5-2009

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THE SHEEP PASS FORMATION, A RECORD OF LATE CRETACEOUS AND PALEOGENE EXTENSION WITHIN THE SEVIER HINTERLAND, EAST-CENTRAL NEVADA

by

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2003

A dissertation submitted in partial fulfillment
of the requirements for the

Doctor of Philosophy Degree in Geoscience
Department of Geoscience
College of Sciences

Graduate College
University of Nevada, Las Vegas
May 2009

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

Dissertation Approval
The Graduate College
University of Nevada, Las Vegas

March 2, 2009

The Dissertation prepared by

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Entitled

THE SHEEP PASS FORMATION, A RECORD OF LATE CRETACEOUS AND PALEOGENE EXTENSION WITHIN THE SEVIER HINTERLAND, EAST-CENTRAL NEVADA

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy Degree in Geoscience

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ABSTRACT

The Sheep Pass Formation, a record of Late Cretaceous and Paleogene extension within the Sevier hinterland, east-central Nevada

by

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The Sevier hinterland of western North America is considered by many to be an ancient proxy for the modern Andean Puna-Altiplano or Tibetan Plateau. However, controversies exist as tectonic setting and overall paleogeography of the Sevier hinterland during the Late Cretaceous and Paleogene. The Sheep Pass Formation type section within the southern Egan Range of east-central Nevada comprises a > 1 km thick sedimentary succession spanning the latest Cretaceous to Eocene, and provides a rare opportunity to test prevailing tectonic and paleogeographic models for the Sevier hinterland. New 1:12,000 scale field mapping in the southern Egan Range indicates that up to three km of stratigraphic throw occurred along the Ninemile fault, a presently low-angle down-to-the-northwest normal fault, during deposition of the Sheep Pass Formation type section. Subsequent reactivation of the Ninemile fault produced an additional ~1 km of stratigraphic throw during deposition of the Garrett Ranch Group, which unconformably overlies the Sheep Pass Formation type section. New U-Pb and (U-Th)/He detrital zircon dating and U-Pb carbonate age analyses from the Sheep Pass Formation type section indicate that the Ninemile fault system was active in latest Cretaceous time, and documents for the first time the presence of surface-breaking, synconvergent normal faults within the Sevier hinterland. New U-Pb detrital zircon and $^{40}Ar/^{39}Ar$ age analyses from the overlying Garrett Ranch Group document reactivation of the Ninemile fault in the middle to late Eocene, indicating that two discrete episodes of extension affected the Sevier hinterland. Movement along the Ninemile fault was coeval with Late Cretaceous and early Paleogene mid-crustal extension within the Sevier hinterland, and suggests a possible link. Middle to late Eocene extension was coeval with extension in the Sevier foreland of central Utah, and foundering of the Farallon slab. Evidence that extension significantly predated volcanism within the Sevier hinterland invalidates the theory that Paleogene volcanism drove coeval extension. Recognition of synconvergent extensional basins within the Sevier hinterland strengthens comparisons to the modern Puna-Altiplano and Tibetan plateau, where similar processes have been documented.

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ACKNOWLEDGEMENTS

I would like to thank the members of my committee, Drs. Andrew Hanson, Michael Wells, Steve Rowland, Wanda Taylor, and Peter Starkweather for their support, guidance and assistance during these past years. In particular, Drs. Hanson and Wells assistance in field work were much appreciated, and their assistance with obtaining NSF support for this project was a huge factor in its success. I thoroughly enjoyed and benefitted from Dr. Hanson teaching his 2007 Field 3 class within Sheep Pass Canyon and Ninemile Canyon. I would also like to thank a large number of co-authors and colleagues who contributed their time, insight, ideas and expertise toward fulfilling the vision of my dissertation project, and whose efforts have vastly improved its scope and quality. George Gehrels and Victor Valencia provided critical assistance with U-Pb detrital zircon dating, data reduction and interpretation, and Danny Stöckli provided his laboratory facilities, time and expertise toward additional (U-Th)/He detrital zircon dating. Troy Rasbury's laboratory facilities, oversight in separation techniques, and donation of mass-spectrometer time made U-Pb carbonate dating of the Sheep Pass Formation possible. Troy also graciously provided her guest room and meals to me during my stay at Stony Brook University. Terry Spell and Kathleen Zanetti screened samples for $^{40}Ar/^{39}Ar$ dating, and provided assistance with mineral separation and data interpretation. Allen McGrew, Jim Schmitt, Tina Niemi, Allan Wallace, Jim Trexler, Tim Lawton, and Kate Giles provided critical reviews of dissertation chapters, grant proposals, and other related materials.

Many additional friends and colleagues graciously donated their time and sweat in the field to keep me sane after many days in the remote Egan Range and other forgotten corners of east-central Nevada. Carrie Druschke, Lael Vetter, Tom Muntean, James MacDonald, Scott MacDonald, Josh Bonde, Kathryn Snell, Susan Potts, Aubrey Shirk and Dick Hilton all at one time or another shared in long, steep hikes and campfire conversations. I thank my wife Carrie for her unwavering support over long summers of field work and long years of graduate study, and always providing a lifeline to the outside world just a phone call away from a dusty phonebooth in east-central Nevada. I thank Neil Marchington and Pete Dronkers of Ely for providing hospitality, and occasionally some much needed diversion from many days of isolated field work. I also thank Friends of Nevada Wilderness, Nevada Wilderness Project, the White Pine County Commission, Nevada BLM, Senator Harry Reid and Neil Kornze for their work in designating the South Egan Range Wilderness in 2006, and protecting the amazing scenery, isolation, wildlife and scientific resources of the southern Egan Range for future generations.

This study was supported by the National Science Foundation under EAR—0610103 (Hanson and Wells). EAR—0443387 and EAR—0732436 (Gehrels) provided support for U-Pb detrital zircon dating at the Arizona LaserChron Center, EAR—0414817 (Stöckli) provided support for the University of Kansas (U-Th)/He Laboratory, and EAR—044715 (Rasbury) provided support for U-Pb carbonate dating at Stony Brook University. Additional support was provided by student grants from the Nevada Petroleum Society (2004-2006), the Geological Society of America Wanek Fund Grant, Rocky Mountain Section SEPM Donald L. Smith Grants (2005 and 2006), and AAPG Grants-in-Aid Funkhauser Memorial Grant (2005 and 2006), the UNLV Graduate College GREAT

Assistantship (2005 and 2006), the Bernada French UNLV Geoscience Scholarship (2003-2006) and the UNLV Graduate and Professional Student Association Grants (2004 and 2005).

CHAPTER 1

DISSERTATION OVERVIEW

The Jurassic to Eocene Sevier orogen of western North America is considered the archetypical example of an ancient noncollisional orogenic belt (DeCelles, 2004), and is considered by many as an ancient proxy for the modern Andean Puna-Altiplano orogenic plateau (Coney and Harms, 1984; Jordan and Alonso, 1987; Jones et al., 1998; House et al., 2001; DeCelles, 2004). While numerous studies that have characterized the combined structural and stratigraphic history of the Sevier foreland (e.g. DeCelles, 1994; DeCelles et al., 1995; DeCelles and Currie, 1996; DeCelles, 2004, Horton et al., 2004a), controversies exist concerning the paleogeography and tectonic setting of the Sevier hinterland. The Sheep Pass Formation type section within the southern Egan Range of east central Nevada comprises a > 1 km thick succession of alluvial, fluvial and lacustrine strata spanning the latest Cretaceous to Eocene (Fouch et al., 1979; Good, 1987), and comprises one of the thickest and most complete sedimentary sections in the Sevier hinterland. This study tests current models for the tectonic setting and paleogeography of the latest Cretaceous to Paleogene Sevier hinterland through 1:12,000 scale field mapping of the Sheep Pass Formation type section combined with stratigraphic, geochronologic and structural analyses, and comparisons with additional sections of the Sheep Pass Formation widely scattered throughout east-central Nevada.

Chapter 1 presents evidence for an extensional basin setting for the Sheep Pass Formation type section through documentation of a series of syndepositional normal faults within the basal Member A that are overlapped by younger members of the Sheep Pass Formation. In addition, the Ninemile fault, a presently low-angle, down-to-the-northwest normal fault exposed 3-5 km to the south and west of the Sheep Pass Formation type section is newly interpreted to represent the basin-bounding fault for the Sheep Pass basin. New U-Pb detrital zircon ages from the uppermost Sheep Pass Formation Member A in combination with a new U-Pb carbonate age from overlying Member B indicate a Maastrichtian age for the basal Sheep Pass Formation type section. Detrital zircon (U-Th)/He dating indicates an 81.3 ± 3.7 Ma cooling age population is present despite the lack of a corresponding Campanian U-Pb detrital zircon crystallization age population, and suggests that up to 6 km of unroofing occurred within the Sevier hinterland between 80-70 Ma. These new data represent the first published absolute age control for the Sheep Pass Formation, and provide the strongest evidence to date for the presence of Late Cretaceous surface-breaking normal faults within the Sevier hinterland.

Chapter 1 comprises a manuscript submitted to the journal *Geology*, which was accepted for May 2009 publication. Fieldwork and interpretations concerning the nature of the Ninemile fault were assisted Dr. Andrew Hanson and Dr. Michael Wells. U-Pb carbonate age analyses presented in this chapter were performed under the guidance of Dr. Troy Rasbury of Stony Brook University. (U-Th)/He zircon age analyses were performed under the guidance of Dr. Daniel Stöckli at the University of Kansas. U-Pb detrital zircon age analyses were performed under the guidance of Dr. George Gehrels at the University of Arizona. Each contributor appears as a co-author for the corresponding *Geology* submission.

Chapter 2 focuses on the U-Pb and (U-Th)/He detrital zircon provenance history of Cretaceous to Eocene sedimentary units within the Sevier hinterland, including the Early Cretaceous Newark Canyon Formation, the latest Cretaceous to Eocene Sheep Pass Formation type sections, and additional sections of middle to late Eocene strata located throughout east-central Nevada previously correlated to the Sheep Pass Formation by Fouch (1979). Over 1,300 detrital zircon analyses are used to test paleogeographic models for the Sevier hinterland, and to link changes in detrital zircon provenance to regional tectonic events. Results indicate that Precambrian zircon populations are dominant within the Newark Canyon and Sheep Pass Formation type sections prior to the ca. 38-35 Ma onset of volcanism locally, reflecting recycling of primarily upper Paleozoic strata originally derived from the Robert's Mountain allochthon. Subordinate Late Jurassic and Early Cretaceous populations were derived from hinterland magmatic centers, and populations of Triassic, Early to Middle Jurassic, and Late Cretaceous populations common in the Sierra Nevada magmatic arc and terranes of western Nevada (Evernden and Kistler, 1970; Stern et al., 1981; Bateman, 1983; Manuszak et al., 2000; Spurlin et al., 2000; DeGraaf-Surpless et al., 2002) are absent. These results indicate that the Sevier hinterland was paleogeographically isolated through high elevation, formation of the central Nevada fold and thrust belt to the west in Early Cretaceous time, and subsequent development of Late Cretaceous to early Paleogene extensional basins.

Chapter 2 comprises a manuscript submitted to the journal *Geological Society of America Bulletin*, which is currently in review. Sample collection, zircon separation, and provenance interpretations were assisted Dr. Andrew Hanson and Dr. Michael Wells. U-Pb detrital zircon dating was performed under the guidance of Dr. George Gehrels at the University of Arizona. (U-Th)/He zircon dating was performed under the guidance of Dr. Daniel Stöckli at the University of Kansas. Each contributor appears as a co-author for the corresponding *Geological Society of America Bulletin* submission.

