Miocene to Holocene landscape evolution of the western Snake River Plain region, Idaho: Using the SHRIMP detrital zircon provenance record to track eastward migration of the Yellowstone hotspot

Luke P. Beranek†
Paul Karl Link‡
C. Mark Fanning§

Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia
Department of Geosciences, Idaho State University, Pocatello, Idaho 83209, USA

Abstract

We report new U-Pb detrital zircon sensitive high-resolution ion microprobe (SHRIMP) age data (702 grains) from 13 samples collected from Miocene to Holocene sedimentary deposits in the western Snake River Plain region. These samples effectively show that modern stream sediments of the Snake River system reliably and repeatedly record the detrital zircon age populations that are present as sources in their drainage basins across the Cordilleran thrust belt and Basin and Range Province. We use this framework and the provenance of Neogene sedimentary rocks in the region to test the effect of the migrating Yellowstone hotspot on regional drainage patterns in southern Idaho since the middle Miocene. Our results indicate that Neogene paleodrainages were first directed radially away from the tumultuous Yellowstone highland, then subsequently reversed their flow toward the subsiding Snake River Plain basin. This occurred in east-progressing time-constrained intervals starting at 16 Ma. In northern Nevada, the drainage divide is represented by a northeast-trending, southwest-migrating crest of high topography.

Specifically, middle to late Miocene (16–10 Ma) sedimentary deposits of the western Snake River Plain and Oregon-Idaho graben contain early to middle Eocene (52–42 Ma) detrital zircon populations sourced in Chalcolithic magmatic rocks north of the Snake River Plain. Middle Jurassic (160 Ma) and middle to late Eocene (42–35 Ma) detrital zircons, sourced from rocks in northern Nevada, are not present. Late Eocene detrital zircons from Nevada are present in two younger than 7 Ma sedimentary units of the Idaho Group along the Oregon-Idaho border. This indicates that by the late Miocene, southeastward headward erosion of the paleo–Owyhee River into the Owyhee Plateau had captured drainage from north-central Nevada and directed it northwestward toward the subsiding western Snake River Plain. The modern Owyhee Plateau is still a topographic high, in contrast to the modern Snake River Plain, suggesting that lowering of the regional Snake River Plain base level, rather than crustal subsidence, drove stream capture. By the late Pliocene (3 Ma), Middle Jurassic detrital zircons are recorded in the Glenns Ferry Formation and Tuana Gravel of the central Snake River Plain, suggesting that surface subsidence reversed the flow direction of paleo–Salmon Falls Creek from southwestern into Nevada to northward toward Idaho.

Miocene strata of the western Snake River Plain lack recycled Proterozoic detrital zircons that are ubiquitous in sedimentary rocks of the central and southeast Idaho thrust belts. Such detrital zircons appear on the central and western Snake River Plain in early Pliocene to Holocene (4–0 Ma) deposits. This records capture of drainage from the eastern Snake River Plain. The Yellowstone hotspot controlled the east-migrating continental divide, in the wake of which formed the western-draining, and progressively eastward-collapsing, Snake River system.

Keywords: Snake River Plain, Yellowstone hotspot, Neogene, SHRIMP detrital zircon, Idaho, Nevada.

Introduction

The Snake River Plain of southern Idaho is a crustal-scale, arcuate topographic depression that is the result of unique geologic phenomena in the northern U.S. Cordillera. Since the early Miocene, time-transgressive northeast-trending volcanism related to the Yellowstone hotspot and northwest-trending Basin and Range extension have markedly altered the landscape of the northern U.S. Rocky Mountains (see reviews by Suppe et al., 1975; Pierce and Morgan, 1992). The presence of a modern-day continental hotspot on the Yellowstone Plateau, and topographic and structural depression in its wake, provides an exceptional laboratory in which geoscientists can understand fundamental concepts of uplift and subsidence related to hotspot tectonics, magmatism, and sedimentation.

The passage of the Yellowstone hotspot through southern Idaho has generated two basins, manifested as two nearly perpendicular segments (Fig. 1). The western Snake River Plain is a northwest-trending, fault-bounded rift basin that began subsiding on the shoulder of the Yellowstone hotspot 11 million years ago. Primarily, it contains middle Miocene to late Pliocene (11–3 Ma) arkosic and tuffaceous fluvio-lacustrine sedimentary deposits (Malde, 1991; Wood and Clemens, 2002). In contrast, the eastern Snake River Plain is a northeast-trending, downwarped, bimodal volcanic field capped with fluvio-aolian sediment, the extent of which marks the late Miocene to Holocene (10–0 Ma) passage of the Yellowstone hotspot (Kirkham, 1931; Leeman, 1982; Malde, 1991).
Mechanisms for surface subsidence in the western Snake River Plain relate to crustal thinning and loading generated by rifting of the upper crust and emplacement of mafic intrusions (Wood and Clemens, 2002). The eastern Snake River Plain has subsided from both thermal cooling and loading due to mid-crustal mafic intrusions and sedimentary cover (McQuarrie and Rodgers, 1998). Both eastern and western segments of the Snake River Plain have undergone significant surface subsidence with respect to the Yellowstone Plateau (Brott et al., 1981) and Basin and Range Province (McQuarrie and Rodgers, 1998; Rodgers et al., 2002).

Geologic investigations of the early Miocene to Pliocene sedimentary deposits in the western and eastern Snake River Plain have established stratigraphic correlation and depositional environments (Malde and Powers, 1962; Kimmel, 1982; Middleton et al., 1985; Repenning et al., 1995). Studies by Geslin et al. (1999, 2002) and Link et al. (2002, 2005) documented the detrital zircon age populations from sedimentary rocks and modern stream deposits in the eastern Snake River Plain, effectively reproducing the geochronology of the northern Rockies. Building on those data, this paper defines the Miocene to Holocene drainage of the western Snake River Plain and Oregon-Idaho graben, as related to uplift and subsidence adjacent to the northeast-migrating tumescent Yellowstone bulge.

TESTING THE TOPOGRAPHIC DEVELOPMENT OF THE SNAKE RIVER PLAIN REGION

Using Yellowstone National Park as a modern analog to the former setting of the Yellowstone hotspot, a regional synthesis by Pierce and Morgan (1992) suggested that the Yellowstone volcanic system existed as a 1-km-high continental divide (cf. Crough, 1983; Hill et al., 1992) that migrated through the Cordilleran thrust belt and Mesozoic to Tertiary magmatic belts of Idaho. A migrating topographic bulge would establish river drainage patterns away from its highland in all directions, possibly developing recognizable features in the sedimentary record, such as radial paleocurrent patterns (Rainbird and Ernst, 2001).

We consider two end-member models for the topographic manifestation of the early Miocene to Holocene Yellowstone volcanic system and the resultant Snake River Plain in its wake: (1) the 1-km-high Yellowstone system existed as a continental divide, developing a radial drainage system away from its thermally inflated volcanic plateau; its wake eventually cooled and subsided, allowing streams that had previously drained away from plateau to be “captured,” or have their flow reversed, into the newly formed Snake River watershed (e.g., Link et al., 1999a, 2002); and (2) the Yellowstone hotspot formed a subtle topographic feature during its migration through southern Idaho, did not develop an extensive radial drainage system, and did not significantly influence existing drainage systems along the margins of the Snake River Plain.

In this paper, we propose to test models of topographic development for the western Snake River Plain region by examining the detrital zircon provenance of sediment deposited alongside...
the ancient positions of the Yellowstone hotspot. We follow the framework generated by Link et al. (2005), who used the detrital zircon age populations of modern stream sediments draining the eastern Snake River Plain region to infer paleodrainage patterns in that region during the latest Cenozoic.

Our test consists of two hypotheses: First, that the detrital zircon populations of sediment from modern streams draining into the western Snake River Plain, like those in the eastern Snake River Plain, reliably record the age signatures of their source rocks. An existing reference frame from continent-scale tectonic syntheses documents detrital zircon provenance of Paleozoic strata in the North American Cordillera (Gehrels et al., 1995; Gehrels and Ross, 1998; Gehrels, 2000). That provenance analysis using detrital zircons in Holocene sediment is credible has been demonstrated by studies of fluvial, shoreface, and aeolian systems in Australia, the Appalachian orogen, and elsewhere (Pell et al., 1997; Sircombe, 1999; Cawood et al., 2003; Eriksson et al., 2003). Second, if the detrital zircon populations of modern streams do record the U-Pb age populations of their source rocks with high fidelity, then determination of late Cenozoic paleodrainage patterns is feasible. Further, given known rates of uplift, we can examine whether Miocene to Pliocene fluvial systems drained the same source terrains as those that are currently eroding into the modern Snake River system.

The Snake River Plain region is an ideal laboratory for detrital zircon provenance analysis because the geochronologic framework of the area varies greatly. This paper will show that region- and age-specific detrital zircon populations from source rocks on the flanks of the Snake River Plain act as unique tracers and thus allow us to determine what specific source regions (i.e., north or south of the Snake River Plain; Cordilleran thrust belt or western magmatic belt) supplied sediment to the western Snake River Plain region from the middle Miocene to Holocene.

Two depocenters adjacent to the ancient position of the Yellowstone hotspot are the Oregon-Idaho graben and western Snake River Plain rift basin (Fig. 1). Characterization of detrital zircon age signatures from middle Miocene to Pliocene deposits, using the established and unique geochronologic framework, will document if there have been any systematic changes in zircon provenance over time. Alterations in provenance will reveal a change in sediment dispersal pattern. The lack of change observed within detrital zircon age populations for a succession of sedimentary deposits should indicate the absence of significant fluvial drainage alteration.

Under the basin-scale terminology of Ingersoll (1990) and Ingersoll et al. (1993), tributary Basin and Range valleys and the eastern Snake River Plain are second-order systems including streams and rivers draining mountain ranges and magmatic arcs, and the Snake River of the western Snake River Plain is a third-order large river system. In the Cretaceous Methow terrane of British Columbia, third-order sedimentary systems (i.e., turbidite fan) have predictable detrital zircon populations, but second-order braided fluvial systems are more variable (DeGraff-Surpless et al., 2003).

