, Paleoproterozoic, Archean) are present in Muddy-Nicholia protobasin sandstone. Likewise, no Atlanta lobe grains were documented in the Grant protobasin. These marked differences in provenance of axial deposits probably reflect an internal divide between these two protobasins, with the Grant protobasin sourced from the north and the Muddy-Nicholia

protobasin sourced, in part, from central Idaho or local Cretaceous rocks. An Oligocene rift-valley lake is recorded by a succession of lacustrine sediments near Grant, Montana, at the southern edge of the Grant protobasin (Janecke et al., 2005). This lake is further evidence of intra-rift drainage disruption and may have been the ultimate sink for two-mica sediment derived from the north.

Zircons in late Eocene (Chadronian) Renova Formation sandstone from south of Whitehall, Montana (R1 and R2) were derived exclusively from local 72-75 Ma sources; most likely the Boulder batholith or the Elkhorn Mountains volcanics to the west. From these data we infer that the Boulder batholith formed a highland in the late-Eocene, possibly the crest of a large north-trending rollover anticline (Houston, 2000) above the Anaconda detachment. Pre-Oligocene exhumation of the Boulder batholith is consistent with the

APPENDIX I: INDIVIDUAL-GRAIN HAFNIUM-ISOTOPE DATA

U-Pb				U-Pb				U-Pb				U-Pb			
Grain	Age	ϵ Hf(0)	ϵ Hf(t1)	Grain	Age	ϵ Hf(0)	ϵ Hf(t1)	Grain	Age	ϵ Hf(0)	ϵ Hf(t1)	Grain	Age	ϵ Hf(0)	ϵ Hf(t1)
BW (201PL97)				ML1 (24PL02)				ML6 (41MH03)				R3 (17PL02)			
42	91	-11.7	-9.8	32	100	-22.7	-20.6	22	93	-11.6	-9.5	27	90	-12.8	-10.9
33	92	-12.3	-10.3	23	102	-23.5	-21.4	32	94	-9.6	-7.6	30	91	-7.3	-5.3
36	92	-11.2	-9.2	25	103	-20.7	-18.5	53	95	-10.3	-8.3	39	93	-9.0	-7.0
39	92	-12.5	-10.6	21	104	-20.5	-18.3	58	97	-10.9	-8.9	4	94	-13.0	-11.0
29	94	-13.1	-11.0	4	104	-22.8	-20.7	19	99	-10.9	-8.8	42	94	-13.7	-11.6
50	95	-13.3	-11.3	49	104	-23.4	-21.2	50	99	-10.3	-8.1	28	95	-9.0	-7.0
27	97	-11.7	-9.5	75	104	-19.8	-17.7	CP2 (2PL04)				26	96	-14.6	-12.6
32	97	-10.6	-8.6	19	105	-23.4	-21.2	20	66	-31.1	-29.7	8	98	-21.9	-19.9
35	102	-13.5	-11.3	27	105	-21.9	-19.7	14	72	-22.9	-21.4	40	98	-9.5	-7.4
43	104	-12.6	-10.4	36	105	-24.4	-22.3	8	72	-20.8	-19.2	41	99	-12.9	-10.8
MC (3PL04)				45	105	-21.2	-19.0	9	75	-32.1	-30.5	36	100	-15.0	-12.9
60	51	-32.2	-31.1	66	106	-19.4	-17.2	15	77	-25.5	-23.9	43	107	-10.6	-8.3
18	56	-26.9	-25.7	ML5 (29PL02)				24	79	-22.1	-20.4	R4 (22CS07)			
27	59	-29.1	-27.8	1	69	-31.0	-29.5	59	83	-29.1	-27.4	2	90	-12.9	-10.9
22	59	-31.9	-30.6	10	71	-29.9	-28.4	10	89	-24.5	-22.6	21	93	-12.9	-10.9
51	60	-27.7	-26.4	16	71	-29.9	-28.4	10	89	-28.8	-26.8	5	96	-13.2	-11.1
26	62	-32.0	-30.7	23	71	-29.8	-28.4	16	92	-28.3	-26.4	25	96	-13.6	-11.5
42	63	-33.8	-32.4	29	72	-28.8	-27.3	5	96	-24.1	-22.1	VN (26CS07)			
32	64	-23.9	-22.6	6	73	-28.3	-26.7	R1 (5CS06)				41	94	-3.6	-1.6
57	65	-27.8	-26.4	9	73	-31.6	-30.1	35	63	-17.9	-16.6	10	96	-4.2	-2.2
50	65	-25.9	-24.4	12	73	-30.5	-28.9	7	66	-17.7	-16.2	9	97	-9.2	-7.1
46	66	-28.4	-27.1	40	73	-28.3	-26.8	3	67	-17.4	-16.0	25	98	-5.2	-3.1
28	69	-31.3	-29.8	11	74	-31.1	-29.5	5	68	-16.7	-15.3	40	99	-17.8	-15.7
55	69	-21.7	-20.2	27	74	-27.9	-26.4	11	68	-17.9	-16.5	38	100	-16.1	-14.0
31	72	-30.5	-29.0	30	74	-29.3	-27.7	15	68	-18.6	-17.2	19	101	-15.2	-13.0
30	73	-23.8	-22.2	32	74	-29.2	-27.7	14	69	-30.1	-28.7	56	101	-9.0	-6.8
17	73	-24.4	-22.8	36	74	-30.3	-28.7	16	69	-17.3	-15.8	21	102	-9.2	-7.1
52	74	-24.0	-22.4	37	75	-32.6	-31.0	12	71	-17.3	-15.8	35	103	-16.9	-14.7
38	74	-29.8	-28.2	43	75	-29.7	-28.2	17	71	-18.4	-16.9	51	104	-9.1	-7.0
40	75	-22.7	-21.2	38	76	-28.4	-26.8	2	72	-17.3	-15.8	52	106	-3.4	-1.2
29	75	-28.6	-27.0	17	77	-28.6	-27.0	8	72	-18.1	-16.5	27	108	-3.4	-1.0
33	75	-29.4	-27.8	34	77	-30.3	-28.7	36	72	-18.2	-16.7				
9	77	-24.5	-22.9	15	78	-30.4	-28.8	1	73	-19.0	-17.4				
				35	78	-29.9	-28.3	7	73	-17.8	-16.3				
				3	79	-28.5	-26.8	4	74	-17.2	-15.6				
				26	79	-31.9	-30.2	18	74	-16.3	-14.8				
				5	80	-30.7	-29.0	6	75	-17.6	-16.0				
				19	82	-31.0	-29.2	9	76	-18.9	-17.3				
				28	89	-28.8	-26.9								
				70	106	-21.7	-19.5								

interpretation of a Boulder batholith provenance for facies of the Cabbage Patch beds near Divide, Montana (Vuke, 2004) and Deer Lodge, Montana (Rasmussen, 1977) on the west and southwest side of this anticline.

Two sandstones sampled in the area of the Montana Pioneer Mountains (R3 and ML1) contain anomalous populations of 90-110 Ma zircons. We suggest these grains may have been proximately derived from tuffs or lithic feldspathic sands in the Cretaceous Blackleaf Formation which crops out along the eastern flank of the Pioneer Mountains. The ultimate source is unknown but may have been the early volcanic carapace of the Atlanta lobe of the Idaho batholith.

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