Chapter 3 presents evidence for continued extension within the Sevier hinterland from latest Cretaceous to early Paleogene time, and a subsequent episode of middle to late Eocene extension that overlapped with the local onset of volcanism. Results of 1:12,000 scale mapping in the Sheep Pass Canyon indicate that the Blue Spring fault system, a splay of the Ninemile fault, repeats the Sheep Pass Formation type section but is overlapped by late Eocene members of the Garrett Ranch Group. A comparison to structural and stratigraphic relationships at Shingle Pass in the southern Egan Range reveals a similar history of early Paleogene extension, followed by renewed middle to late Eocene extension. New $^{40}Ar/^{39}Ar$ ages from Eocene volcanic strata of the southern and central Egan Range and Schell Creek Range indicate that deposits of middle to late Eocene age overlapping with the ca. 38-35 Ma initiation of volcanism are separated from earlier deposits of the Sheep Pass Formation type section by a regional unconformity. These data strongly suggest that the latest Cretaceous to Eocene Sevier hinterland experienced two discrete episodes of extension.

Chapter 3 comprises a manuscript submitted to a special Sevier hinterland issue of the journal *International Geology Review*, which is currently in review. Fieldwork and interpretations concerning the structural and stratigraphic history of the southern Egan

Range were assisted by Dr. Andrew Hanson and Dr. Michael Wells, who appear as co-authors for the corresponding journal submission.

Together, the results of this study challenge previous concepts of a high-elevation, low relief Sevier hinterland that experienced either Late Cretaceous to early Paleogene regional shortening or tectonic quiescence (Armstrong, 1968, 1972; Gans and Miller, 1983). New results suggest that the Sevier hinterland formed a high-elevation, paleogeographically isolated plateau that experienced a Late Cretaceous transition from contraction to extension, and that rugged topography and locally high relief formed in response to extension. Latest Cretaceous to early Paleogene extension temporally overlapped with hinterland mid-crustal extension (Wells et al., 1990; Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; McGrew et al., 2000; Harris et al., 2007; Wells and Hoisch, 2008), as well as with continued contraction within the Sevier foreland (DeCelles, 1994; 2004). Synconvergent extension within the Sevier hinterland is similar to processes within the modern Andean Puna-Altiplano and Tibetan Plateau (Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Allmendinger et al., 1997; Kapp et al., 2008), strengthening the hypothesis that the Sevier hinterland is an ancient proxy for an orogenic plateau. In contrast, middle to late Eocene hinterland extension and volcanism coincided with extension within the Sevier foreland (Constenius, 1996), and signals a shift toward orogen-wide extension and orogenic collapse. The observation that extension significantly predated volcanism within the Sevier hinterland invalidates the hypothesis that volcanism was a driver for Eocene extension (Coney and Harms, 1984; Gans et al., 1989; Armstrong and Ward, 1991).

CHAPTER 2

SYNCONVERGENT SURFACE-BREAKING NORMAL FAULTS OF LATE CRETACEOUS AGE WITHIN THE SEVIER HINTERLAND, EAST-CENTRAL NEVADA

Abstract

The hinterland of the Sevier orogenic belt of western North America is widely interpreted as a Cretaceous to Paleogene orogenic plateau. Although evidence for mid-crustal extension of Late Cretaceous age within the Sevier hinterland is widespread, coeval surface-breaking normal fault systems have not been documented. New 1:12,000 scale mapping within the type section of the latest Cretaceous to Eocene Sheep Pass Formation of east-central Nevada suggests that deposition occurred in response to normal fault movement recording up to 4 km of Late Cretaceous and Paleogene stratigraphic throw. Intrabasinal normal faulting caused lateral thickness variations within the basal Sheep Pass Formation, although upper members are largely unaffected. An extensional basin setting best explains the fanning of bedding dips, the deposition of megabreccia and the presence of syndepositional normal faults within the Sheep Pass Formation. Deposition of the basal member of the Sheep Pass Formation is bracketed between ca. 81.3 ± 3.7 Ma and 66.1 ± 5.4 Ma, based on the (U-Th)/He cooling ages of detrital zircons, and on a U-Pb carbonate age derived from the overlying lacustrine limestone

member. These new data provide the strongest evidence to date for the existence of Late Cretaceous, surface-breaking normal faults in the Sevier hinterland. Normal faulting was coeval with mid-crustal hinterland extension and with continued contraction within the Sevier foreland to the east.

Introduction

Synconvergent extension and associated extensional basins are recognized within hinterlands of modern orogens such as the Puna-Altiplano and Tibetan Plateau (e.g., Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Allmendinger et al., 1997). Some workers (e.g., Coney and Harms, 1984; DeCelles, 2004) have speculated that the Late Cretaceous to Paleogene Sevier hinterland of western North America was analogous to the modern Andean Puna-Altiplano. However, surface-breaking synconvergent extensional fault systems were not previously recognized within the Sevier hinterland (Hodges and Walker, 1992). The Late Cretaceous and Paleogene Sevier hinterland has generally been interpreted as a tectonically quiescent, low relief setting (Armstrong, 1972).

Although disagreement persists as to whether the Late Cretaceous hinterland was low-relief and tectonically quiescent, the existence of coeval mid-crustal extension is well established within the Raft River-Albion-Grouse Creek and Ruby-East Humboldt core complexes (Wells et al., 1990, Hodges and Walker, 1992; Camilleri and Chamberlain, 1997). Late Cretaceous extension is interpreted to have resulted in 10–20 km of vertical crustal thinning based on barometry of Barrovian metamorphic mineral assemblages and thermochronometry (Hodges and Walker, 1992; Camilleri and Chamberlain, 1997, Wells and Hoisch, 2008). ^{40}Ar/^{39}Ar cooling ages on barometrically constrained plutons within the Raft River-Albion-Grouse Creek and Ruby-East Humboldt core complexes indicate that mid-crustal extension initiated in the Late Cretaceous (88-84 Ma) and continued during the early Paleogene (Wells et al., 1990; Camilleri and Chamberlain, 1997; McGrew et al., 2000). The lack of evidence for surface-breaking normal faults within the Sevier hinterland led Hodges and Walker (1992) to hypothesize that Late Cretaceous to early Paleogene extension was limited to the mid-crust, while the upper crust was decoupled, allowing it to be tectonically neutral or in compression. Late Cretaceous mid-crustal extension has not been documented in the Snake Range core complex, although Paleocene to middle Eocene (57-50 Ma) ^{40}Ar/^{39}Ar muscovite cooling ages have been reported from the northern Snake Range decollement (Lee and Sutter, 1991).

The distribution of the latest Cretaceous to Eocene Sheep Pass Formation within the Sevier hinterland is currently highly fragmented owing to subsequent extension and erosion (Fig. 1). Nevertheless, the Sheep Pass Formation provides a critical sedimentary record with which to test many models pertaining to the tectonic and paleogeographic evolution of orogenic hinterlands. Vandervoort and Schmitt (1990) previously interpreted a Late Cretaceous transition from contraction to extension in the Sevier hinterland based on sedimentology and biostratigraphy. However, due to the lack of absolute age control or direct evidence for the synextensional nature of these deposits, this interpretation has remained speculative.

Here we present new evidence for syndepositional normal faulting within the basal members of the Sheep Pass Formation type section based on 1:12,000 scale geologic mapping, new LA-ICP-MS U-Pb and (U-Th)/He dating of detrital zircons, and U-Pb carbonate dating. These data demonstrate that sedimentation was related to movement along surface-breaking normal faults, and that upper-crustal extension was coeval with regional mid-crustal extension.

Previous Work

The Sheep Pass Formation

The Sheep Pass Formation is named for exposures of non-tuffaceous alluvial, fluvial and lacustrine strata in east-central Nevada. The type section, at Sheep Pass Canyon in the southern Egan Range, exceeds 1 km in thickness and is divided into six members (A-F) (Winfrey, 1960). The Sheep Pass Formation type section unconformably overlies upper Paleozoic strata, and is unconformably overlain by the volcaniclastic late Eocene to Oligocene Garrett Ranch Group (Winfrey 1960; Kellogg, 1964). Previous age assignments for the Sheep Pass Formation type section are based on invertebrate biostratigraphy and palynology, and suggest a Maastrichtian (ca. 70–65 Ma) to Paleocene age for Member B, and a middle Eocene age (ca. 50.5–45.4 Ma) for Member E (Fouch, 1979; Good, 1987). No biostratigraphic control exists for Member A and no tuffaceous beds have been identified within the Sheep Pass Formation type section.

Winfrey (1960) interpreted an extensional half-graben setting for the Sheep Pass Formation based on westward thinning and fining of members. However, no associated normal faults were identified. Documenting the presence of megabreccia within the Sheep Pass Formation type section, Kellogg (1964) similarly interpreted an extensional basin setting. The initiation of widespread extension within east-central Nevada, as documented by clear evidence of normal faulting and associated volcanism, is generally accepted as late Eocene (ca. 38-35 Ma) (Gans et al., 1989; Axen et al., 1993; Gans et al., 2001).

Revised Age Control

U-Pb and (U-Th)/He Detrital Zircon Dating

LA-ICP-MS U-Pb detrital zircon dating of Member A was performed at the University of Arizona. Results from 167 analyses indicate that Precambrian and Paleozoic zircons reworked from Paleozoic sedimentary rocks dominate the detrital zircon population, with a subordinate Mesozoic component (Fig. 2A) (Appendix I). Peaks at 420 Ma (Silurian) and between 1.4 and 1.8 Ga are typical for local upper Paleozoic strata, and ca. 1.1 Ga peaks have been identified within the Roberts Mountain allochthon of central Nevada (Gehrels et al., 2000). Two zircons of respective 70 and 68 Ma (Maastrichtian) age were analyzed from the uppermost portion of Member A, whereas the youngest detrital zircon population from the middle portion of the member is mid-Cretaceous, ca. 103 Ma, with additional peaks at 108 Ma and 111 Ma (Albian) (Fig.2B).

Nine detrital zircons from the middle portion of Member A were dated by the (U-Th)/He method at the University of Kansas to constrain the exhumation history of the Sheep Pass basin. Four subrounded zircons and five euhedral zircons were selected. Results indicate that a majority of the zircons preserve Permian (U-Th)/He ages defining a broad peak between 320 and 220 Ma (Fig. 2C) (Appendix II). Three euhedral zircons define a Late Cretaceous peak at ca. 81.3 ± 3.7 Ma.

The lack of a corresponding U-Pb age peak suggests that these zircons crystallized prior to the Late Cretaceous and cooled through 180 °C (~6 km burial depth) at 81 Ma.

However, while U-Pb and (U-Th)/He dating was performed on zircons obtained from the same samples, they were not conducted on the same zircons (Reiners et al., 2005). 81 Ma cooling ages may therefore correspond to an unidentified U-Pb age population, although the large number of U-Pb detrital zircon analyses (167) performed does not favor this interpretation. Results from (U-Th)/He dating demonstrate that source areas for the Sheep Pass basin, dominantly upper Paleozoic strata, did not undergo deep stratigraphic or tectonic burial during the Sevier orogeny owing to the preservation of Paleozoic (U-Th)/He zircon cooling ages.

U-Pb Microbial Carbonate Dating

Member B was deposited within a shallow freshwater lake (Fouch, 1979) and contains abundant microbially laminated limestone. Recent studies of lacustrine carbonates have shown that calcite may contain elevated levels of uranium due to complexation with organic matter from sources such as microbial mats, and that U-Pb ages representing depositional ages may be determined by TIMS (Cole et al., 2005).