**REGIONAL GEOLOGIC SETTING AND SOURCE ROCKS**

The greater Snake River Plain region of the northern U.S. Rocky Mountains has a complex geologic history that includes several phases of magmatism, crustal deformation, and sedimentation. This geologic history has created a distinctive geochronologic framework. A simplified geologic map of the Snake River region, showing various provenance areas that are discussed in the following, is presented in Figure 2.

**The Yellowstone Hotspot**

Whole-rock K-Ar radiometric dating of volcanic rocks on the Snake River Plain determined a northeast-younging trend from the Oregon-Idaho-Nevada border region through southern Idaho (e.g., Armstrong et al., 1975). The tectonic model used to describe northeast-trending Miocene to Holocene magmatism and associated deformation of the northern Basin and Range Province involves the southwest-migrating North American plate traveling over a “fixed” mantle plume, or hotspot (Morgan, 1972; Suppe et al., 1975; Anders et al., 1989; Rodgers et al., 1990). The present locus of magmatism is on the Yellowstone Plateau of Idaho and Wyoming, lending the name “Yellowstone hotspot” to the time-transgressive volcanism.

A transition zone in the Yellowstone hotspot track occurs near longitude 114°W in southern Idaho, coincident with the inflection point from the western to eastern Snake River Plain. Pierce and Morgan (1992) and Hughes and Mccurry (2002) attributed the geochemical and physiographic change from anhydrous, high-temperature (up to 1100 °C) magmatism in the elevated plateaus of southwestern Idaho to hydrous, lower-temperature (up to 900 °C) magmatism within the downwarped eastern Snake River Plain to reflect the transition from Proterozoic and younger crust in the west to the Archean Wyoming craton in the east. This lithospheric transition zone is consistent with the ⁸⁷Sr/⁸⁶Sr = 0.706 isopleth shown just west of the Albion Range in southernmost Idaho by Reed et al. (1993).

The distribution and ages of middle Miocene to Holocene (17–0 Ma) Yellowstone hotspot volcanic fields in southern Idaho, compiled by Pierce and Morgan (1992), are displayed in Figures 1 and 2. The terminology of named hotspot eruptive centers (e.g., Owyhee-Humboldt, Bruneau-Jarbridge) in Figures 1 and 3 will be used throughout this paper.

**Cordilleran Thrust Belt**

The Snake River Plain region contains Proterozoic to Mesozoic strata involved in east-vergent Antler-, Sevier-, and Laramide-age contraction (Burchfiel and Davis, 1975; DeCelles, 2004) and subsequent Cenozoic extensional collapse (Armstrong, 1982; Constenius, 1996; Dickinson, 2002). The central Idaho and Idaho-Wyoming (southeast Idaho) thrust belts are located north and south, respectively, of the Snake River Plain and are cut by Basin and Range normal faults.

Neoproterozoic to middle Paleozoic strata deposited along the western margin of Laurentia are divided into two successions that are separated by the frontal thrust of the Devonian Antler orogeny: (1) shallow-water siliciclastic and carbonate strata (eastern assemblage or miogeocline); and (2) fine-grained, deep-marine deposits (western assemblage or eugeoclinal; e.g., Burchfiel and Davis, 1975). Detrital zircon provenance analyses of eastern and western assemblage rocks within the Antler orogenic belt (Gehrels, 2000) and Proterozoic to Triassic Cordilleran margin (Gehrels et al., 1995; Gehrels and Ross, 1998; Stewart et al., 2001) determined that Grenville-age (1300–950 Ma), Yavapai-Mazatzal-age (1800–1600 Ma), Peace River Arch-age (2000–1800 Ma), and Archean basement-age (older than 2500 Ma) grains form the majority of the detrital zircons in sandy miogeoclinal and eugeoclinal strata (see Table 1). These zircon populations are persistently recycled through the Paleozoic strata of the thrust belt, such that their presence in a modern stream defines recycling through Neoproterozoic to Paleozoic sedimentary rocks with ultimate provenance in Laurentia (Link et al., 2005).

The Cordilleran thrust belt contains other scarce, but persistent, detrital zircon age populations that are recycled through Proterozoic to Paleozoic siliciclastic sedimentary rocks (see Table 1). A 1610–1500 Ma non-North American population and a 1450–1400 Ma population are present in areas that drain from the 1470–1400 Ma Belt Supergroup (Ross and Velleneuve, 2003). The 1400 Ma population was
Figure 2. Simplified geologic map of the greater Snake River Plain region. Source rocks of the Cordilleran magmatic belt are shaded to accent their location on the flanks of the western Snake River Plain. Geology is after Pierce and Morgan (1992) and Muehlberger (1996).
likely derived from anorogenic granite magmatism in the Colorado province (Anderson and Morrison, 2005). Neoproterozoic to middle Paleozoic detrital zircon populations are also present and interpreted to be recycled through rocks of the miogeocline. In this paper, we use the presence of recognizable populations of recycled Proterozoic and Archean detrital zircons in both modern stream sediments and Neogene rocks of the western Snake River Plain region and the western Snake River drainage belt to establish two criteria. Firstly, broad populations of Proterozoic detrital zircons (in particular Grenville, 1300–950 Ma, and Yavapai-Mazatzal, 1800–1600 Ma) define provenance from the thrust belt and Basin and Range Province in Idaho. Secondly, and important to paleodrainage reconstructions we offer in this paper, Precambrian detrital zircons are not found in recognizable populations (at least three grains or 5% of the sample) in streams that drain the Idaho batholith and Challis magmatic rocks west of the Wood River Valley (~115°W longitude). Given the abundance of zircon in Cretaceous and Eocene igneous rocks north of the Snake River Plain, the sparse Paleozoic metasedimentary inliers within the magmatic belt do not supply significant volumes of zircons. Therefore, the presence of significant Proterozoic-age populations in the western Snake River Plain region is a clear reflection of through-going westward Snake River drainage from the Montana-Idaho-Wyoming thrust belt.

Cordilleran Magmatic Belt

East-dipping subduction beneath the North American plate since the Mesozoic allowed the generation of west-facing volcanic arcs and granitic batholiths that extend for over 4000 km along the Cordilleran margin (e.g., Anderson, 1990). In the Snake River Plain region, the Cordilleran magmatic belt is broken into three time slices: Middle to Late Jurassic (170–150 Ma), early Late to Late Cretaceous (110–70 Ma), and Eocene to Oligocene (52–35 Ma). The following age descriptions are noted in Table 1. The location of Eocene and Cretaceous source rocks in this study is critical, and we emphasize their importance by highlighting their rock exposures on the geologic map of Figure 2.

Jurassic magmatism in the immediate Snake River Plain region is concentrated in northern Nevada and is absent in much of central and southern Idaho (Worl and Johnson, 1995; Camilli et al., 1997). The Contact pluton (CP in Fig. 2) and related intrusive packages in northern Elko County, northeastern Nevada, record an eastward sweep of arc magmatism that affected the backarc region of Nevada and is contemporaneous with crustal shortening along the Luning-Fencemaker thrust belt in western Nevada (Lawton, 1994; Wyld and Wright, 1997; DeCelles, 2004).

The Cretaceous Idaho batholith is divided into two portions: the 110–70 Ma Atlanta lobe of southern Idaho found to the north and south of the Snake River Plain and the 80–60 Ma Bitterroot lobe of northern Idaho and western Montana (Armstrong et al., 1977; Criss and Fleck, 1987; Foster et al., 2001). The Snake River Plain region is bordered only by the Atlanta lobe, which intrudes the central Idaho thrust belt on the east (Johnson et al., 1988) and is bounded by the Seven Devils–Wallowa terrane, Salmon River belt, and Columbia River Basalt Group to the west (McDougall, 1976; Aliberti and Manduca, 1988; Gray and Oldow, 2005).

Eocene magmatism in the Snake River Plain region shows a progressive younging pattern to the west and south, possibly associated with Paleogene slab rollback of the Farallon plate (Dewey, 1980; Dickinson, 2002). Commencing ~60 million years ago, a migratory extensional arc was established in the Rocky Mountain region (see Table 1; Janecke, 1992; Janecke et al., 1997). From west to east, the late Paleocene to middle Eocene (60–45 Ma) Absaroka volcanics of western Wyoming and southern Montana, early to middle Eocene (52–42 Ma) Challis volcanics of south-central Idaho, and middle Eocene to late Oligocene (42–27 Ma) volcanics of northern Nevada and Utah record the westward and southern sweep of magmatic
detrital zircon population & Minimum age (Ma) & Maximum age (Ma) & Source regions \\
--- & --- & --- & --- \\
Yellowstone hotspot system & 0 & 17 & Snake River Plain and Yellowstone system, north-central Nevada to northwest Wyoming (Pierce and Morgan, 1992) \\
Early Oligocene Almo pluton & 30 & 33 & Point source in Albion Mtns. metamorphic core complex (Egger et al., 2003; AP on Fig. 2) \\
Middle to late Eocene northern Nevada volcanics & 35 & 42 & North-central Nevada \\
Early to middle Eocene Challis Volcanic Group & 42 & 52 & South-central Idaho, north of Snake River Plain \\
Late Paleocene to early Miocene Absaroka Volcanic Supergroup & 45 & 60 & Northwest Wyoming, southwest Montana (Link et al., 2005) \\
Cretaceous Atlantic lobe of the Idaho batholith and equivalents & 70 & 110 & South-central Idaho, north of Snake River Plain; Owyhee Mtns., south of Snake River Plain \\
Jurassic intrusive rocks of northern Nevada & 150 & 170 & Point source in Contact pluton, Salmon Falls Ck. (CP on Fig. 2) \\
Early to middle Paleozoic & 330 & 450 & Central Idaho thrust belt (Antler allochthon), Idaho-Wyoming thrust belt \\
Neoproterozoic Bannock Volcanic Member & 680 & 720 & Pocatello, Idaho area (Fanning and Link, 2004; BV on Fig. 2) \\
Ghost Neoproterozoic & 580 & 800 & Pioneer Mtns. metamorphic core complex (Beranek et al., 2004; PC on Fig. 2); recycled through Cretaceous granites, unmapped Neoproterozoic igneous rocks(?), miogeocline(?) \\
Recycled Grenville grains & 950 & 1300 & Central Idaho and Idaho-Wyoming thrust belts; Neoproterozoic to Paleozoic miogeocline (Gehrels, 2000; Link et al., 2005) \\
Syn– Belt Supergroup volcanics and A-type Wyoming magmatism & 1400 & 1470 & Missoula and Lemhi Groups (Evans et al., 2000; Link and Fanning, 2003); Wyoming anorogenic granites (Frost et al., 1993) \\
Non–North American grains recycled through Belt Supergroup & 1500 & 1610 & South Australia, Gawler Craton (Ross et al., 1992; Link and Fanning, 2003) \\
Recycled Yavapai-Mazatzal Province and southwest Montana Proterozoic grains & 1600 & 1800 & Recycled from Cretaceous sandstones, Mesoproterozoic Missoula and Lemhi Groups, Cordilleran miogeocline, Pennsylvanian–Permian Sun Valley Group and Albion Mtns. core complex (Link et al., 2005) \\
Recycled Peace River Arch grains & 1800 & 2000 & Recycled through Ordovician sandstones and Mississippian Copper Basin Group (Smith and Gehrels, 1994; Link et al., 1996) \\
Archean basement & 2400 & 2800 & Exposed Archean Wyoming Province; also recycled through Cordilleran miogeocline (Gehrels, 2000; Link et al., 2005) \\