Phosphor imaging of thick sections from carbonates within Member B indicate radioactivity localized along microbial laminae, consistent with microbially–induced uranium enrichment. A sample from the base of Member B in the type section was analyzed by TIMS at Stony Brook University following the method of Cole et al. (2005). The resulting errorchron age of 66.1 ± 5.4 Ma (MSWD = 34) (Appendix III) corroborates earlier Maastrichtian to Paleocene fossil age assignments (Fouch, 1979; Good, 1987). Given that Member A has produced two zircon ages of 68 ± 1 Ma and 70 ± 1.3 Ma, and that its contact with Member B is gradational, the Sheep Pass basin may have initiated in the Maastrichtian with a significant lag following Campanian (ca. 81 Ma) (U-Th)/He detrital zircon cooling.

New Structural Interpretations

The Ninemile Fault

In Ninemile Canyon, ~3 km south of Sheep Pass Canyon, a presently low-angle normal fault juxtaposes Ordovician strata in its footwall against upper Paleozoic strata in its hanging wall (Fig 3A). Striking NE and dipping 15–25° NW with ~4 km of stratigraphic throw, this normal fault was mapped by Kellogg (1964) as the Ninemile fault. Ordovician carbonates in the footwall within close proximity to the fault are highly sheared and recrystallized, and exhibit extensive calcite veining. A normal, down-to-the-northwest sense of motion is inferred from the younger over older relationship displayed between the respective hanging wall and footwall, in addition to fault surfaces exhibiting Riedel shears consistent with normal fault motion and a NW direction of transport.

Within the hanging wall of the Ninemile fault, the Sheep Pass Formation unconformably overlies upper Paleozoic strata. Where exposed in contact above the Ninemile fault, the Sheep Pass Formation does not display the extensive calcite veining, recrystallization and shearing that is prevalent in footwall strata. Portions of the Sheep Pass Formation are cut by splays of the Ninemile fault; however, stratigraphic offset of the Sheep Pass Formation along the Ninemile fault is less than 1 km, with juxtaposition of lower members against upper members. Stratigraphic offset of Paleozoic strata and the Sheep Pass Formation along the Ninemile fault suggests that up to 3 km of stratigraphic throw occurred in the latest Cretaceous and Paleocene, with later reactivation producing up to 1 km of additional stratigraphic throw.

We interpret the Ninemile fault to be the basin-bounding normal fault for the Sheep Pass basin. Member A within Sheep Pass Canyon contains megabreccia composed of upper Paleozoic lithologies that comprise block-slide deposits extending over 1 km laterally in outcrop (Kellogg, 1964). Member A was deposited as a complex of alluvial fans that thin and fine to the west (Winfrey, 1960; Fouch, 1979), suggesting derivation from highlands to the east. Beds of Member A display dips of 65° to 45° to the east, while the dips of upper members of the Sheep Pass Formation average 35° to the east. This pattern of fanning dips further suggests the presence of a basin-controlling normal fault to the east.

Intra-basinal Faulting and Influence on Stratigraphy

Member A displays significant lateral thickness variations controlled by syndepositional normal faults. Along the main drainage of Sheep Pass Canyon, Member A is ~250 m thick (Winfrey 1960; Fouch, 1979). To the south, Member A thins and fines abruptly across a series of normal faults that display relatively minor offset, and pinches to zero thickness (Fig. 3C). A similar pinch-out occurs across an intrabasinal normal fault in Ninemile Canyon. Here up to 100 m of Member A is preserved in the hanging wall, but in the footwall Member B is deposited on Pennsylvanian Ely Limestone with Member A locally absent (Fig 3A).

Intrabasinal faults south of Sheep Pass Canyon strike largely E/W and dip moderately to steeply north. The syndepositional nature of these faults is evident from the following observations: (1) Member A abruptly thins across the faults, (2) several of the faults cut the lower beds of Member A, but beds of Member B overlap the faults, and (3) boulder-sized clasts and megabreccia common within Member A in Sheep Pass Canyon are absent to the south.

Discussion and Conclusions

Initiation of the Sheep Pass basin and syndepositional normal faulting within its basal member are now bracketed between ca. 81.3 ± 3.7 Ma and 66.1 ± 5.4 Ma based on new (U-Th)/He detrital zircon cooling ages from Member A and a U-Pb carbonate age from the base of the overlying Member B. Megabreccia, fanning of dips, and syndepositional intrabasinal normal faults provide strong evidence that the Sheep Pass Formation was deposited in an extensional basin setting in response to up to 4 km of normal, down-to-the-west stratigraphic throw along the Ninemile fault. These data demonstrate that normal faulting associated with initiation of the Sheep Pass basin was coeval with mid-crustal extension in the Sevier hinterland (Wells et al., 1990; Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; Wells and Hoisch, 2008), challenging earlier models in which Late Cretaceous hinterland extension was inferred to have been confined to the middle crust (Hodges and Walker, 1992).

Structural and stratigraphic evidence from the Sheep Pass Formation challenges low relief interpretations for the Late Cretaceous to early Paleogene Sevier hinterland, at least locally (Armstrong, 1972). Armstrong (1972) concluded that the unconformity separating the Sheep Pass Formation from upper Paleozoic strata was typically <10°, and hypothesized that this relationship was due to low relief at the time of deposition. However, Late Cretaceous and Paleogene deposits found directly above this unconformity are commonly composed of coarse fanglomerates with evidence for mass wasting. These features are associated with significant relief and steep gradients between source areas and basin. New observations suggest that dip discordance between the Sheep Pass Formation and underlying upper Paleozoic strata is highly variable and locally exceeds 40°. While the modern distribution of the Sheep Pass Formation is sparse, this may be due in part to a low preservation potential for high-altitude basins, and to subsequent erosion and fragmentation during extension.

The Late Cretaceous and Paleogene Sevier hinterland is hypothesized to represent an orogenic plateau, broadly analogous to the modern Andean Puna-Altiplano (e.g. Coney and Harms, 1984; DeCelles, 2004). Widely documented examples of synconvergent extension in the Puna-Altiplano and Tibet (Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Allmendinger et al., 1997), and new evidence for synconvergent extensional basins within the Sevier hinterland, strengthen this hypothesis.

Extension in mid-crustal core complexes of the Sevier hinterland closely follows maximum Barrovian metamorphism (ca. 100–85 Ma) representing maximum crustal thickening (Camilleri and Chamberlain, 1997; McGrew et al., 2000; Wells and Hoisch, 2008). Latest Cretaceous and Paleogene extension may therefore have been driven by gravitational potential energy as hinterland crust reached a maximum sustainable thickness and spread laterally toward the lower elevation foreland (Vandervoort and Schmitt, 1990; DeCelles, 2004; Platt, 2007). Initiation of hinterland extension corresponds with the Sierran amagmatic gap and the onset of the Laramide orogeny, suggesting that lithospheric delamination during flat-slab subduction also played an important role in extension (Platt, 2007; Wells and Hoisch, 2008).

While previous workers have interpreted the Sheep Pass Formation as an extensional basin system (Winfrey, 1960; Kellogg, 1964; Vandervoort and Schmitt, 1990), these new data provide the first evidence directly linking the deposition of the Sheep Pass Formation to a surface-breaking extensional fault system of demonstrably Late Cretaceous age. Late Cretaceous megabreccia-containing deposits have also been documented over 100 km to the west (Vandervoort and Schmitt, 1990), suggesting that coeval extensional basin systems were widespread within the Sevier hinterland. Although the magnitude of synconvergent upper crustal extension within the Sevier hinterland is still poorly understood, its occurrence may have played an important role in the early unroofing history of mid-crustal core complexes, and influenced structural patterns during later extension in the Basin and Range Province.

Figure Captions

Figure 1. A: Generalized geologic map of the Sevier orogen in the vicinity of east-central Nevada. LFTB—Luning-Fencemaker thrust belt, CNTB—central Nevada thrust belt, REH—Ruby-East Humboldt core complexes, GRA—Grouse Creek-Raft River-Albion core complex, SR—Snake Range core complex (modified from DeCelles, 2004). Box corresponds to area of Figure 1B. B: Geologic map of the southern Egan Range in the vicinity of Sheep Pass Canyon (modified from Kellogg, 1964). Boxes correspond to area of Figure 3A (Ninemile Canyon) and 3B (Sheep Pass Canyon). K—Cretaceous.

Figure 2. Probability density plots for U-Pb and (U-Th)-He detrital zircon age analyses. A: U-Pb detrital zircon age plot for Member A of the Sheep Pass Formation. B: U-Pb age

plot displaying the Mesozoic age distribution of Member A. C: (U-Th)/He detrital zircon age plot for Member A. Mean age of Cretaceous age peak is 81.3 ± 3.7 Ma.

Figure 3. A: Geologic map of Ninemile Canyon. B: Cross-section from A to A' in Figure 2B. Sheared blebs of the Mississippian Chainman Shale and Scotty Wash Sandstone form discontinuous outcrops along the Ninemile fault. C: Geologic map of Sheep Pass Canyon. Abbreviations: Cretaceous = K, Formation = Fm.

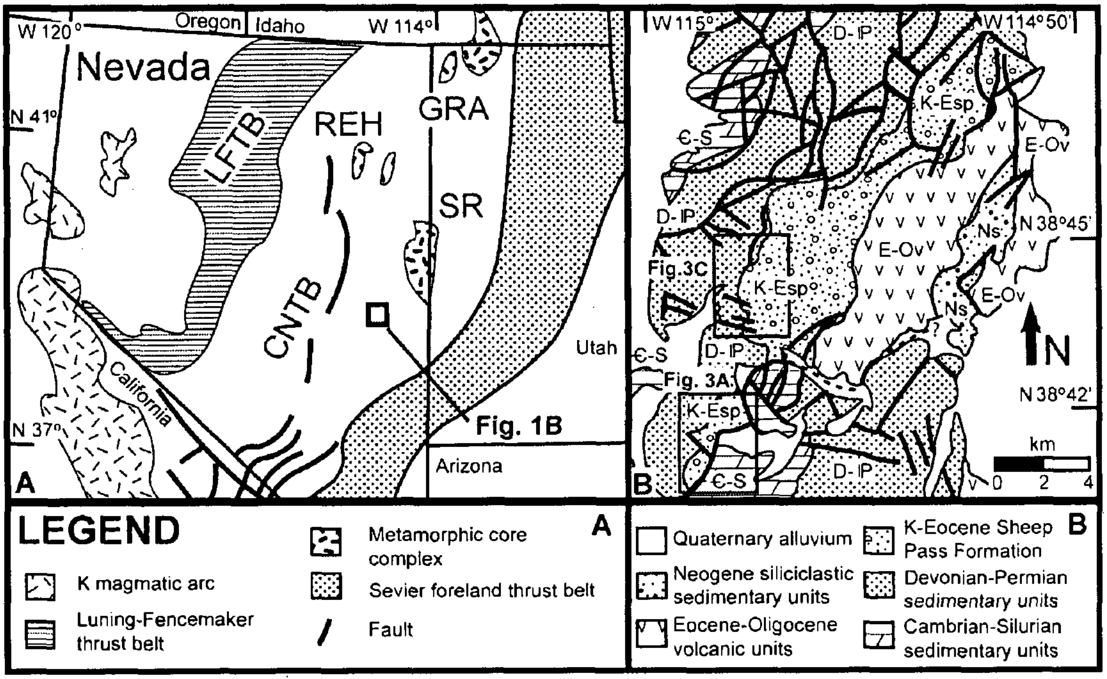


Figure 1.