activity. The distribution of Tertiary volcanics is crucial to this provenance study, because middle Eocene to late Oligocene volcanics are found only south of the Snake River Plain, while the Challis Volcanic Group rocks blanket the Atlanta lobe and central Idaho thrust belt north of the Snake River Plain.

The Snake River system records minor input of zircon grains from small igneous point sources. The 33–30 Ma early Oligocene Almo pluton, which intrudes the Albion Range metamorphic core complex in southernmost central Idaho (AP in Fig. 2), and the 720–670 Ma Neoproterozoic Bannock Volcanic Member of the Pocatello Formation of southeast Idaho (BV in Fig. 2) are examples. Although not aerially extensive, we show that the influence of these point sources in the geologic record is significant.

**Accreted Terranes**

The northeastern Oregon–western Idaho border region contains island-arc terranes of Paleozoic to Mesozoic age that accreted to North America during the Late Jurassic to Early Cretaceous (Vallier and Brooks, 1987; Gray and Oldow, 2005). Examples include Triassic to Jurassic arc packages of the Wallowa, Baker, Izee, and Olds Ferry terranes. North American rocks of this region are separated from accreted terranes by the western Idaho shear zone (Manduca et al., 1993). Syn- to postkinematic (145–90 Ma) granites intrude the western Idaho shear zone and sedimentary and volcanic units of the present-day Blue and Wallowa Mountains of eastern Oregon (Vallier et al., 1997; Gray and Oldow, 2005).

**MIocene Basin Development**

The deposition of Neogene sedimentary units within the Oregon-Idaho graben and western Snake River Plain, two continental rift basins that formed adjacent to the Yellowstone hotspot and the earliest phase of Basin and Range extension, is essential to the understanding of sediment provenance in this study. We combine terminology used by Lambiase (1990) and Carrroll and Bohacs (1999) when referring to the sediment-supply and subsidence rates within these rift basins. Following these workers, the initial rifting and subsidence phase is marked by a high sediment-supply rate, which generates an overfilled or fluvial stage. As the rift evolved and rates of subsidence increased, the basin became starved of sediment, and an underfilled or lacustrine phase developed. In the final rift stage, subsidence waned and the basin returned to an overfilled or fluvial setting. To assist the following discussion, specific phases of Miocene basin development with respect to regional extension, sedimentation, and extent of the Yellowstone magmatic system in the western Snake River Plain region are presented in Figure 3.

**Oregon-Idaho Graben**

The Oregon-Idaho graben (Fig. 1) is a middle to late Miocene (15.4–10.5 Ma), north-trending, fault-bounded basin along the eastern Oregon–southwestern Idaho border that contains fluvio-lacustrine, epiclastic, and volcanic flow deposits (Ferns et al., 1993; Cummings et al., 2000). Cummings et al. (2000) interpreted the 50–60-km-wide and 100-km-long basin to have formed during regional east-west extension and caldera-forming eruptions of the Yellowstone hotspot system. Analysis of sedimentary and volcanic
mings et al. (2000) to generate three deposits, in concert with local structural data.

Stage 1 (15.4–14.3 Ma; initial basin and range phase of Fig. 3) marks uniform sedimentation across the basin as the Oregon-Idaho graben was overfilled. Muscovite-bearing arkosic channel sands and tuffaceous sandstone, siltstone, and mudstone are assigned to the middle Miocene (ca. 15.5 Ma) Sucker Creek Formation (Lawrence, 1988; Ferns et al., 1993). No sediments of this age are exposed in the western Snake River Plain (Kimmel, 1982; Wood and Clemens, 2002), suggesting that no accommodation space had been created.

Stage 2 (14.3–12.6 Ma) is characterized by widespread calc-alkaline volcanism and development of local, 15–20-km-wide subbasins filled with arkosic and tuffaceous deposits as the basin became underfilled.

Stage 3 (12.6–10.5 Ma) marks the return of an overfilled, fluvial setting. Strata contain both intrabasinal (local volcanic detritus) and extrabasinal (granitic detritus) components. Subsidence in the Oregon-Idaho graben ceased with northwest-trending extension associated with the younger western Snake River Plain.

Cummings et al. (2000) used the presence of arkosic sediment found throughout the basin, and northwest-directed paleocurrents in stages 1 and 3 in the southern Oregon-Idaho graben, to infer that extrabasinal granitic detritus was derived from areas south of the Snake River Plain, specifically from Cretaceous plutons in the Owyhee Mountains (see location in Fig. 2). The modern drainage system of the Oregon-Idaho graben consists of the axial Owyhee River, the headwaters of which are in north-central Nevada. The Owyhee River flows into the Snake River north of Adrian, Oregon (see Fig. 1).

Western Snake River Plain

The late Miocene to late Pliocene (11.5–3 Ma) western Snake River Plain (Fig. 1) is a north-west-trending, 70 km by 300 km, fault-bounded rift basin. It formed along the northwest shoulder of the 12.5–11 Ma Bruneau-Jarbidge eruptive center, and cuts across the northermost structural fabric of the Oregon-Idaho graben (hotspot shoulder phase of Fig. 3; Malde, 1991; Pierce and Morgan, 1992; Wood and Clemens, 2002).

From late Miocene to Pliocene time, the subsiding western Snake River Plain was predominantly a lacustrine depocenter known as Lake Idaho (Middleton et al., 1985; Jenks and Bonnichsen, 1989; Malde, 1991; Sadler and Link, 1996). The presence of alkaline lacustrine strata suggests that the western Snake River Plain established an internal drainage system, possibly due to the absence of an oceanic outlet (Wood, 1994; Wood and Clemens, 2002). The base level of Lake Idaho sediment accumulation progressively fell through the late Miocene as the lake went through cycles of evaporation, and the western Snake River Plain subsided at a decreasing rate. Lake Idaho also progressively captured drainage from the tributary-rich middle and upper Snake River system (Lake Idaho phase of Fig. 3; Kimmel, 1982).

The Holocene drainage system in the western Snake River Plain consists of the longitudinal Snake River that flows from east to west along the arcuate path of the Snake River Plain, and is fed by transverse streams that are themselves axial drainages of Basin and Range valleys. The modern longitudinal Snake River system (longitudinal drainage phase of Fig. 3) is thought to have been established around 2.5 million years ago, where an outlet of Lake Idaho was cut south of Hells Canyon along the Oregon-Idaho border (Wood and Clemens, 2002). Prior to its capture by the Columbia River, it is not known where the main Snake River traveled. It has been suggested that the Snake River flowed southwest through southeastern Oregon (Wheeler and Cook, 1954) or south through northern Nevada or Utah (Repenning et al., 1995; Link et al., 2002; Hershler and Liu, 2004) and into the Humboldt-Sacramento River system of Nevada and California.

Sedimentary deposits of the western Snake River Plain are assigned to the Idaho Group (Kimmel, 1982; Smith et al., 1982; Middleton et al., 1985; Repenning et al., 1995). Description of stratigraphic units (Fig. 3) within the Idaho Group will be presented individually along with their detrital zircon age data.

ANALYTICAL TECHNIQUES, SAMPLING STRATEGY, AND DATA DISPLAY

This study analyzed 13 new detrital zircon samples from the western Snake River Plain and included 22 samples from the eastern Snake River Plain discussed by Link et al. (2005). Samples generally consisted of 2–4 kg of rock or sediment, and we attempted to collect fine- to coarse-grained sand-sized material. Specifically, this study contained 17 coarse-grained and 18 fine- to medium-grained samples. Grain-size information is described individually with their detrital zircon age data.

Heavy mineral concentrates were prepared for each sample using standard mineral separation procedures such as washing, heavy liquid (methylene iodide), and paramagnetic methods at Idaho State University, University of British Columbia, and The Australian National University. A random portion of the heavy mineral concentrate, rich in zircon, was poured onto double-sided tape and cast into an epoxy disk together with FC1 reference zircon grains, and was sectioned and polished. Reflected and transmitted light photomicrographs were taken for all grains, and cathodoluminescence (CL) scanning-electron microscope images were prepared to determine the internal structure of the grains.

The zircon grains were analyzed using the sensitive high-resolution ion microprobe (SHRIMP) facilities at The Australian National University following standardized procedures as discussed in Williams (1998, and references therein). The data have been reduced using the SQUID Excel macro (Ludwig, 2000); U-Pb ages are calibrated relative to the FC1 Duluth Gabbro reference zircon (Paces and Miller, 1993). For areas analyzed that are older than ca. 800 Ma (or for very high U zircon areas) correction for common Pb has been made in the normal manner using the measured 206Pb/238U ratio. For analyses that are younger than ca. 800 Ma, it is difficult to determine the 206Pb/207Pb ratio for the ~1 nanogram of material sputtered from the ion microprobe pit. As has been explained in detail elsewhere, for such analyses, the correction for common Pb is made via the ~207Pb correction method (see Williams, 1998, and references therein) using the measured 238U/206Pb ratio and 207Pb/206Pb ratio. For grains that yield ages older than ca. 800 Ma, the 206Pb/238U age is used. For the younger grains, in general the 206Pb/207U age is used, and, as most of the analyses are within uncertainty of the Tera and Wasserburg (1972) concordia, common Pb corrections and assessment of concordance is not an issue. For those that have elevated measured 207Pb/206Pb ratios, each analysis has been assessed for inclusion or rejection in terms of the spot location, degree of common Pb correction, and therefore the significance of the 206Pb/207U age.

For each sample, a 60 random-grain set of analyses was determined. The random nature of the grain selection is important and was optimized by arbitrarily choosing a photomicrograph of an area and analyzing every grain in that photo. Metamict or strongly cracked grains were avoided. CL images were used to ensure that the youngest component within structured grains was analyzed. For this study, all samples initially had 30 grains analyzed. Subsequently, complex samples or locations of high priority received another 30 grain analysis, to total 60. Although not presented in this paper, we found a profound similarity in detrital zircon age populations between the 30 and 60 grain analyses, showing the utility of our random-grain analysis.
Analytical data (702 grains) are presented in the associated GSA Data Repository material (Table DR1). Precambrian zircons with more than 10% discordance are not presented in this paper; however, we include them as cross-rows in the Data Repository. The data are shown on relative probability plots, with stacked histograms, using the Isoplot 3.0 Excel macro of Ludwig (2003).

Miocene to Pliocene detrital zircon samples from the Oregon-Idaho graben and western Snake River Plain were collected using published regional geologic maps as guides to locate rock exposures (e.g., Ekren et al., 1981; Ferns et al., 1993). Figure 3 shows a composite time-rock diagram and approximate stratigraphic location of detrital zircon samples. Detrital zircon samples and related UTM coordinates are presented in Table 2. For ease, each detrital zircon sample has been assigned a sample number (1–35) that is shown on the sample location map of Figure 4 and correlates to detrital zircon age plots of Figures 5 and 6. Modern stream sediment samples (see Fig. 4) were taken from all major drainages feeding the modern western Snake River Plain and are used in conjunction with stream samples that define detrital zircon “bar codes” for drainages of the eastern Snake River Plain (Link et al., 2005).

The majority of igneous rocks in the Snake River Plain region have been dated by the whole-rock K-Ar method (e.g., Armstrong et al., 1975, 1980; Coats, 1987). K-Ar ages, especially from plutonic sources, may be younger than U-Pb detrital zircon ages, since they represent a system with a lower closure temperature. Therefore, in order to compare detrital zircon in Neogene sedimentary deposits with possible parent rock, it is more useful if the U-Pb signature of a specific source rock is obtained.

Detrital zircon data are presented in relative probability plots that contain both a relative probability curve and histogram to show the distribution of specific grain populations (e.g., Fedo et al., 2003; Link et al., 2005). Each detrital zircon sample contains two plots; one from 0 to 150 Ma (5 Ma bins), and one from 150 to 3000 Ma (25 Ma bins). The Snake River Plain region is flooded by Cenozoic and Mesozoic rock exposures (e.g., Ekren et al., 1981; Ferns et al., 1993). Figure 3 shows a composite time-rock diagram and approximate stratigraphic location of detrital zircon samples. Detrital zircon age plots of Figures 5 and 6. Modern stream sediment samples (see Fig. 4) were taken from all major drainages feeding the modern western Snake River Plain and are used in conjunction with stream samples that define detrital zircon “bar codes” for drainages of the eastern Snake River Plain (Link et al., 2005).

Recent provenance studies, such as Mahoney et al. (1999) and Ross and Villeneuve (2003), have determined that the occurrence of definable grain populations at the 5%–10% level is the salient feature of detrital zircon studies, not the total number of grains, or the absolute population size. We have used the framework outlined by Dodson et al. (1988), which suggests that if 59 detrital zircons are analyzed at random within one sample, a population present at the 5% level will be observed with 95% confidence. Likewise, a 30 grain analysis will find every population present at the 10% level with 95% confidence; however, some resolution of age populations may be lost. Vermeech (2004) has shown that in the worse-case scenario, 117 grains per sample would be required to have 95% confidence of finding a population present at the 5% level of the total. As noted already, in most of the samples that we analyzed, the difference between the 30 grain initial sampling and the 60 grain data set is negligible. That is, the dominant peaks or age groups are the key to the provenance for this work, and so, be it 30, 60, or even 120 grains, our data sets are meaningful and show the important provenance groups that enable us to have confidence in the conclusions.

### Table 2. List of Detrital Zircon Samples for the Snake River Plain Region, Their Figure Numbers, and UTM Locations

<table>
<thead>
<tr>
<th>№</th>
<th>Figure</th>
<th>Detrital zircon sample locality</th>
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<td>4761212</td>
</tr>
</tbody>
</table>

1Link et al. (2005).
3Link et al. (2002).
Landscape evolution of the western Snake River Plain region

Reynolds Creek

Reynolds Creek, just east of the Oregon-Idaho border, drains the Owyhee Mountains of southwestern Idaho and feeds into the modern Snake River. Geologic mapping by Ekren et al. (1981) demonstrated that Reynolds Creek flows through Cretaceous granite (whole-rock K-Ar ages of 87–60 Ma from Armstrong, 1975), which represents the southern extension of the Idaho batholith, arkosic sediment of the Miocene Poison Creek Formation (Smith et al., 1982), and Miocene rhyolite tuff assigned a whole-rock K-Ar age of 11.2 ± 0.65 Ma by Armstrong et al. (1980). South of the headwaters of Reynolds Creek, the Owyhee Plateau contains Miocene and Oligocene dikes, plugs, and epiclastic deposits (Ekren et al., 1982). Armstrong et al. (1980) dated a succession of silicic flows and tuff at 44.7 ± 0.8 Ma (whole-rock K-Ar) and assigned the local exposure to the Eocene Challis Volcanic Group. If the K-Ar system has not been disturbed, this represents the only exposure of Challis-age (52–42 Ma) volcanic rock south of the western Snake River Plain.

Detrital zircons ($n = 60$; Fig. 5A) from a fine- to medium-grained feldspathic volcanic lithic sand of modern Reynolds Creek have a simple, second-order set of three main grain groupings: (1) early to middle Miocene (16.7–14.4 Ma; 3 grains; 5%); (2) Cretaceous (110–65 Ma; 53 grains; 88%), with 35 grains (58%) between 100 and 90 Ma, 6 grains from 90 to 80 Ma (10%), and 5 grains from 80 to 70 Ma (8%); and (3) Neoproterozoic-Cambrian (757, 657, 633, 505 Ma) representing 7% of the sample. One grain gave an Early Jurassic (185 Ma) age. Cretaceous grains are interpreted to have derived from the Silver City pluton and related intrusions of the Owyhee Mountains, which represent the southernmost portion of the Idaho batholith. Though from detrital grains, these are the first U-Pb ages for Cretaceous rocks south of the Snake River Plain. Neoproterozoic grains are presumed to be inherited and recycled through the Silver City pluton or weathered directly from unmapped Neoproterozoic roof pendants. Neoproterozoic ages in modern Reynolds Creek overlap with known 750–650 Ma zircon ages that record the protracted rifting of Rodinia in Idaho (Lund et al., 2003; Beranek et al., 2004; Fanning and Link, 2004).

Boise River

The Boise River drains the highlands north of the western Snake River Plain and flows onto it at Boise, Idaho. The Boise River drainage consists of granitoids associated with the Atlanta lobe of the Cretaceous Idaho batholith that are...
Figure 5 (on this and previous page). Modern stream sediment detrital zircon age information shown in histogram with superimposed relative probability curve. Samples are numbered in Table 2 and listed as S#. (A) Reynolds Creek (S1); (B) Boise River (S2); (C) Bruneau River (S3); (D) Wood River system (S4–S7); (E) Salmon Falls Creek (S8–S10); (F) Raft River–Goose Creek composite (S11–S12); (G) Portneuf River system composite (S13–S14); (H) Composite Middle Snake River (S1, S3–S24).
Figure 6 (on this and previous page). Neogene sedimentary rock detrital zircon age information shown in histogram with superimposed relative probability curve. Samples are numbered in Table 2 and listed as S#. (A) Sucker Creek formation (S25); (B) Table Rock Sandstone (S26); (C) Poison Creek Formation (S27); (D) Middle Idaho Group near Adrian, Oregon (S28–S29); (E) Upper Terteling Springs Formation (S30); (F) Lower to Upper Glenns Ferry Formation (S31–S32); (G) uppermost Glenns Ferry Formation and Tuana Gravel (S33–S35).
intruded by mafic and felsic dikes and overlain locally by silicic flows and volcanoclastic deposits of the Eocene Challis Volcanic Group (Johnson et al., 1988; Clemens and Wood, 1993). The age of the Atlanta lobe is constrained by various K-Ar ages from 110 to 65 Ma (with 80–70 Ma peak), and U-Pb zircon dates around 90 Ma (Armstrong et al., 1977; Lewis et al., 1987; King and Valley, 2001).

A coarse-grained, micaceous arkosic sand from the modern Boise River yielded a simple set of grain populations (n = 29; Fig. 5B) with: (1) early to middle Eocene (52–42 Ma; 10 grains; 33%); (2) Cretaceous (115–72 Ma, mainly 90–80 Ma; 10 grains; 33%); and (3) scattered Triassic (207 Ma; 1 grain), Permian (260 Ma; 1 grain), Neoproterozoic (690–630 Ma; 3 grains), and Archean (2555–2535 Ma; 3 grains) ages.

Early to middle Eocene (52–42 Ma) detrital zircons are interpreted to be sourced from the Challis Volcanic Group, which is aerially extensive in central Idaho. In terms of this provenance study, we emphasize that Challis-age detrital zircons are being derived from rocks north of the Snake River Plain. Neoproterozoic and Archean detrital zircons are interpreted to be inherited and recycled from wall rocks in the Atlanta lobe. These wall rocks may have been, for example, Paleozoic sedimentary rocks from the Pennsylvanian-Permian Sun Valley Group. The ultimate source for Permian and Triassic detrital zircons is not clear. These grains may have been recycled through latest Cretaceous granites of the Atlanta lobe that sample rocks of the Wallowa terrane or similar arc complexes exposed in eastern Oregon that were accreted to the western margin by the Early Cretaceous.