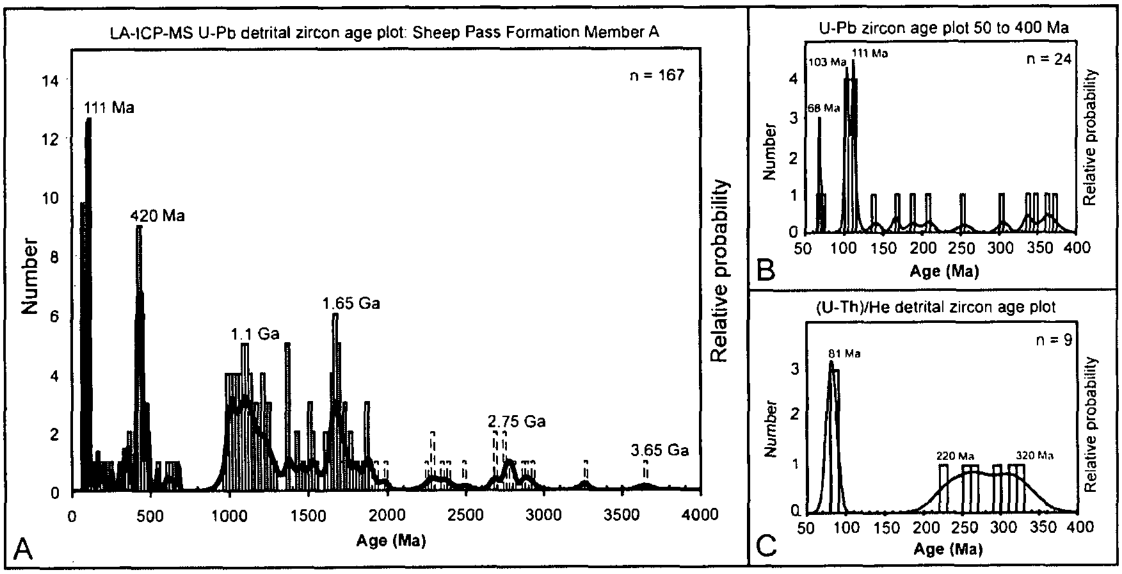


Figure 2.

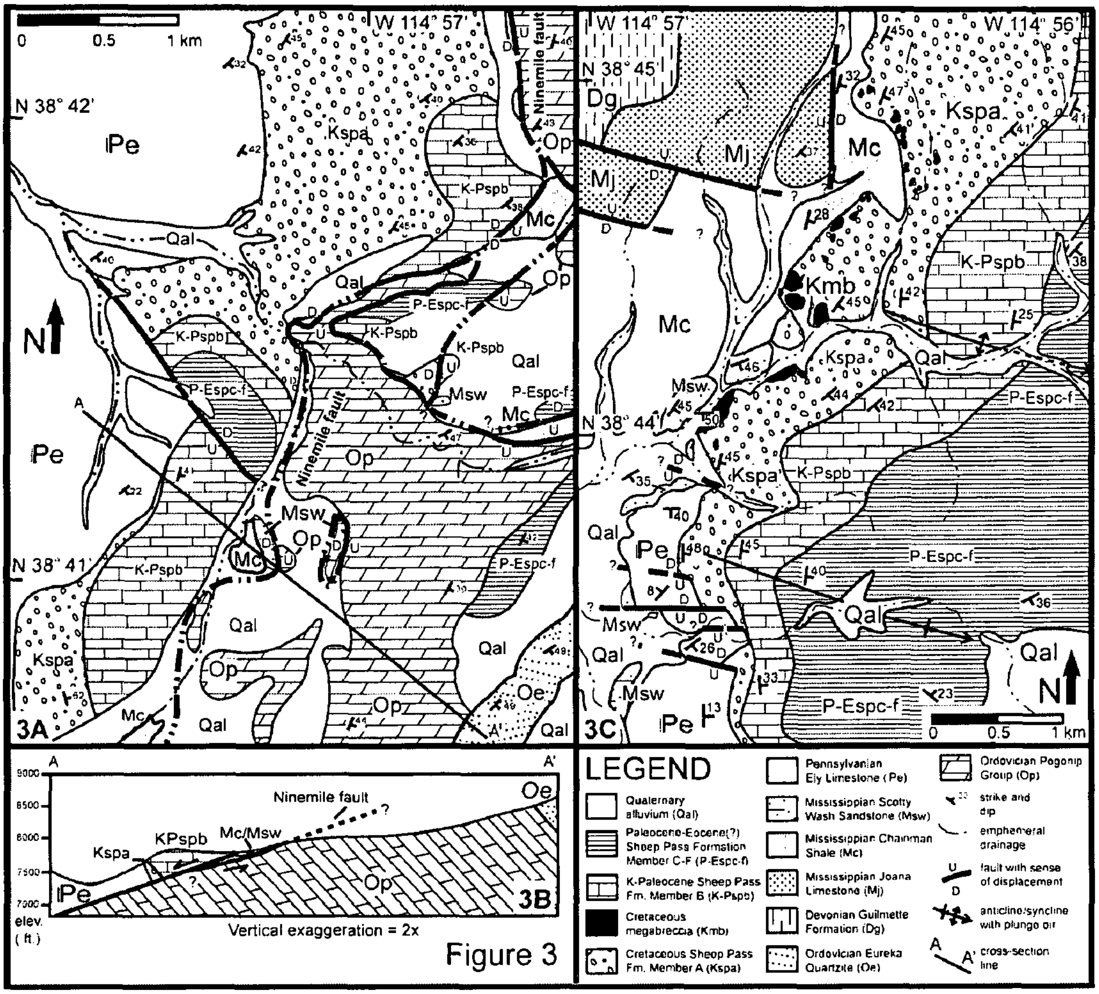

3A
0 0.5 1 km
W 114° 57'
N 38° 42'
N 38° 41'
Ninemile fault
IPe
Kspa
K-Pspb
P-Espc-f
Qal
Mc
Op
Msw
Oe
A
A'
N
3B
Ninemile fault
Kspa
KPspb
Mc/Msw
IPe
Op
Oe
9000
8500
8000
7500
7000
elev. (ft.)
Vertical exaggeration = 2x
Figure 3
3C
W 114° 57'
W 114° 56'
N 38° 45'
N 38° 44'
Dg
Mj
Mc
Kspa
Kmb
K-Pspb
P-Espc-f
Msw
IPe
Qal
0 0.5 1 km
N
LEGEND
Quaternary alluvium (Qal)
Paleocene-Eocene(?) Sheep Pass Formation Member C-F (P-Espc-f)
K-Paleocene Sheep Pass Fm. Member B (K-Pspb)
Cretaceous megabreccia (Kmb)
Cretaceous Sheep Pass Fm. Member A (Kspa)
Pennsylvanian Ely Limestone (Pe)
Mississippian Scotty Wash Sandstone (Msw)
Mississippian Chainman Shale (Mc)
Mississippian Joana Limestone (Mj)
Devonian Guilmette Formation (Dg)
Ordovician Eureka Quartzite (Oe)
Ordovician Pogonip Group (Op)
strike and dip
emphemeral drainage
fault with sense of displacement
U
D
anticline/syncline with plunge dir
cross-section line

Figure 3.

CHAPTER 3

PALEOGEOGRAPHIC ISOLATION OF THE CRETACEOUS TO EOCENE SEVIER HINTERLAND, EAST-CENTRAL NEVADA: INSIGHTS FROM U-Pb AND (U-Th)/He DETRITAL ZIRCON AGES OF HINTERLAND STRATA

Abstract

The Late Cretaceous to Paleogene Sevier hinterland of east-central Nevada is widely regarded as an ancient orogenic plateau that has since undergone topographic collapse. New U-Pb and (U-Th)/He detrital zircon age data from Cretaceous to Eocene sedimentary strata of east-central Nevada shed new light on the tectonic and paleogeographic evolution of the Sevier plateau. Precambrian detrital zircon populations are dominant within Sevier hinterland strata, including the Early Cretaceous, syn-contractional Newark Canyon Formation, and the latest Cretaceous to Eocene, syn-extensional Sheep Pass Formation. These results reflect recycling of local Paleozoic sedimentary strata. Subordinate Mesozoic zircon populations are derived from backarc volcanic centers of latest Jurassic and Early Cretaceous age. The local onset of late Eocene syn-extensional volcanism is recorded within sections of hinterland strata containing ca. 36 Ma detrital zircon age peaks. The Sheep Pass Formation type section records Permian, Early Cretaceous, and Campanian (U-Th)/He cooling ages. Ca. 80 Ma cooling ages within the Sheep Pass Formation type section suggest a link with hinterland mid-crustal extension, and initiation of the Sheep Pass basin.

Sevier hinterland deposits of east-central Nevada lack significant Early Mesozoic and Late Cretaceous zircon populations common in terranes of western Nevada and the Sierra Nevada magmatic arc. Long-term paleogeographic evolution of the Sevier Plateau involved isolation through a combination of high relief and rugged topography related to Early Cretaceous shortening, and later, through development of latest Cretaceous to Paleogene extensional basins. These data provide support for previous interpretations that the Sevier hinterland represents an ancient high-elevation orogenic plateau.

Introduction

The Late Cretaceous to Paleogene hinterland of the noncollisional Sevier retroarc fold and thrust belt is widely hypothesized to represent an ancient high-altitude orogenic plateau similar to the modern Andean Puna-Altiplano (Coney and Harms, 1984; Jordan and Alonso, 1987; Allmendinger, 1992; Jones et al., 1998; Sonder and Jones, 1999; House et al., 2001; DeCelles, 2004). Widely scattered outcrops of Early Cretaceous to Eocene sedimentary strata across east-central Nevada record a transition from Early Cretaceous contraction and orogenic uplift (Allmendinger, 1992; Taylor et al., 2000; DeCelles, 2004), to Late Cretaceous-Paleogene extension and collapse of the Sevier orogen (Vandervoort and Schmitt, 1990; Druschke et al., in press). While numerous studies within the Sevier foreland fold-thrust belt and basin system have established a pattern of sediment accumulation, development of regional unconformities, and evolving provenance in response to changes in the kinematics of the contractional wedge (e.g., Wiltschko and Dorr, 1983; Allmendinger, 1992; DeCelles, 1994; DeCelles and Currie, 1996; DeCelles et al., 1995; Lawton et al., 1997; DeCelles, 2004, Horton et al., 2004a) the tectonic and paleogeographic implications of coeval sedimentary deposits within the Sevier hinterland are poorly understood by comparison.

The Sevier hinterland west of the foreland fold-thrust belt has been interpreted as a tectonically quiescent region dominated by low topographic relief (Armstrong, 1968, 1972; Gans and Miller, 1983; Miller and Gans, 1989; DeCelles, 2004). Low-relief interpretations have been developed in part on the generalization that hinterland deposits display less than 10^0 of dip discordance with underlying upper Paleozoic strata (Armstrong, 1968, 1972; Gans and Miller, 1983). In accordance with these interpretations, the dominant structural style of the Late Cretaceous to Paleogene Sevier hinterland has been characterized as broad, open folds (Armstrong, 1968; 1972; Gans and Miller, 1983). Tectonic quiescence is interpreted to have persisted until the onset of late Eocene (38-35 Ma) magmatism and associated extension in east-central Nevada (Gans et al., 1989; Armstrong and Ward, 1991; Axen et al., 1993; Gans et al., 2001), with high topographic relief evolving in response to Neogene establishment of the Basin and Range (Dickinson, 2002, 2006).