**Bruneau River**

The Bruneau River flows north from the northern Nevada–southern Idaho border onto the Snake River Plain. Before its confluence with the Snake River near Bruneau, Idaho, the Bruneau River and its headwaters travel through fluvo-lacustrine deposits of the Pliocene (5–3 Ma) Glenns Ferry Formation, rhyolite of the Challis (16.5–11 Ma) and Owyhee-Humboldt (12–12 Ma) volcanic fields (see Fig. 3). Paradoxically, no Bruneau-Jarbidge-age (12.5–11 Ma) detrital zircons are present within the Bruneau River. This may reflect the grain size that was sampled, as small volcanic detrital zircons from the Bruneau-Jarbidge field are not present in the medium sand. The presence of Cretaceous and Proterozoic detrital zircon is interpreted to be from the recycling of grains through the Pliocene Glenns Ferry Formation (cf. Link et al., 2002).

**Wood River System**

The south-draining Wood River system represents a composite of the Big Wood River, Little Wood River, Trail Creek, and the headwaters of the Salmon River. The detrital zircon signature is predictably complex, since the Wood River system drains the: (1) Atlanta lobe of the Cretaceous Idaho batholith and early to middle Eocene Challis Volcanic Group (Johnson et al., 1988; Worl and Johnson, 1995); (2) central Idaho thrust belt, containing Paleozoic rocks of the Cordilleran eastern and western assemblages involved in Antler- and Sevier-age deformation (Dover, 1980, 1983; Turner and Otto, 1988; Rodgers et al., 1995); (3) westerly sourced siliciclastics of the Antler foreland flysch (Mississippian Copper Basin Group) and Pennsylvanian-Permian Wood River basin (Mahoney et al., 1991; Link et al., 1995, 1996; Geslin, 1998); and (4) an early to middle Cenozoic extensional province highlighted by the Pioneer Mountains metamorphic core complex that exposes Paleoproterozoic to Neoproterozoic(? crystalline basement (Wust and Link, 1988; Burton and Link, 1995; Beranek et al., 2004).

Prominent populations of detrital zircon (n = 184; Fig. 5D) from fine- to medium-grained sands within the Wood River system are: (1) early to middle Eocene (52–42 Ma; 68 grains; 37%); (2) Cretaceous (100–70 Ma; 36 grains; 20%); (3) Ordovician to Devonian (ca. 450–350 Ma; 5 grains; 3%); (4) early Neoproterozoic to middle Mesoproterozoic (1300–950 Ma; 11 grains; 6%); (5) late Mesoproterozoic (1610–1580 Ma; 5 grains; 3%); (6) late to middle Paleoproterozoic (1800–1600 Ma; 23 grains; 13%); (7) early Paleoproterozoic (2000–1800 Ma; 12 grains; 6%); and (8) early Paleoproterozoic to Archean (2200–2900 Ma; 9 grains; 5%) in age.

For this provenance study, early to middle Eocene (52–42 Ma) grains from the Challis Volcanic Group form a region- and age-specific population in the Wood River system like that of the Boise River system. Interestingly, Ordovician to Devonian (450–350 Ma) detrital zircons may be derived from the Antler allochthon (e.g., Dover, 1980, Link et al., 2005). Strong Proterozoic (1300–950 Ma; 1800–1600 Ma; 2000–1800 Ma) populations show recycling of detrital zircons through Paleozoic rocks of the Cordilleran passive margin.

**Salmon Falls Creek**

Modern Salmon Falls Creek drains north onto the Snake River Plain from northeastern Nevada. Salmon Falls Creek and its headwaters travel through: (1) Ordovician to Permian units (i.e., Valmy Formation, Edna Mountain Formation) associated with the Antler orogeny and its overlap assemblage (Stewart, 1980; Coats, 1987); (2) Jurassic (ca. 160 Ma) intrusive rocks of the Cordilleran magmatic belt (Wyld and Wright, 1997); (3) middle Eocene to Miocene strata, such as the Elko and Humboldt Formations, which contain tuffaceous material dated by K-Ar, 40Ar/39Ar, and U-Pb zircon fission-track methods at 40–35 Ma and 14–10 Ma, respectively (Coats, 1987; Mueller and Snake, 1993; Mueller et al., 1999); and (4) Miocene Jarbidge Rhyolite (16–14 Ma) and Cougar Point Tuff (11–10 Ma), associated with the ancient Yellowstone system (Coats, 1987; Perkins and Nash, 2002, and references therein).

Detrital zircon samples from modern Salmon Falls Creek were taken at three locations along the length of the stream. Detrital zircon ages from fine- to coarse-grained sands compare favorably with existing K-Ar ages for northern Nevada assembled by Coats (1987) on Jurassic to Miocene igneous rocks, and form a relatively simple set of age populations (N = 145; Fig. 5E): (1) Miocene (17–10 Ma; 111 grains; 77%); (2) middle to late Eocene (42–35 Ma; 7 grains; %); and (3) Middle Jurassic (mainly 170–160 Ma; 20 grains; 14%). One Proterozoic grain (920 Ma) was observed.

The Salmon Falls Creek region contains significant and unique populations of late to middle Eocene and Middle Jurassic detrital zircons. These age populations are not observed in modern stream sediment draining rocks north of the Snake River Plain (Boise River, Wood River system) and represent an important provenance fingerprint of northern Nevada.

**Goose Creek and Raft River**

North-northeast–trending Goose Creek and Raft River drain the westernmost expression of Basin and Range–style valleys in southern Nevada.
grains in Neogene basin fill may record the path of Challis Creek, not exposures of Challis volcanic Group that is exposed only north of the Snake River Plain, represents recycling of basin floor sand from the modern Raft River (Armstrong and Morgan, 1992; McCurry et al., 1997).

Detrital zircon age populations from Pleistocene gravels of Goose Creek and coarse-grained sand from the modern Raft River (n = 117) are combined in Figure 5F. The populations are complex and include: (1) Miocene (56 grains; 47%); mainly 14–8 Ma); (2) Oligocene (33–31 Ma; 4 grains; 3%); (3) middle to late Eocene (42–36 Ma; 4 grains; 3%); (4) early to middle Eocene (56–54 Ma; 5 grains; 4%); (5) scattered Paleozoic (mainly 500–465 Ma, 430–330 Ma; 14 grains; 11%); (6) Neoproterozoic (mainly 740–690 Ma; 6 grains; 5%); (7) early Mesoproterozoic (1265–1120 Ma; 5 grains; 4%); (8) late to middle Paleoproterozoic (1800–1600 Ma; 9 grains; 7%); (9) early Paleoproterozoic (2000–1800 Ma; 7 grains; 5%); and (10) Archean (3315–2545 Ma; 5 grains; 4%). This broad zircon assemblage reflects the diverse geology of the composite Albion–Raft River–Grouse Creek core complex.

The presence of Precambrian detrital zircons reveals provenance from the Cordilleran thrust belt and separates this region from Reynolds Creek and the Boise and Bruneau Rivers. We believe the presence of early to middle Eocene detrital zircons, correlative with the Challis Volcanic Group and Idaho batholith. The Idaho-Wyoming thrust belt defines a provenance region that is similar to that of the central Idaho thrust belt (Wood River system); both contain recycled early and middle Proterozoic zircons from the Cordilleran miogeocline and western assemblage. The Portneuf River system contains isolated grains of Eocene and Cretaceous age; however, it lacks rocks of the Challis Volcanic Group and Idaho batholith. We explain the presence of these grains by the recycling of Pleistocene loess of the Portneuf Valley into the local drainage system (c.f. Link et al., 2005).

Composite Middle Snake River

The modern Snake River, the headwaters of which are near the Idaho-Montana border (Henry’s Fork) and in northwestern Wyoming (South Fork), is the drainage system flowing longitudinally through the Snake River Plain. The Snake River is the base level for all tributaries feeding the Snake River Plain, with the only exception being the Big Lost River system, where the streams sink into the Big Lost Trough of the eastern Snake River Plain (Geslin et al., 1999). Detrital zircon age populations for main Snake River samples can be combined with data of its tributaries feeding the Snake River (i.e., Reynolds Creek, Goose Creek, Portneuf River, etc.) to create a composite signature that characterizes the complex provenance of sediment in the regional system. We include eight Pleistocene to Holocene (5 fine-grained; 3 coarse-grained) samples of the upper Snake River watershed from Link et al. (2005) in this compilation. A composite Snake River signature using modern stream data allows us to recognize the “integrated” third-order Snake River in the rock record. Therefore, if we can observe the composite Snake River signature in ancient deposits, we can better constrain the initiation and timing of the modern Snake River system.

Detrital zircon ages (n = 1196) for the composite middle Snake River (headwaters of Snake River to Marsing, Idaho, near the Oregon-Idaho border) are shown in Figure 5F. Two new fine-grained, main Snake River samples at Marsing (59 grains) and Glenns Ferry (56 grains) were added to existing tributary and main Snake River compilations. The distribution of populations is complex, with two large populations (Cretaceous and Miocene to Holocene) and numerous small populations, as would be expected in a major river system. Populations present in the composite middle Snake River are: (1) Miocene to Holocene (ca. 17–0 Ma; 305 grains; 25%); (2) late Eocene (42–35 Ma; 15 grains; 1%); (3) early to middle Eocene (52–42 Ma; 97 grains; 8%); (4) Cretaceous (mainly 110–70 Ma; 199 grains; 17%); (5) Jurassic (mainly 170–160 Ma; 22 grains; 2%); (6) Ordovician–Mississippian (ca. 450–330 Ma; 27 grains; 2%); (7) Cambrian-Ordovician (540–460 Ma; 17 grains; 1%); (8) middle to late Neoproterozoic (750–600 Ma; 9 grains; 9%); and (9) late Paleoproterozoic to early Neoproterozoic (1300–950 Ma; 81 grains; 7%); (10) early to middle Paleoproterozoic (1800–1600 Ma; 136 grains; 12%); and (11) early Paleoproterozoic (2000–1800 Ma; 72 grains; 6%); and (12) early Paleoproterozoic to Archean (2000–3000 Ma; 93 grains; 8%).

STRATIGRAPHIC DESCRIPTION AND PROVENANCE INTERPRETATION OF NEOGENE UNITS

Description of Miocene to Pliocene sedimentary units of the western Snake River Plain region, their detrital zircon age populations, and interpreted provenance is described from oldest to youngest here. Sample location information is presented in Table 2 and Figure 3 and shown on the regional map of Figure 4.

Miocene Sucker Creek Formation

The Miocene Sucker Creek Formation of the Oregon-Idaho graben represents the earliest sedimentation preserved in the Oregon-Idaho region (Stage 1 of Cummings et al., 2000) that overlapped in time and space with the Yellowstone hotspot (Fig. 3; Ferns et al., 1993; Wood
and Clemens, 2002). Near Adrian, Oregon, the Sucker Creek Formation (SC in Fig. 4) consists of coarse-grained, muscovite-bearing arkosic sandstone, matrix-supported polymict (chert, felsic volcanic, two-mica granite) conglomerate, and fine-grained floodplain siltstone and mudstone (Ferns et al., 1993).

A coarse-grained, muscovite-bearing arkosic channel sandstone with west-trending paleocurrent indicators yielded the following simple detrital zircon distributions (n = 59; Fig. 6A): (1) Miocene (18.0–15.0 Ma; 3 grains; 5%); (2) early to middle Eocene (52–45 Ma; 14%); and (3) Cretaceous (mainly 100–90 Ma; 44 grains; 75%). Permian-Triassic (ca. 250, 225 Ma) and Neoproterozoic (ca. 660, 515 Ma) grains are also present. The maximum depositional age is constrained by the youngest grains, 15.2 ± 0.9 Ma and 15.7 ± 0.3 Ma (±1σ), which agree with age determinations for the Sucker Creek Formation by Ferns et al. (1993) and Cummings et al. (2000).

Detrital zircon populations within the Sucker Creek Formation share an overlap in Cretaceous ages with both the Boise River and Reynolds Creek. However, we favor the hypothesis that the Sucker Creek Formation was derived from a similar source as that of the modern Boise River. The Sucker Creek Formation contains a major population of early to middle Eocene detrital zircons, which we interpret to have been derived from rocks of the Challis Volcanic Group. Because modern Reynolds Creek does not record such ages, we interpret these arkosic sediments to have a provenance north of the Snake River Plain. The presence of Permian and Triassic detrital zircons in the Boise River and Sucker Creek Formation is interesting but not definitive since source rock control is uncertain. Accreted island-arc units of eastern Oregon, such as the Wallowa terrane, may be a candidate to supply sediment to the south or be included in Late Cretaceous intrusive phases of the Atlanta lobe. No Neoproterozoic detrital zircons of the Cordilleran thrust belt have been found.

Miocene Table Rock Sandstone, Lower Terteling Springs Formation

The Miocene Table Rock Sandstone is located within the Boise foothills on the north-eastern margin of the western Snake River Plain (TR in Fig. 4; Wood and Burnham, 1987). The Table Rock Sandstone is a micaceous arkosic unit from the Lower Idaho Group (ca. 10 Ma) and part of the Lower Terteling Springs Formation (Fig. 4). It is underlain by the basalt of Aldape Park, which has a whole-rock K-Ar date at 9.6 ± 0.6 Ma, and Idavada Group rhyolite at 11.3 ± 0.3 Ma (Fig. 4; Wood and Burnham, 1987; Clemens and Wood, 1993).

Dominant detrital zircon populations (n = 59; Fig. 6B) from the coarse-grained Table Rock Sandstone are: (1) Miocene (10.9–10.7 Ma; 2 grains; 3%); (2) early to middle Eocene (52–45 Ma; 11 grains; 38%); and (3) Cretaceous (115–65 Ma; 29 grains; 49%). Permian (250 Ma), Neoproterozoic-Cambrian (ca. 670, 515 Ma), and Archean (ca. 3240–2530 Ma) grains are also present. A maximum depositional age from a single detrital zircon for the Table Rock Sandstone is 10.7 ± 0.6 Ma, within error of the K-Ar ages of Clemens and Wood (1993).

Age populations in the Table Rock Sandstone show close correlation to the modern Boise River (and Sucker Creek Formation) with the presence of early to middle Eocene and Cretaceous detrital zircons. The absence of Precambrian grains from the Cordilleran miogeoclinal precludes the thrust belt being a source component for this sediment. We suggest that the early to middle Eocene population records a provenance for the Table Rock Sandstone that is north of the Snake River Plain where rocks of the Challis Volcanic Group are widely exposed.

Miocene Poison Creek Formation

The Miocene Poison Creek Formation of the Lower Idaho Group is exposed along the south-western margin of the western Snake River Plain in the Reynolds Creek and Murphy, Idaho, areas (PC in Fig. 4; Smith et al., 1982; Wood and Clemens, 2002). Deposits of the Poison Creek Formation unconformably overlie Idavada Group rhyolite (Smith et al., 1982; Wood, 1994) and have a whole-rock K-Ar date at 11.4 ± 0.6 Ma (recalculated from Ekn et al. [1981] in Wood and Clemens, 2002).

A coarse sand and gravel arkosic lag of the Poison Creek Formation near Reynolds Creek was dated by K-Ar at 7.4 Ma (Fiebelkorn et al., 1982; Ferns et al., 1993). Detrital zircon ages (n = 90; Fig. 6D) from these two sedimentary units in the Middle Idaho Group near Adrian, Oregon, are combined to form the following populations: (1) Miocene (18.1–7.4 Ma; 65 grains; 72%); (2) middle Eocene (42–38 Ma; 10 grains; 11%); (3) early to middle Eocene (54–44 Ma; 7 grains; 7%); (4) Cretaceous (120–95 Ma; 6 grains; 6%); and (5) Mesoproterozoic (1520, 1175 Ma).

The Middle Idaho Group at this location records the first observed influx of sediment derived from northern Nevada into the western Snake River Plain region. The presence of middle Eocene (42–38 Ma) detrital zircons, significantly younger than the Challis Volcanic Group and consistent with ages of modern Salmon Falls Creek in northern Nevada, implies a dramatic change in drainage pattern for the southwestern Idaho region during the late Miocene. Cretaceous ages overlap with those observed in both the Boise River and Reynolds Creek. With the presence of unique middle Eocene, post-Challis detrital zircons, we prefer that the provenance of these sedimentary deposits is north-central Nevada and south-western Idaho, south of the Snake River Plain.

Miocene Upper Terteling Springs Formation

Middle Idaho Group sediments in the Boise area are assigned to the late Miocene (6 Ma) Upper Terteling Springs Formation (TS in Fig. 4), which consists of micaceous arkosic sand, mudstone, and oolitic sedimentary units associated with multiple transgressive-regressive facies of Lake Idaho (Wood and Clemens, 2002). These deposits lie above the Table Rock Sandstone and the basalt of Aldape Park (K-Ar
age of 9.6 ± 0.6 Ma by Clemens and Wood, 1993), and appear to lie between the regional Chalk Hills and Glenns Ferry Formations (Wood and Clemens, 2002). An un lithified, coarse-grained, micaceous arkosic sand of the Upper Terteling Springs Formation from Freezout Hill, 40 km northwest of Boise, near Emmett, Idaho, contained the following simple detrital zircon populations (n = 61; Fig. 6E): (1) early to middle Eocene (49–44 Ma; 10 grains; 16%); (2) Cretaceous (mainly 100–70 Ma; 46 grains; 75%); and (3) scattered Jurassic (ca. 175 Ma), Neoproterozoic (ca. 695, 675, 620 Ma), and Archean (2540 Ma).

The presence of early to middle Eocene detrital zircon populations in the Upper Terteling Springs Formation suggests a provenance north of the Snake River Plain, where Challis’s Volcanic Group rocks are currently draining into fluvial systems. Cretaceous grains are also consistent with a provenance north of the Snake River Plain; however, those ages do not have the spatial resolution that early to middle Eocene grains do. The one Jurassic (173 Ma) grain was most probably recycled from the Idaho batholith.

Pliocene Lower to Upper Glenns Ferry Formation

The Pliocene (4 Ma) Glenns Ferry Formation (GF in Fig. 4), well-exposed at Hagerman Fossil Beds National Monument, near Hagerman, Idaho, contains fluvial and lacustrine sediments interbedded with ash-fall tuff and basalt. The Glenns Ferry Formation unconformably overlies the Miocene Chalk Hills Formation (Middleton et al., 1985; Sadler and Link, 1996). Link et al. (2002) characterized and interpreted detrital zircon populations from two coarse-grained samples within the Lower to Upper Glenns Ferry Formation. Grain populations (n = 74; Fig. 6F) present in these Pliocene sediments are: (1) Miocene to Pliocene (17–4 Ma; 23 grains; 32%); (2) early to middle Eocene (52–42 Ma; 9 grains; 12%); (3) Cretaceous (110–62 Ma; 20 grains; 27%); (4) Ordovician–Devonian (455, 405 Ma; 2 grains); and (5) assorted Proterozoic (2700–1000 Ma; 16 grains; 21%).

The presence of recycled Proterozoic grains indicates that the Cordilleran orogenic belt was a source region for the Glenns Ferry Formation, which is consistent with modern observations of such grains in stream deposits of the Big Wood, Raft, and Portneuf Rivers. Early to middle Eocene detrital zircons allowed Link et al. (2002) to infer that the Lower to Upper Glenns Ferry Formation was fed by sources north of the Snake River Plain. The association of Eocene, Cretaceous, Ordovician, and Proterozoic detrital zircons in the Glenns Ferry Formation compares well with the modern Wood River system of south-central Idaho. No middle to late Eocene or Middle Jurassic detrital zircons from nearby northern Nevada (Salmon Falls Creek) are present, suggesting that the region was not draining north to the Snake River Plain in the early Pliocene.