Despite interpretations of tectonic quiescence, exposures of coeval mid-crustal rocks represented by the Grouse Creek-Raft River-Albion, Ruby-East Humboldt and Snake Range metamorphic core complexes (Fig. 1) record a dynamic tectonic history within the Late Cretaceous to Paleogene Sevier hinterland. Peak Barrovian metamorphism occurred within hinterland core complexes during the Late Cretaceous ca. 100-75 Ma, and is interpreted to represent maximum crustal thickening (Miller et al., 1988; Miller and Gans, 1989, Wells, 1997; Lewis et al., 1999; McGrew et al., 2000; Sullivan and Snoke, 2007, Wells and Hoisch, 2008). Following peak metamorphism, an estimated 14 km of mid-crustal extensional thinning occurred within the Grouse-Creek-Raft-River-Albion and Ruby-East Humboldt core complexes beginning in the Late Cretaceous to (ca. 75-67 Ma) based on Barrovian metamorphic mineral assemblages and thermochronometry (Wells et al., 1990; Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; Wells et al., 1998; Harris et al., 2007; Wells and Hoisch, 2008). Within the Snake Range core complex, clear evidence for Late Cretaceous mid-crustal extension has not been documented, although sparse thermochronometry and U-Pb monazite ages may indicate Late Cretaceous to early Paleogene tectonic unroofing (Lewis et al., 1999). By middle to late Eocene time (42-36 Ma), all three core complexes experienced significant extension followed by voluminous magmatism (Sullivan and Snoke, 2007). Despite evidence for significant mid-crustal extension, Hodges and Walker (1992) hypothesized that given the lack of evidence for significant latest Cretaceous to early Paleogene surface breaking normal faults within the Sevier hinterland, the upper crust was decoupled from the mid-crust and behaved either passively, or experienced compression.

Stratigraphic studies of fragmented but widespread Cretaceous to Eocene hinterland sedimentary deposits of east-central Nevada suggest that extension may have affected the upper crust of the Sevier hinterland beginning in latest Cretaceous time, synchronous with continued Late Cretaceous to Early Eocene contraction within the Sevier foreland to the east. While Early Cretaceous hinterland deposits are interpreted to have been deposited within piggy-back basin systems (Vandervoort, 1987; Vandervoort and Schmitt, 1990), deposition of Late Cretaceous to Eocene strata within the Sevier hinterland is interpreted to have occurred in extensional basins (Winfrey, 1958, 1960; Kellogg, 1964; Vandervoort and Schmitt, 1990; Fouch et al., 1991; Potter et al., 1995;

Dubiel et al., 1996). Recently, syndepositional, surface-breaking normal faults of latest Cretaceous to Paleocene age have been documented within the south Egan Range type section of the Sheep Pass Formation, supporting a latest Cretaceous timing for the transition from contraction to extension, and suggesting that mid-crustal extension was coupled with upper crustal extension in the Sevier hinterland (Druschke et al., in press). In this interpretation, Late Cretaceous to Eocene basins of the Sevier hinterland are potentially analogous to modern extensional basin systems documented within the hinterlands of the modern Puna-Altiplano and Tibetan Plateaus (Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Allmendinger et al., 1997; Kapp et al., 2008).

This study presents new LA-ICP-MS U-Pb detrital zircon geochronology from the Early Cretaceous Newark Canyon Formation and the latest Cretaceous to Eocene Sheep Pass Formation of east-central Nevada (Fig. 2). Results indicate the presence of Precambrian, Paleozoic, and subordinate Mesozoic to Cenozoic detrital zircon populations that evolved in response to changing tectonics and paleogeography within the Sevier hinterland from the Early Cretaceous to late Eocene. These new detrital zircon ages provide depositional age constraints for units previously lacking absolute age control, as well as a crucial test for previous lithostratigraphic correlations of highly dismembered Sevier hinterland strata. In addition, new (U-Th)/He detrital zircon thermobarometry of the Sheep Pass Formation and underlying Mississippian strata help to constrain the Late Paleozoic to Paleogene shallow crustal thermal history of east-central Nevada. Together these data offer new insight into the tectonic and paleogeographic evolution of the Sevier hinterland, and provide a proxy for long-term processes affecting modern orogenic hinterland regions.

Geologic Background

Pre-Mesozoic Framework

The Pre-Mesozoic tectonic framework of the western U.S. strongly influenced the provenance of Sevier hinterland deposits, given that reworked Paleozoic lithologies are a dominant constituent of Cretaceous to Paleogene siliciclastic deposits within east-central Nevada (Nolan et al., 1956; Winfrey, 1958, 1960; Fouch, 1979; Vandervoort, 1987). Initiation of rifting of western Laurentia in the Late Precambrian resulted in the deposition of voluminous Neoproterozoic to lower Cambrian siliciclastic syn-rift to early post-rift strata derived primarily from the adjacent craton, followed by development of a carbonate-dominated passive margin that persisted from mid-Cambrian to latest Devonian time in eastern Nevada (Stewart and Poole, 1974; Poole et al., 1992). Subduction initiated outboard of the western Laurentian margin during the Late Ordovician to Silurian, and western Nevada transitioned to a backarc basin setting bordered by fringing island arcs to the west and a carbonate ramp/shelf system to the east (Burchfiel et al., 1992; Poole et al., 1992; Dickinson, 2000).

Successive slab-rollback within the fringing arc system led to initiation of the Antler backarc fold-thrust belt in latest Devonian time (Burchfiel, 1992; Dickinson, 2000, 2006). As a result, dominantly fine-grained deep marine strata of the Roberts Mountain allochthon derived from arc terranes to the west and the Laurentian craton to the east were thrust up to 200 km eastward onto the adjacent carbonate shelf (Roberts et al., 1958; Speed and Sleep, 1982; Poole et al., 1992). A thick succession of latest Devonian to Early Mississippian clastic sediments, derived from the Roberts Mountain allochthon, was shed eastward into the Antler foreland basin system (Roberts et al., 1958; Speed and Sleep, 1982; Goebel, 1991; Poole et al., 1992; Miller et al., 1992; Giles and Dickinson, 1995). Intermittent backarc contraction following the initial Antler orogenic pulse controlled deposition of widespread middle Mississippian to Early Permian mixed clastic-carbonate strata in eastern Nevada (Miller et al., 1992; Trexler et al; 2004; Dickinson, 2000; 2006). Late Paleozoic backarc contraction culminated in the Permian to Early Triassic Sonoma orogeny, during which Cambrian to Permian deep marine and volcaniclastic backarc strata comprising the Golconda allochthon were thrust up to 50 km eastward over portions of the older Antler fold-thrust belt (Oldow, 1984; Miller et al., 1992, Dickinson, 2000, 2006). In total, tectonic events initiated in pre-Mesozoic time resulted in the deposition of a 13-15 km thick, mixed-sedimentary succession of Neoproterozoic to Early Triassic age, which presently dominates the geology of east-central Nevada (Stewart and Poole, 1974; Poole et al., 1992; Miller et al., 1992).

Mesozoic to Cenozoic Tectonic Framework

Following the Sonoma orogeny, Middle to Late Triassic backarc extension and thermal subsidence resulted in the establishment of a backarc marine basin in western Nevada and the deposition of upwards of 6 km of Triassic to Early Jurassic mixed carbonate and volcaniclastic marine strata (Speed, 1978; Wyld, 2000). Final closure of the backarc seaway occurred following establishment of the Middle Jurassic Luning-Fencemaker retroarc fold and thrust belt in western Nevada, during which time Triassic to Jurassic backarc basin strata were thrust eastward over the Golconda allochthon (Oldow, 1984; Wyld, 2001; Wyld et al., 2002; DeCelles, 2004). Contraction along the Luning-Fencemaker fold-thrust belt was followed by a period of widespread Middle-to-Late Jurassic backarc volcanism (165-145 Ma) (Smith et al., 1993; du Bray, 2007), possibly related to the opening of an asthenopheric window following foundering of the subducting Mezcalera Plate (Dickinson, 2006).

A period of waning magmatism and westward arc migration followed in the earliest Cretaceous, potentially representing a lull in retroarc contraction (Armstrong and Ward, 1993; DeCelles, 2004; Dickinson, 2006). The Early Cretaceous also marks a period of dextral strike/slip faulting within the Sierra magmatic arc and hinterland of western Nevada, with estimates of 200 to 400 km of dextral offset (Schweikert and Lahren, 1990; Dickinson, 2000; Wyld and Wright, 2001; Martin et al., in press). In northwestern Nevada, the terriginous King Lear Formation was deposited during Barremian time (ca. 123-125 Ma, Quinn et al., 1997) within a series of transtensional basins that received sediment from the coeval arc to the west, as well as from highlands to the east that contained Paleozoic strata (Martin et al., in press). By Aptian time, the locus of retroarc contraction had migrated eastward to the Sevier foreland fold and thrust belt of western Utah (DeCelles et al., 1995), while several hundred km to the west in the Sevier hinterland, the central Nevada fold-thrust belt experienced coeval contraction as recorded by deposition of the Albian-Aptian Newark Canyon Formation (Vandervoort and Schmitt, 1990; Allmendinger, 1992; Carpenter et al., 1993; Taylor et al., 2000). While pre-Late Cretaceous paleoelevation of the Sevier hinterland is poorly constrained, relatively high relief is hypothesized to have been reached by the Early Cretaceous (DeCelles, 2004). Deformation along the central Nevada fold-thrust belt had ceased by the mid-to-Late Cretaceous, as documented by the emplacement of undeformed plutons (ca. 100-85 Ma) that cut earlier compressional structures (Taylor et al., 2000).

The Late Cretaceous to early Paleogene marks an increase in the rate of shortening across the foreland of the Sevier orogen as recorded by coeval shortening in the thin-skinned fold and thrust belt, and basement-involved deformation in the Laramide foreland to the east (DeCelles, 2004). Onset of Laramide deformation coincided with a cessation of volcanism within the Sierra Nevada magmatic arc and rapid eastward migration of the magmatic front, brought on by flattening dip of the subducting Farallon Plate (Dickinson and Snyder, 1978). Late Cretaceous (U-Th)/He apatite cooling ages and paleodrainage profiles preserved in deeply incised canyons of the Sierra Nevada have been interpreted as antecedent river systems similar to modern western Andean drainages, and suggest that a $\geq$ 3km plateau lay to the east (House et al., 2001). Similar paleoelevation estimates of 3 to 5 km for the Late Cretaceous to Paleogene Sevier hinterland have been based on comparison to the modern Puna-Altiplano and Tibetan Plateaus (Coney and Harms, 1984; Dilek and Moores, 1999; DeCelles, 2004). Throughout much of the Sevier hinterland, the Late Cretaceous (ca. 80-75 Ma) marks a period of widespread intrusion of peraluminous granitic plutons at mid-crustal levels (Miller and Bradfish, 1980; Lee et al., 1986; du Bray, 2007), which overlap temporally and spatially with mid-crustal extension in the Grouse Creek-Raft River-Albion and Ruby-East Humboldt core complexes (Wells et al., 1990; Hodges and Walker; 1992; Camilleri and Chamberlain, 1997; Harris et al., 2007; Wells and Hoisch, 2008). Mid-crustal extension has been attributed to gravitational spreading of overthickened Sevier hinterland crust towards the low-elevation foreland (Hodges and Walker, 1992; Jones et al., 1998; DeCelles, 2004), or lithospheric delamination and uplift coupled with thermal weakening of the middle crust during the transition to flat-slab subduction (Wells and Hoisch, 2008).

Thermochronometry of mid-crustal rocks in the Ruby-East Humboldt Range suggests additional early Paleogene cooling from 63-49 Ma (Paleocene to middle Eocene) (McGrew and Snee, 1994; McGrew et al., 2000), and from 57-46 Ma (late Paleocene to middle Eocene) within the northern Snake Range (Lee and Sutter, 1991; Lee, 1995; Lewis et al., 1999). To the northeast of the Snake Range core complex, the Paleocene(?) to early Eocene White Sage Formation of west-central Utah is interpreted to have been deposited within an extensional basin setting (Potter et al., 1995; Dubiel et al., 1996). Direct evidence for post Late Cretaceous contraction within the Sevier hinterland is limited to post-early Eocene, pre-late Eocene folding of portions of the White Sage Formation (Potter et al., 1995), although no distinction was made in this study between regional shortening deformation and more localized contraction due to extensional fault-propagation. Potential alternation of contraction and extension in the Sevier hinterland is supported by the structural sequence and by PT paths from the Grouse Creek-Raft River-Albion core complex indicating an episode of middle Eocene shortening (Wells, 1997; Harris et al., 2007).

Eastward-propagating contraction and syntectonic sedimentation along the Sevier foreland fold-thrust belt and basin system of central Utah continued into the early Eocene (DeCelles, 1994; Lawton et al., 1997; DeCelles, 2004). However, by the middle Eocene (ca. 49 Ma), contraction within the Sevier foreland had ceased, as recorded by a change from shortening to extension in the fold-thrust belt locally over a time interval as short as 1-2 m.y. (Constenius, 1996). Asymmetrical foundering of the Farallon slab initiated southward propagating extension and magmatism within the Sevier hinterland of the Pacific Northwest in the Early Eocene (Humphreys, 1995). These developments were partially coeval with westward extensional collapse of the Sevier fold-thrust belt (Constenius, 1996; DeCelles, 2004). Southward-progressing, synextensional magmatism is documented in northeastern Nevada beginning in the middle Eocene ca. 43-41 Ma (Armstrong and Ward, 1991; Brooks et al., 1995). Synextensional magmatism subsequently affected east-central Nevada beginning in the late Eocene ca. 38-35 Ma (Gans et al., 1989; Axen et al., 1993; Gans et al., 2001). Plant fossils within the middle Eocene Copper basin are interpreted to represent a paleoelevation of approximately 2 km within the Sevier hinterland of north-central Nevada (Wolfe et al., 1998). $\delta^{18}O$ analyses of lacustrine carbonate within the Elko Formation have been interpreted as recording a rise in elevation of up to 2 km (to 4 or 5 km) following initiation of middle to late Eocene volcanism in north-central Nevada (Horton et al., 2004b).

Cretaceous-Eocene Hinterland Stratigraphy

Newark Canyon Formation

The Newark Canyon Formation consists of scattered exposures of fluvial and lacustrine deposits extending from the Piñon Range and Cortez Mountains of north-central Nevada to the Diamond Mountains, Fish Creek, and Pancake Ranges of east-central Nevada (Fig. 2). Within the Diamond Mountains type section, the Newark Canyon Formation is approximately 500 m thick and is composed of alternating beds of conglomerate, sandstone, siltstone and carbonaceous mudstone deposited in fluvial, alluvial and lacustrine settings (Nolan et al., 1956) (Fig. 3). An Early Cretaceous age is assigned on the basis of floral and invertebrate fossil assemblages (Aptian-Albian ca. 121 to 112 Ma) (Nolan et al., 1956; Smith and Ketner, 1976; Swain, 1999). Apatite fission-track analyses from Newark Canyon Formation deposits of the Fish Creek Range indicate Aptian exhumation (116 ± 13 Ma) (Carpenter et al., 1993).

Within east-central Nevada, the Newark Canyon Formation was deposited unconformably on upper Paleozoic strata, although in north-central Nevada it was deposited in part on upper Jurassic volcanic strata (Smith and Ketner, 1976). Modal analyses of sandstone within the Newark Canyon Formation indicate a recycled orogen provenance with no identifiable arc-sourced detritus; conglomerate clast populations are similarly composed of reworked local Permian to Ordovician sedimentary units (Vandervoort, 1987). The tectonic setting of the Newark Canyon Formation is interpreted to have been a series of piggyback basins due to the interbedding of coarse braided fluvial and lacustrine deposits, and the presence of east-vergent folds (Vandervoort, 1987; Vandervoort and Schmitt, 1990). In the Fish Creek Range and Diamond Mountains, the Newark Canyon Formation is overlain in part by megabreccia composed of upper Paleozoic lithologies, and in part by lacustrine limestone containing Maastrichtian to Paleocene floral and invertebrate fossils. The fossils suggest that Upper Cretaceous megabreccia and laucstrine deposits of the Fish Creek Range are correlative to the basal members of the Sheep Pass Formation type section (Fouch et al., 1979; Vandervoort and Schmitt; 1990).

Sheep Pass Formation

The Sheep Pass Formation forms a series of isolated exposures located throughout east-central Nevada, with outcrop and subcrop scattered over an area of > 15,000 km^2

(Fouch et al., 1991). The Sheep Pass Formation was originally designated to describe sections of non-tuffaceous fluvial, alluvial and lacustrine strata located in the Pancake, Grant and Egan Ranges. The type section is at Sheep Pass Canyon in the southern Egan Range (Winfrey, 1958, 1960) (Fig. 3). Six members (A-F) are recognized within the Sheep Pass Formation type section (Winfrey 1958, 1960; Fouch, 1979).

Sparse Maastrichtian detrital zircons (68-70 Ma) analyzed within the basal conglomeratic member (A), and a 66.1 ± 5.4 Ma U-Pb carbonate age from the lower fossiliferous lacustrine limestone member (B) indicate a Maastrichtian age for basal members of the Sheep Pass Formation in the type section (Druschke et al., in press). A Maastrichtian to late Paleocene age (70-55 Ma) had been previously assigned to Members B-C in the type section on the basis of palynomorphs and invertebrates, while fossils within Member E of the type section indicate a middle Eocene age (Bridgerian, 50.5-45.4 Ma) (Fouch, 1979; Good, 1987; Swain, 1999). No major unconformities have been documented within the Sheep Pass Formation type section (Winfrey, 1958, 1960; Kellogg, 1964; Fouch, 1979), although it is possible that the sharp transition from the latest Cretaceous-Paleocene members (A-C) to middle Eocene members (D-F) represents a poorly exposed unconformity. The Sheep Pass Formation is unconformably overlain by the Garrett Ranch Group, a thick succession of late Eocene to Oligocene volcanic tuff, welded tuff, small-volume basalt and andesite flows, and volcaniclastic sediment (Winfrey, 1958; Hose et al., 1976).

The Sheep Pass Formation unconformably overlies sedimentary strata of Devonian to Permian age throughout much of its outcrop area. Within the type section, the Sheep Pass Formation is deposited upon mixed siliciclastic-carbonate units of Mississippian to

Pennsylvanian age, and to the south is deposited upon undivided Permian strata (Kellogg, 1963, 1964). Conglomerate clast lithologies within the Sheep Pass Formation are dominated by upper Paleozoic carbonate lithologies, and it has been reported that no clasts older than Devonian age are discernable (Winfrey, 1958, 1960; Kellogg, 1964; Fouch, 1979). This observation suggests that source areas for clastic sediment within the Sheep Pass Formation consisted entirely of upper Paleozoic units, and that lower Paleozoic strata were not exposed locally during the Late Cretaceous and early Paleogene.

An extensional half-graben basin setting has been hypothesized for the Sheep Pass Formation based on the dominance of lacustrine strata and general westward thinning of the Sheep Pass Formation (Winfrey 1958, 1960). The presence of megabreccia within the Sheep Pass Formation type section has been cited as evidence for an extensional basin setting (Kellogg, 1964). This interpretation is reinforced by the presence of megabreccia and lacustrine limestone deposits of Maastrichtian to Paleocene age in the Fish Creek Range (Fig. 2) that unconformably overly the Newark Canyon Formation; Vandervoort and Schmitt (1990) interpreted these deposits to represent a transition from contraction to extension coeval with Late Cretaceous mid-crustal extension in the Sevier hinterland. More recently, megabreccia deposition and slip on a series of surface-breaking, syndepositional normal faults within the Sheep Pass Formation type section have been shown to be Maastrichtian in age (Druschke et al., in press). Deposition of the Sheep Pass Formation within the type section is interpreted to have been controlled by up to 3 km of latest Cretaceous to Paleocene, down-to-the-northwest stratigraphic throw along the

Ninemile fault, presently a low-angle normal fault exposed in the southern Egan Range to the southeast of the Sheep Pass Formation type section (Druschke et al., in press).

Eocene Volcanism and "Tuffaceous" Sheep Pass Formation

Throughout much of its outcrop area the Sheep Pass Formation is unconformably overlain by regionally extensive ash-flow tuff units that mark a major change from lacustrine deposition to the local onset of late Eocene volcanism (Fouch, 1979). In the southern Egan Range the Sheep Pass Formation is unconformably overlain by >500 m of the volcanic Garrett Ranch Group, with 10^{o} of angular discordance between these units (Kellogg, 1964). In Sheep Pass Canyon, the basal member of the Garrett Ranch Group is a conglomerate >150 m thick, designated the Stinking Spring Conglomerate (Kellogg, 1964). The Stinking Spring Conglomerate is thickest where it overlies the Sheep Pass Formation type section, and thins significantly to the north and south. Overlying the Stinking Spring Conglomerate is a ash-flow tuff unit that Hose et al., (1976) correlated to the Stone Cabin Formation. The Stone Cabin Formation forms the basal welded tuff member of the Garrett Ranch Group within the Grant and Pancake Ranges to the east; it has produced a late Eocene $^{40}Ar/^{39}Ar$ sanidine age of 35.3 ± 0.8 Ma (Radke, 1992).

The Stinking Spring Conglomerate is dominantly a carbonate-clast conglomerate similar to the basal Member A of the Sheep Pass Formation, but it contains a much more diverse clast population. Clasts of local Ordovician to Devonian formations are relatively abundant within the Stinking Spring Conglomerate, as are clasts derived from the underlying Sheep Pass Formation (Kellogg, 1964). Clasts are dominantly cobble-sized, though boulders up to 2 m in diameter are present. In the upper portion of the Stinking Spring Conglomerate, there is a series of beige sandstone lenses containing detrital sanidine and biotite, indicating a tuffaceous component. Approximately 20 km to the south of Sheep Pass Canyon, the basal portion of the Garrett Ranch Group consists of megabreccia and block-slide deposits derived from Pennsylvanian limestone and Mississippian sandstone (Kellogg, 1964). These mass-movement deposits unconformably overlie portions of the Sheep Pass Formation that are late Paleocene age, based on molluscan fossil assemblages (Good, 1987). These in turn are overlain by late Eocene to Oligocene tuffs of the Garrett Ranch Group.

Although the Sheep Pass Formation, as originally defined by Winfrey (1958, 1960) lacks an obvious volcaniclastic component, the definition was later expanded to include lacustrine and fluvial deposits within the central Egan Range that are in part tuffaceous (Brokaw, 1967; Hose et al., 1976). Elderberry Canyon, located in the central Egan Range immediately south of Ely, Nevada (Fig. 2), contains approximately 120 m of conglomerate and lacustrine limestone that thickens toward the south. This interval is non-volcaniclastic in its lower part, but it grades upward into increasingly tuffaceous lacustrine deposits (Fouch, 1979). A mammalian fossil assemblage in the lower, non-volcaniclastic portion of the Elderberry Canyon section establishes a middle Eocene depositional age (Bridgerian 50.5-45.4 Ma), indicating a potential age overlap with the upper members of the Sheep Pass Formation in the type section (Fouch, 1979, Good, 1987, Emry, 1990). On the basis of similarity of depositional facies and possible age overlap, Fouch (1979) correlated the Elderberry Canyon section to the Sheep Pass Formation as "type 2" (tuffaceous), although the tuffaceous interbeds were not dated.