Pliocene Uppermost Glenns Ferry Formation and Tuana Gravel

Uppermost Pliocene sedimentary units near Hagerman, Idaho, are silt and mud floodplain deposits encasing fluvial sands of the Glenns Ferry Formation (Middleton et al., 1985; Link et al., 2002). Unconformably overlying the uppermost Glenns Ferry Formation (ca. 3.3 Ma) is the Tuana Gravel (ca. 2.5 Ma), which records several cut and fill sequences that document the progressive lowering of base level, as the outlet of Lake Idaho lowered by erosion at Hells Canyon and the western Snake River Plain changed from an underfilled to overfilled basin (Sadler and Link, 1996; Wood and Clemens, 2002). The Tuana Gravel, interpreted to represent several cycles of progradation rather than one catastrophic event, contains rhyolite, basalt, granite, chert, argillite, and micaceous quartzite clasts (Sadler and Link, 1996; Link et al., 2002).

Link et al. (2002) interpreted the detrital zircon signatures within coarse-grained sediments of the uppermost Glenns Ferry Formation and the overlying Tuana Gravel. These data are used in concert with a new coarse-grained, 60-grain sample of tuffaceous Pliocene strata west of Hagerman near Oreana, Idaho. Detrital zircon populations (n = 147; Fig. 6G) are complex and major populations are: (1) Pliocene (ca. 4.0–2.5 Ma; 10 grains; 7%); (2) Miocene (ca. 15.0–6.0 Ma; 23 grains; 15%); (3) Oligocene (ca. 33.0–27.0 Ma; 2 grains); (4) early to middle Eocene (52–43 Ma; 33 grains; 22%); (5) Cretaceous (mainly 100–75 Ma; 30 grains; 20%); (6) Middle Jurassic (mainly ca. 165–155 Ma; 6 grains; 4%); (7) Cambrian to Mississippian (ca. 515–335 Ma; 4 grains; 2%); and (8) assorted Archean and Proterozoic (2700–685 Ma; 39 grains; 26%). Detrital zircon populations in late Pliocene sedimentary deposits near Hagerman contribute two salient findings (Link et al., 2002). First, these units record the earliest presence of Middle Jurassic grains from northern Nevada on the central Snake River Plain, suggesting a major change in stream pattern since the early Pliocene. Second, the late Pliocene sedimentary deposits of the Hagerman area record a signature similar to that of the modern longitudinal drainage system, confirming that an integrated Snake River was captured by the Columbia River system by this time. Early Oligocene detrital zircons, distinctly younger than northern Nevada volcanics, are interpreted to be sourced from the Almo pluton of the Albion metamorphic core complex, which also suggests northward drainage from the southern Idaho–northern Nevada border region.

NEOGENE DRAINAGE RECONSTRUCTIONS

The presence and absence of detrital zircons within deposits of the western Snake River Plain region allow us to confirm that both modern streams and Neogene sedimentary units reliably record age populations of their source rock. Therefore, we propose four paleogeographic drainage maps (Figs. 7–10) to summarize the middle Miocene to late Pliocene drainage evolution of the Snake River Plain region with respect to the passage of the Yellowstone hot-spot. These diagrams are modified from Link et al. (1999b) and were produced at the U.S. Department of Agriculture Forest Service Geographic Information Systems (GIS) Center of Excellence in Ogden, Utah, using ESRI ArcInfo 7.1.2 software and Defense Mapping Agency 1:100,000 scale digital elevation data.

Middle Miocene (15 Ma)

Middle Miocene (15 Ma) drainage patterns for the western Snake River Plain region in this study are constrained by the Sucker Creek Formation (SC) in the northern reaches of the north-trending Oregon–Idaho graben (Fig. 7). Although only one sample from this time slice exists, our interpretation relies on the presence of early to middle Eocene detrital zircons that are unique to the Challis Volcanic Group of central Idaho. The Sucker Creek Formation also contains Miocene (18–15 Ma) input that could be extrabasinal (McDermitt volcanic field) or intrabasinal (Oregon-Idaho graben), since those ages are observed in both settings. Cretaceous Silver City pluton (modern Reynolds Creek) ages overlap with the Atlanta lobe (modern Boise River) and may be supplying detritus to the northern Oregon–Idaho graben via short, northeast-flowing streams. However, the regional drainage was southwest from the Atlanta lobe and Challis magmatic rocks north of the Snake River Plain. The appearance of scarce Permian and Triassic detrital zircons in the Sucker Creek Formation and modern Boise River, and absence in Reynolds Creek and the Poison Creek Formation, is interesting but not definitive. It appears likely that these grains are being recycled through Cretaceous granite north of the Snake River Plain, the magmas of which sampled accreted island-arc assemblages.
Figure 7. Middle Miocene (15 Ma) drainage reconstruction. AL—Atlanta lobe of Idaho batholith; CVG—Challis Volcanic Group; M—McDermitt volcanic field; OIG—Oregon-Idaho graben; SC—Sucker Creek Formation detrital zircon sample. White arrows—drainage from rocks of the Yellowstone hotspot; black arrows—drainage from Cretaceous and early to middle Eocene rocks of the Cordilleran magmatic belt; gray striped arrows—drainage from central Idaho and Idaho-Wyoming thrust belts. Map was modified from Link et al. (1999b).

Figure 8. Late Miocene (9 Ma) drainage reconstruction. AL—Atlanta lobe of Idaho batholith; B-J—Bruneau-Jarbidge volcanic field; CVG—Challis Volcanic Group; M—McDermitt volcanic field; OIG—Oregon-Idaho graben; O-H—Owyhee-Humboldt volcanic field; PC—Poison Creek Formation detrital zircon sample; TR—Table Rock Sandstone detrital zircon sample; WSRP—western Snake River Plain. White arrows—drainage from rocks of the Yellowstone hotspot; black arrows—drainage from Cretaceous and early to middle Eocene rocks of the Cordilleran magmatic belt; gray striped arrows—drainage from central Idaho and Idaho-Wyoming thrust belts. Map was modified from Link et al. (1999b).
Landscape evolution of the western Snake River Plain region

Figure 9. Early Pliocene (4 Ma) drainage reconstruction. AL—Atlanta lobe of Idaho batholith; CVG—Challis Volcanic Group; GF—Lower to Upper Glenns Ferry Formation; IG—Middle Idaho Group rocks near Adrian, Oregon; TS—Upper Terteling Springs Formation. White arrows—drainage from rocks of the Yellowstone hotspot; black arrows—drainage from Cretaceous and early to middle Eocene rocks of the Cordilleran magmatic belt; gray striped arrows—drainage from central Idaho and Idaho-Wyoming thrust belts. Map was modified from Link et al. (1999b).

Figure 10. Late Pliocene (2 Ma) drainage reconstruction. GF—Uppermost Glenns Ferry Formation and Tuana Gravel at Hagerman, Idaho; GO—late Pliocene sediment near Oreana, Idaho. White arrows—drainage from rocks of the Yellowstone hotspot; black arrows—drainage from Cretaceous and early to middle Eocene rocks of the Cordilleran magmatic belt; gray striped arrows—drainage from central Idaho and Idaho-Wyoming thrust belts; white arrows with snake fill—main Snake River drainage to Pacific Ocean. Map was modified from Link et al. (1999b).
like the Wallowa terrane. The absence of geographically proximal middle to late Eocene (42–35 Ma) and Middle Jurassic (ca. 160 Ma) grains observed in northern Nevada suggests that the region was not draining into the Oregon-Idaho graben during the middle Miocene.

We propose that streams draining those source rocks were traveling south-southeastward, away from the northeast-trending upland and the drainage divide created by the McDermitt eruptive center.

It is unlikely that middle to late Eocene and Middle Jurassic source rocks in northern Nevada were sufficiently covered by Miocene volcanic eruptions to hinder their erosion into regional drainage systems. Modern streams draining the late Pliocene to Pleistocene Huckleberry Ridge, Mesa Falls, and Lava Creek eruptions of the Yellowstone Plateau contain complex detrital zircon populations that still produce visible Proterozoic and younger signatures through the volcanic ‘noise’ (Link et al., 2005).

Northwest-directed palaeocurrent determinations by Cummings et al. (2000) in middle Miocene rocks within the southern Oregon–Idaho graben suggest that sediment was shed from the Owyhee Mountains on the northwestern flank of the McDermitt volcanic field. Further sampling of the Oregon-Idaho graben will constrain middle Miocene paleodrainage patterns.

Recycled Proterozoic and Archean detrital zircons from the Cordilleran thrust belt are not present in the Sucker Creek Formation. We suggest that their absence reflects the presence of a regional continental divide in central Idaho, oriented perpendicular to thrust belt vergence, west of the central Idaho thrust belt (Wood River system) and within the Atlantic lobe. In addition to detrital zircon information, our evidence is based on the absence of rocks that are age-equivalent to the Sucker Creek Formation on the Snake River Plain. Thus, no accommodation space had been created because the initiation of subsidence on the western Snake River Plain did not occur for another 4 million years.

The central and southeast Idaho thrust belts at this time, therefore, drained eastward, away from the relative highland of the Idaho batholith into southwestern Montana (cf. Fritz and Sears, 1993; Sears and Ryan, 2003) and southeast toward the Atlantic Ocean via the paleo–Green River system (Ore, 1999).

**Late Miocene (9 Ma)**

The Late Miocene (9 Ma) paleodrainage model of Figure 8 is constrained by detrital zircon samples from the Poison Creek Formation (PC) and Table Rock Sandstone (TR). Superimposed on the 9 Ma time slice is the northwest-trending western Snake River Plain, which cuts across the older, now tectonically quiescent, north-trending Oregon-Idaho graben.

The Poison Creek Formation, which lacks early to middle Eocene grains of the Challis Volcanic Group and contains Miocene hotspot and Cretaceous detrital zircons, has a provenance south of the Snake River Plain but north of northern Nevada. The lack of middle to late Eocene and Middle Jurassic detrital zircons suggests a topographic highland acted as a drainage divide, not allowing those age populations to reach the western Snake River Plain from northern Nevada. Nine million years ago, the active Twin Falls volcanic center overprinted the previous continental divide in the Atlanta lobe and manifested itself as a thermally inflated bulge, dispersing radial drainage patterns. At this time, the McDermitt, Owyhee-Humboldt, and Bruneau-Jarbidge volcanic fields in the wake of the hotspot were still tunnusmes, acting as a drainage divide separating Nevada and Idaho.

On the northern margin of the western Snake River Plain, the Table Rock Sandstone contains early to middle Eocene (52–45 Ma), Cretaceous (115–65 Ma), Neoproterozoic (ca. 670 Ma), and Archean (ca. 2500 Ma) ages that are also present in the modern Boise River. Therefore, the Table Rock Sandstone is inferred to have a provenance north of the Snake River Plain, with the majority of grains having been recycled from the Atlanta lobe and Challis Volcanic Group.

Both the Poison Creek Formation and Table Rock Sandstone lack multiply-recycled Proterozoic and Archean detrital zircons of the central Idaho or Idaho-Wyoming thrust belt. There are no known late Miocene deposits observed on the Snake River Plain that are believed to have been sourced from the Cordilleran thrust belt. However, Fritz and Sears (1993) and Sears and Ryan (2003) documented the presence of distinctive Devonian Milligen Formation (western assemblage, Antler allochthon; Wood River system) quartz-veined chert and Mesoproterozoic Swauger Quartzite (Big Lost River region, central Idaho thrust belt) clasts in middle to late Miocene sands of southwestern Montana, demonstrating northeastward drainage from central Idaho. Based on this evidence, Figure 8 shows the late Miocene continental divide as the Twin Falls volcanic field, the bulge of which pushed central Idaho thrust belt streams to the north and east. Drainage of the Idaho-Wyoming thrust belt was southeast toward Wyoming and also into the developing Bonneville basin of northern Utah, where subsidence was ultimately controlled by movement on the Wasatch fault.

**Early Pliocene (4 Ma)**

Early Pliocene (4 Ma) drainage patterns (Fig. 9) in the western Snake River Plain are based on detrital zircon data from Middle Idaho Group (ca. 7 Ma) sediments of Oregon, Upper Terteling Springs Formation (6 Ma) near Boise, and Lower to Upper Glenns Ferry Formation at Hagerman (4 Ma). Middle Idaho Group sediments south of Adrian, Oregon, contain middle Eocene (42–38 Ma) detrital zircons interpreted to have been derived from north-central Nevada. Detrital zircons of this age are not observed in deposits of the western Snake River Plain before this time. We propose that the presence of these grains records capture of the paleo–Owyhee River and its headwaters in north-central Nevada by headward erosion seven million years ago. The southward-cutting paleo–Owyhee River generated a northeast-trending drainage divide that migrated southeast. The capture of drainage of north-central Nevada by the western Snake River Plain in the Owyhee Plateau region is not interpreted to have been caused directly by detumescence or thermal deflation in the wake of the Yellowstone hotspot because the Owyhee Plateau is still a relative topographic high that has not undergone significant surface subsidence. It is likely that the lowering base level, controlled by the subsidence of the western Snake River Plain, was the ultimate cause of this stream capture. On the northern margin of the western Snake River Plain, the Upper Terteling Springs Formation, northwest of Boise, Idaho, contains a simple set of Cretaceous and early to middle Eocene detrital zircon age populations consistent with derivation from rocks north of the Snake River Plain.

Detrital zircon data from all middle to late Miocene (15–7 Ma) strata suggest that before 7 Ma the Cordilleran thrust belt was not draining onto the western Snake River Plain. The two sedimentary units of the Middle Idaho Group that record the ca. 7 Ma drainage capture of north-central Nevada contain only two Proterozoic (1175 and 1520 Ma) detrital zircons out of a total of 90 grains analyzed. These detrital zircons do not form a significant grouping. Modern streams draining zircon-rich magmatic rocks in eastern Idaho contain persistent small populations of recycled Proterozoic detrital zircons from the regional thrust belt (Link et al., 2005).

The Pliocene (4 Ma) Lower to Upper Glenns Ferry Formation contains detrital zircon populations that mimic the modern Wood River system, suggesting derivation from rocks north of the Snake River Plain. Early to middle Eocene (52–42 Ma), Cretaceous (111–62 Ma), early Paleozoic (455, 405 Ma), and Proterozoic (1300–1000, 1800–1600 Ma) detrital zircons
demonstrate that the Lower to Upper Glenns Ferry Formation drained both the Cordilleran magmatic belt and Cordilleran thrust belt. These data suggest that by 4 Ma, the subsiding Snake River Plain captured drainage from the central Idaho thrust belt, when it had reversed its course from southwest Montana to the central Snake River Plain. Middle to late Eocene (42–35 Ma) and Middle Jurassic (ca. 160 Ma) grains from northern Nevada are absent in the Lower to Upper Glenns Ferry Formation (Link et al., 2002).

Late Pliocene (2 Ma)

The late Pliocene (2 Ma) drainage reconstruction (Fig. 10) is generated from detrital zircon data of the uppermost Glenns Ferry Formation, Tuana Gravel, and sediment of Tuana Gravel age west of Hagerman. The late Pliocene strata contain late Eocene to early Oligocene (ca. 33–27 Ma), early to middle Eocene (52–42 Ma), Cretaceous (mainly 100–75 Ma), Jurassic (ca. 160 Ma), and Proterozoic detrital zircons, the presence of which could only be generated by mixing rocks of the Cordilleran magmatic belt north and south of the Snake River Plain. The occurrence of Jurassic detrital zircons, only sourced from rocks in northern Nevada, records capture of a paleo–Salmon Falls Creek by 3 Ma. By this time, the central Snake River Plain of southernmost Idaho underwent surface subsidence by detumescence, allowing the once south-flowing streams in northern Nevada to travel northward (Link et al., 2002). As the Lower to Upper Glenns Ferry Formation is interpreted to be a deposit of the paleo–Wood River system, it is predictable that the uppermost Glenns Ferry would contain a detrital zircon signature that mixes central Idaho with the new northern Nevada (Salmon Falls Creek) sediment influx.

By the late Pliocene (ca. 2.5 Ma), the ancient Snake River was captured by the Columbia River system and became the longitudinal drainage system for the Snake River Plain region (Sadler and Link, 1996; Wood and Clemens, 2002). Detrital zircon age populations from the Tuana Gravel support this model; the Tuana Gravel contains an integrated central Idaho–northern Nevada signature, similar to that which we observe today in the modern main Snake River.

The timing of drainage capture for Basin and Range streams in the eastern Snake River Plain is unclear because there are no region- or age-specific detrital zircon populations in southeast Idaho or northeast Utah to indicate capture of the headwaters of the Portneuf River. Recent regional syntheses (Link et al., 1999b; Ore, 1999; Osier, 2004) suggest that the Portneuf River had northward flow around 2.5 Ma, coincident with the capture of the Snake River into the Columbia River system and downwarping of the eastern Snake River Plain.

PRESENT CONSIDERATIONS AND FUTURE WORK

We acknowledge that the comparison of detrital zircon age populations from fine- to coarse-grained sedimentary deposits may have some statistical limitations. However, “grain masking” of age populations crucial to this study is unlikely. Proterozoic detrital zircons derived from the Cordilleran thrust belt have been documented in a range of grain sizes in Idaho and along the Cordilleran margin. Eocene and Oligocene detrital zircons from north and south of the Snake River Plain are observed in this study to be present in both fine- and coarse-grained siliciclastic sedimentary units. Still, we recognize this limitation and have built it into our interpretations of the western Snake River Plain region.

This study only analyzed, and was limited to, surface exposures of Miocene to Holocene sediments of the Snake River Plain and surrounding regions. Future investigation into the detrital zircon signature of this region should incorporate the analysis of sedimentary units in the subsurface. Detrital zircon data from Snake River Plain drill cores may determine, for example, if an axial drainage system was ever present in the western Snake River Plain or the location of middle to late Miocene streams draining the central Idaho thrust belt. Additional provenance studies in this region could investigate the detrital zircon age populations in the southern Oregon–Idaho graben and modern Owyhee River to better constrain middle Miocene paleodrainage directions.

CONCLUSIONS

The detrital zircon provenance record described in this study for the western Snake River Plain region effectively reproduces the geochronology of central and western Idaho, like its counterpart in the east by Link et al. (2005), and supports an interpretation that the Yellowstone hotspot existed as a continental divide for nearly 17 million years. Our hypothesis concerning the fidelity of detrital zircon age populations in relation to modern source rock in Holocene stream sediments is substantiated. This framework allows us to determine the provenance of Neogene sedimentary rocks because they were derived from the same source rocks as Holocene streams.

Our findings indicate that middle to late Miocene (15–7 Ma) volcanic highlands created by the Yellowstone hotspot formed a northeast-trending drainage divide between northern Nevada and adjacent rift basins to the northwest. Therefore, sedimentary deposits in the northern Oregon–Idaho graben and western Snake River Plain mainly contain early to middle Eocene and Cretaceous detrital zircons sourced from rocks of the Cordilleran magmatic belt north of the Snake River Plain.

Two late Miocene (7 Ma) sedimentary units of the western Snake River Plain along the Oregon–Idaho border contain middle to late Eocene (42–35 Ma) detrital zircons derived from source rocks in north-central Nevada. We infer that drainage capture of the paleo–Owyhee River explains this introduction of detrital zircons. Southeastward headward erosion into the high Owyhee Plateau captured streams in north-central Nevada and established a progressively southeast-migrating drainage divide.

The first appearance of Precambrian detrital zircons from Proterozoic and younger sedimentary rocks of the Cordilleran margin (central Idaho and Idaho–Wyoming thrust belts) occurs in sedimentary units of the central Snake River Plain region around 4 Ma, within the Pliocene Glenns Ferry Formation. This provenance change is interpreted to record the paleo–Wood River system being captured by the subsiding central Snake River Plain at this time. Previously, the paleo–Wood River system drained northeastward into southwestern Montana during the late to middle Miocene. Before this time, no rocks of the Cordilleran thrust belt supplied sediment to the Snake River Plain, suggesting interplay between a pre-existing continental divide orthogonal to thrust convergence in central Idaho and the thermally inflated Yellowstone hotspot. After deflation of the hotspot wake, a new base level was established and streams flowed into the central Snake River Plain. Capture of northern Nevada streams into the Hagerman area of the central Snake River Plain occurred by 3 Ma, as indicated by the presence of Middle Jurassic detrital zircons within the uppermost Glenns Ferry Formation and Tuana Gravel.

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