Fouch (1979) also expanded the definition of "type 2" Sheep Pass Formation deposits to include conglomerate and lacustrine limestone of the Kinsey Canyon Formation of

Young (1960) within the central Schell Creek Range, fluvial conglomerate exposed in Murphy Wash of the southern Snake Range, and scattered exposures of tuffaceous lacustrine and fluvial strata in the Grant and Pancake Ranges (Fig. 2). Each of these sections unconformably overlie upper Paleozoic strata, and are in turn overlain by late Eocene to Oligocene tuff units. In the Grant and Pancake ranges, tuffaceous Sheep Pass Formation strata are overlain by the Stone Cabin Formation, and in the Schell Creek Range the Kinsey Canyon section is overlain by the 35.5 ± 0.5 Ma (K-Ar) Kalamazoo Tuff (Hagstrum and Gans, 1989). In Elderberry and Sawmill canyons of the central Egan Range, the Sheep Pass Formation is overlain by the 32.8 ± 1.1 Ma (K-Ar) Charcoal Ovens Tuff (McKee et al., 1976).

Conglomeratic clasts within tuffaceous Sheep Pass Formation sections are dominated by upper Paleozoic lithologies similar to conglomeratic intervals within the Sheep Pass Formation type section (Fouch, 1979). However, a greater abundance of clasts derived from lower Paleozoic units is apparent in "tuffaceous Sheep Pass Formation" sections. Within Eocene conglomeratic sections of the Schell Creek Range, Neoproterozoic to lower Cambrian Prospect Mountain Quartzite and distinctive Late Jurassic granitic clasts have been identified and are interpreted to have been derived from the Snake Range to the east (Drewes, 1967; Gans et al., 1989). The presence of Prospect Mountain Quartzite and Jurassic granitoid clasts suggests up to 7 km of unroofing within the Snake Range by the late Eocene (38-35 Ma) (Gans et al., 1989). Middle Eocene lacustrine limestone of the Sheep Pass Formation immediately east of Ely, Nevada (Good, 1987), is overlain by a series of synextensional tuff units that bracket a period of rapid late Eocene extension between 37.56 ± 0.03 Ma and 36.68 ± 0.04 Ma (^{40}Ar/^{39}Ar sanidine) (Gans et al., 2001).

Methods

U-Pb Zircon Geochronology

A total of 15 samples were selected from six stratigraphic sections of Early Cretaceous to late Eocene age within the Sevier hinterland of east-central Nevada (Fig. 2), and we report 1,307 U-Pb detrital zircon age analyses. One sample was obtained from Mississippian Scotty Wash Sandstone in Sheep Pass Canyon, which is overlain by and comprises one of the most common siliciclastic clast types in conglomerate exposures of the Sheep Pass Formation type section. Two samples were collected from the Diamond Mountains type section of the Early Cretaceous Newark Canyon Formation. Eight samples were collected from the Late Cretaceous to middle Eocene Egan Range type section of the Sheep Pass Formation, which comprises the thickest and best exposed section of latest Cretaceous through Eocene strata regionally (Fig. 3). Two samples were obtained from the Stinking Spring Conglomerate, the basal member of the Garrett Ranch Group. Lastly, four sections of tuffaceous fluvial and lacustrine strata correlated to the Sheep Pass Formation by Fouch (1979) were sampled (sample locations DW, SC, KC, MW shown on Fig. 2). Two to five kg of material was collected per sample depending on the textural and compositional maturity of the sandstone, which ranged across a broad spectrum from well-sorted quartz arenite to poorly sorted litharenite.

Zircon separates were processed by crushing and Wifley table gravity separation, followed by standard heavy liquid and magnetic separation. For each sample, a large fraction of the recovered zircons was mounted in epoxy resin and polished. Typically 100 zircons were analyzed per sample, with the beam centered on the core of grains to avoid metamorphic overgrowth or alteration. Fractured grains were generally avoided due to possible Pb loss from leaching or alteration along fractures. In general, 10-15% of the analyses per sample displayed strong discordance, and these results were discarded.

Analyses were performed at the University of Arizona LaserChron Center with a Micromass Isoprobe multicollector-inductively coupled plasma-mass spectrometer (ICP-MS) equipped with a New Wave DUV 193 nm Excimer laser ablation system. Laser beam diameter was 35 μm with an output energy of 32 mJ (at 22kV) and a pulse of 8 Hz. An in-house zircon standard with a concordant TIMS age of 563.5 ± 3.2 Ma (Dickinson and Gehrels, 2003) was analyzed once after every five unknowns. In addition, U and Th concentrations were monitored by analyzing the National Institute of Standards 610 glass standard.

Age probability plots in this study were constructed using the $^{206}Pb/^{238}U$ age for zircons younger than 1 Ga, and the $^{206}Pb/^{207}Pb$ age for grains older than 1 Ga. For Paleoproterozoic and Archean grains, ages with >20% discordance or >10% reverse discordance were considered unreliable and were discarded. A population is considered statistically robust if three or more different grains within one sample yield overlapping $^{206}Pb/^{238}U$ or $^{206}Pb/^{207}Pb$ ages. For samples containing significant population clusters of euhedral, potentially tuff-sourced zircons, the TuffZirc (Ludwig and Mundil, 2002) age extractor program was used to evaluate the probability of a single source for age clusters within 90% statistical confidence. While the TuffZirc ages typically represent a reworked volcaniclastic/epiclastic component within mixed-sourced sedimentary strata, we generally interpret these as depositional ages within the range of 2σ statistical uncertainty. Regardless, TuffZirc ages indicate the maximum age of deposition.

Additional data tables used for the construction of Concordia diagrams, probability plots and TuffZirc ages are presented in the appendices (Appendix I).

(U-Th)/He Zircon Thermochronology

Zircon is a commonly used (U-Th)/He thermochronometer that is characterized by a He closure temperature of ~180-200°C, assuming a cooling rate of 10°C/m.y. (e.g., Reiners et al., 2005) and a partial retention zone spanning a temperature range from ~120-180°C (e.g., Stöckli, 2005; Wolfe and Stöckli., 2008). For this study, a total of 52 zircons from the Sheep Pass Formation, Scotty Wash Sandstone, and Stinking Spring Conglomerate were selected for (U-Th)/He thermochronology at the University of Kansas. Zircons were selected from the remaining unmounted fractions of samples that had previously undergone U-Pb dating, but were not performed on zircons that had been previously dated (Reiners et al., 2002). Heavy mineral separates from the Sheep Pass Formation were also screened for apatite, but apatite crystals were found to be sparse and too highly abraded to be amenable to (U-Th)/He dating.

Zircons were handpicked, and selected based on minimum dimensions of 70 μm across a/b axes, between 80-200 μm along the c axis, and on the lack of visible fractures and minimal inclusions. Zircons were also selected based on two general morphologies; euhedral to subhedral zircons that typically have Mesozoic U-Pb crystallization ages, and subrounded zircons that typically have Precambrian crystallization ages (Fig. 4). Roughly 2/3 of the zircons selected were of the subrounded type based on the fact that zircons with Precambrian crystallization ages are dominant in the Sheep Pass Formation, comprising roughly 65% of the population. All analyses were carried out on single grains.

All (U-Th)/He age determinations were carried out at the University of Kansas using laboratory procedures described in Biswas et al. (2007). Selected zircons were wrapped in Pt foil, heated for 10 minutes at ~1300°C and reheated until >99% of the He was extracted. All ages were calculated using standard α-ejection corrections using morphometric analyses (Farley et al., 1996; Reiners, 2005). After laser heating, zircons were unwrapped from Pt foil and dissolved using HF-HNO_3 and HCl pressure vessel digestion procedures. U and Th concentrations were determined by isotope dilution ICP-MS analysis. Uncertainties (2σ) of single-grain ages reflect the reproducibility of replicate analyses of laboratory standard samples (Farley et al., 2001) and are ~8% (2σ) for zircon He ages. All single grain zircon (U-Th)/He data tables are presented in the appendices (Appendix II).

Results

U-Pb Detrital Zircon Geochronology

Results of LA-ICP-MS U-Pb detrital zircon dating yielded crystallization ages ranging from Archean to Late Cretaceous, with a significant component of Eocene zircons from samples collected from the "tuffaceous" Sheep Pass Formation at several localities (Fig. 5). The detrital zircon age distribution for each sample and significant age peak determinations are displayed as a series of probability-density plots (Fig. 6).

Scotty Wash Sandstone

One sample was collected from the Mississippian Scotty Wash Sandstone in Sheep Pass Canyon, directly below the basal contact with the Sheep Pass Formation. This sample was analyzed to provide direct comparison with detrital zircon age distributions within the Sheep Pass Formation type section, due to the prevalence of Scotty Wash Sandstone clasts in conglomerates of the Sheep Pass Formation. Within Sheep Pass Canyon, the Scotty Wash Sandstone consists of a well-sorted, ripple-marked and cross-stratified quartz arenite deposited in a shallow marine setting during the Late Mississippian to Early Pennsylvanian (Kellogg, 1963). Detrital zircon separates from the Scotty Wash Sandstone are dominantly pale yellow to dull white and sub-rounded to well-rounded. A small percentage of blocky, subhedral grains were observed. Results of U-Pb age analyses indicate dominant age peaks at 1.82 Ga, 1.49 Ga, and 1.11 Ga. Smaller peaks occur at 2.53 Ga, 1.65 Ga, and 426 Ma (Silurian).

Newark Canyon Formation

Two samples were collected from the Newark Canyon Formation type section, from the Upper Conglomerate Member and the Upper Carbonaceous Assemblage. Sample 07NW2 from the Upper Conglomerate Member yielded a mix of pale yellow to clear subrounded to rounded zircons, with a nearly equal proportion of clear, prismatic, euhedral zircons. Results of U-Pb age analyses yield zircons ranging from Archean to Early Cretaceous in age, with the most significant age peaks at 1.85 Ga, 1.17 Ga and 121 Ma (Aptian). Smaller peaks are recorded at 1.42 Ga, 1.25 Ga, 976 Ma, 449 Ma (Late Ordovician), 437 Ma (Silurian) and 129 Ma (Barremian). TuffZirc age extraction computations (Ludwig and Mundil, 2002) performed on the Cretaceous zircon component from sample 07NW2 suggests a single tuff source with an eruptive age of 120.7 ± 3.2 Ma (Aptian) (Fig. 7A).

Sample 06NW1 was collected from a thin bed of poorly sorted sandstone within the mudstone-dominated Upper Carbonaceous Assemblage. Separates yielded only relatively large (>100 μm) clear, prismatic, euhedral zircons. U-Pb age results from 06NW1 indicate that this sample is a water-lain tuff with a U-Pb age of 116.1 ± 1.6 Ma (Aptian) (Fig. 5), rather than sandstone as indicated in previous stratigraphic sections (Nolan et al., 1956; Vandervoort, 1987). This is the first report of a directly datable tuff within the Newark Canyon Formation type section.

Sheep Pass Formation Type Section

A total of five samples were collected from the Maastrichtian to middle Eocene Sheep Pass Formation type section in the southern Egan Range, including two samples (06SP29 and 06SP20) from the respective middle and upper portions of conglomeratic Member A, two samples (05SP14 and 05SP18) from the respective lower and middle portions of the fluvial sandstone dominated Member C, and one sample (06MR19) from sandy interbeds within Member E. Detrital zircon separates reveal a population dominated throughout the Sheep Pass Formation type section by yellow to dull white, abraded, rounded to subrounded zircons. A smaller population of clear, blocky to prismatic, euhedral to subhedral zircons is also discernable, but constitutes only approximately 10-15% of the zircon population. Euhedral to subhedral zircons are most abundant within Member A, generally decreasing upsection.

Samples from Member A were collected from coarse-to medium-grained, poorly sorted litharenites within sandstone lenses of the predominantly conglomeratic member. The lowermost interval of Member A was not sampled due to a lack of channel sands or sandy matrix within the debris-flow dominated base of the section. Results from Member

A reveal zircon crystallization ages ranging from Archean to Late Cretaceous (Figs. 5 and 6). While the two youngest zircons (two single analyses of 68 and 70 Ma) were obtained from the uppermost portion of Member A (06SP20) (Druschke et al., in press), overall similarity of the age peaks allows for the combination of the two analyses into a single probability plot (Fig. 6). Major age peaks for Member A include1.67 Ga, 1.1 Ga, 424 Ma (Silurian), 110 Ma and 103 Ma (Albian). Smaller peaks occur at 2.78 Ga, 2.36 Ga, 1.88 Ga, 1.38 Ga and 363 Ma (Late Devonian).

Member C is dominated by medium to coarse-grained litharenitic sandstones that generally display a greater degree of sorting than sandstone lenses within Member A. Member C is locally present in Sheep Pass Canyon, but is absent within sections located to the south in the Egan Range, and in the subsurface of White River to the west (Winfrey 1958, 1960; Fouch, 1979), suggesting derivation from the east. Results from samples collected from the lower and middle portion of the member were combined into a single age probability plot. The dominant age peaks for Member C include 1.91 Ma, 1.63 Ga, 1.5 Ga, 1.2 Ga, 1.05 Ga, and 155 Ma (Late Jurassic). Minor age peaks include 3.12 Ga, 2.88 Ga, 2.67 Ga, 650 Ma, 423 Ma (Silurian) and 186 Ma (Early Jurassic).

The final sample analyzed from the Sheep Pass Formation type section was obtained from medium-grained, well sorted and quartz-rich sandstone interbeds within the base of the lacustrine-limestone-dominated Member E. Sandy interbeds occur within the basal portion of the member only in the easternmost exposures within the type section (Milk Ranch Canyon), and are absent from exposures to the west and south. Results indicate major age peaks at 1.85 Ga, 1.75 Ga, 1.48 Ga, 1.18 Ga, 1.06 Ga and 112 Ma (Albian). Minor peaks occur at 2.77 Ga, 1.94 Ga, 1.65 Ga, and 1.0 Ga.

Stinking Spring Conglomerate

Two samples were obtained from the middle (06SP21) and uppermost (06SP22) portions of the Stinking Spring Conglomerate within Sheep Pass Canyon. Similar to Sheep Pass Formation Member A, samples were not collected at the base of the Stinking Spring Conglomerate due to a lack of sandy matrix within the conglomerate and a lack of sandstone lenses or interbeds. Sample 06SP21 was obtained from a poorly sorted, dominantly medium-grained sandstone lens. Sample 06SP22 was collected from near the top of the member from a thick, medium-grained sandstone bed containing detrital biotite and sanidine indicative of a tuffaceous component. Zircon separates from 06SP21 consisted of largely pale yellow to dull white, rounded to subrounded zircons, with a small component of clear, elongate, euhedral zircons. Separates from 06SP22 were similar, but euhedral zircons comprised roughly 50% of the population. Results from these samples were combined into a single age probability plot. The dominant age populations within the Stinking Spring Conglomerate are 1.65 Ga, 1.15 Ga, 1.1 Ga, 422 Ma (Silurian), and 37 Ma (late Eocene). A TuffZirc age extraction of Eocene zircons within sample 06SP22 indicates a single tuff source with an eruptive age of 37.7 ± 0.6 Ma (Fig. 7B).

"Tuffaceous" Sheep Pass Formation

A total of 5 samples were collected from widely separated sections of tuffaceous lacustrine and fluvial strata previously correlated to the Sheep Pass Formation (Fouch, 1979). Sample 05DW1 was collected immediately north of Duckwater Mountain in the northern Pancake Range. The lower portion of this section consists of coarse fanglomerate containing boulders of Devonian and Mississippian lithologies up to 2 m in diameter; the section fines upward into coarse sandstone and conglomerate interfingering with marginal lacustrine strata. The Duckwater Mountain section is unconformably overlain by the late Eocene Stone Cabin Formation (35.3 ± 0.8 Ma) (Radke, 1992); and although its contact with underlying units is not exposed, it contains 140 m of strata. Sample 05DW1 was collected from a coarse, poorly sorted sandstone bed approximately 40 m above the base of the section. The zircon separates reveal nearly equal proportions of pale yellow to dull white, rounded to subrounded zircons, and clear, elongate, euhedral zircons with abundant accessory barite. Results of U-Pb age analyses indicate major peaks at 36 Ma (late Eocene), 1.86 Ga, and 1.91 Ga. Smaller peaks occur at 2.73 Ga, 2.08 Ga, 1.02 Ga, and 112 Ma (Albian). A TuffZirc age extraction of the Eocene age component suggests a single tuffaceous source with an eruptive age of 35.7 ± 0.7 Ma (Fig. 7C).

Sample 04LC1 was collected at Lowry Spring section in the central Egan Range. The Lowry Spring section is contiguous with the Elderberry Canyon section to the north, which was designated as the type locality for the "tuffaceous" Sheep Pass Formation (Fouch, 1979). The Lowry Spring section consists of approximately 50 m of conglomerate and coarse-to-medium-grained sandstone deposited unconformably on the Permian Arcturus Formation (Brokaw, 1967). Conglomerate clasts consist dominantly of upper Paleozoic limestone and siliciclastic strata, with no volcaniclastic component discernable. Lowry Spring lies immediately north of Sawmill Canyon, but the two sections are separated by a normal fault with an unknown amount of displacement. Sample 04LC1 was collected from a medium-grained, well-sorted, quartz-rich sandstone near the top of the section. Detrital zircon separates consist of pale yellow to dull white, subrounded to well-rounded zircons, with a very small component of subhedral zircons. Results reveal major populations at 1.77 Ga, 1.68 Ga, 1.3 Ga, and 1.11 Ga. Smaller peaks occur at 2.88 Ga, 2.76 Ga, 1.83 Ga, 953 Ma, and 420 Ma (Silurian). A single zircon with an age of 154 Ma (Late Jurassic) was analyzed; high analytical precision (± 1.5 Ma) creates a large probability peak despite the fact that this single analysis does not constitute a statistically robust population.

Sample 05SM2 was collected from Sawmill Canyon immediately to the south of Lowry Spring. The sample was collected from a coarse-grained, poorly sorted litharenite within the lower portion of the section. Detrital biotite within the sandstone and small well-rounded clasts of basalt within the dominantly Paleozoic-clast conglomerates at Sawmill Canyon indicate a volcaniclastic component. This volcaniclastic component increases upsection, with thick beds of tuffaceous sandstone dominating the upper portion of the section below the Charcoal Ovens Tuff. Detrital zircons from 05SM2 consisted of roughly 70% clear, elongate, euhedral zircons, with the remainder consisting of pale yellow to dull white, rounded to subrounded zircons. Results indicate a major age peak at 36 Ma (late Eocene), with smaller peaks at 1.86 Ga, 1.65 Ga, and 1.11 Ga. A TuffZirc age extraction indicates a single tuff source with an eruptive age of 36.8 ± 1.1 Ma (Fig. 7D).

Sample 05KC1 was collected from the Kinsey Canyon section in the northern Schell Creek Range. This is the type section of the Kinsey Canyon Formation of Young (1960), and was later correlated to the Sheep Pass Formation (Fouch, 1979). The Kinsey Canyon section consists of approximately 120 m of dominantly carbonaceous and tuffaceous siltstone deposited within a shallow lacustrine setting (Young, 1960; Fouch, 1979). The contact between the Kinsey Canyon section and underlying strata is not exposed, but it is unconformably overlain by the late Eocene Kalamazoo Tuff. Sample 05KC1 was collected from a coarse, litharenitic sandstone at the base of the section; separates consist predominantly of clear, prismatic, euhedral zircons with approximately 10% of the population consisting of pale yellow to dull white, rounded to subrounded detrital zircons. Results of U-Pb dating indicate a dominant population at 36 Ma, with minor peaks at 1.41 Ga and 1.08 Ga. A Tuffzirc age extraction suggests a single tuff source with an eruptive age of 35.8 ± 0.5 Ma (Fig. 7E).

The final "tuffaceous" Sheep Pass Formation sample (07SR1) was collected from the Murphy Wash section of the southern Snake Range. Murphy Wash is the easternmost section correlated to the Sheep Pass Formation (Fouch, 1979); it lies in close proximity to the northern Snake Range core complex. The Murphy Wash section consists of 120 m of fluvial to alluvial conglomerate and sandstone deposited unconformably on the Mississippian Chainman Formation. The Murphy Wash section is unconformably overlain by a n ash-flow tuff that has produced a $^{40}Ar/^{39}Ar$ age of 31.07 ± 0.07 Ma (Oligocene) (Miller et al., 1999). Sample 07SR1 was collected near the top of the section, and zircon separates consist mainly of clear, prismatic, euhedral zircons, with <10% consisting of pale yellow to dull white rounded to subrounded zircons. The dominant U-Pb age population is 32 Ma (Oligocene) with minor peaks at 1.17 Ga and 1.02 Ga. A Tuffzirc age extraction of the Oligocene zircon population suggests a single tuff source with an eruptive age of 31.9 ± 0.6 Ma (Fig 7F).

(U-Th)/He Detrital Zircon Thermochronology Results

Twelve zircons were analyzed from the Scotty Wash Sandstone in Sheep Pass Canyon (06SP30) in order to constrain the thermal history for the upper Paleozoic section serving as basement for the Sheep Pass basin. (U-Th)/He ages represent zircon cooling through 180° C, equivalent to approximate 6 km burial depths under normal crustal conditions. Results are also compatible with somewhat shallower depths under conditions of higher crustal heat flow; metamorphism at relatively shallow crustal levels accompanied Late Cretaceous intrusion within the Snake Range core complex (Miller et al., 1988; Miller and Gans, 1989). Results from (U-Th)/He detrital zircon dating of the Scotty Wash Sandstone indicate a broad peak at 265 Ma (Permian), with a single outlier at 680 Ma (Fig. 8).

A total of 26 zircons from the Sheep Pass Formation type section were analyzed from three samples corresponding to Member A (06SP29), Member C (05SP18) and Member E (06MR19). In addition, 9 zircons from the overlying Stinking Spring Conglomerate were analyzed. Dominant (U-Th)/He age peaks occur at 304 Ma (Permian), 135 Ma (Berriasian) and 106 Ma (Albian), with the largest age peak at 80 Ma (Campanian). A total of three euhedral zircons from the Stinking Spring Conglomerate (06SP21) comprise a 40 Ma cooling peak.

Discussion

Zircon Provenance

Detrital zircon U-Pb age populations of Sevier hinterland strata are largely dominated by Precambrian peaks. We attribute this to the predominance of recycled Paleozoic sedimentary strata within the Newark Canyon and Sheep Pass Formations, and also to the fact that Sevier hinterland deposits unconformably overlie Devonian to Permian strata (Nolan et al., 1956; Winfrey 1958, 1960, Fouch, 1979). Detrital zircon populations of the Mississippian Scotty Wash Sandstone presented here provide a useful addition to the large, previously established U-Pb detrital zircon provenance framework for Paleozoic strata of western Laurentia, and they also provide a direct comparison to Paleozoic and Precambrian U-Pb detrital zircon populations of Sevier hinterland deposits. The most significant detrital zircon population of the Scotty Wash Sandstone is defined by a 1.1 Ga peak, but includes a broad age cluster ranging from 900 Ma to 1.2 Ga (n=53 or 55%). Similar Grenville age peaks make up the major Precambrian populations of the Newark Canyon Formation (1.08 to 1.25 Ga, n=33 or 35%) and the Sheep Pass Formation type section (30%). Grenville-age populations are also significant within the Stinking Spring Conglomerate and the Lowry Spring section. Smaller populations of Grenville-age zircons are found in the Duckwater Mountain, Sawmill Canyon, Kinsey Canyon, and Murphy Wash sections.

Cambrian to Ordovician strata within the Roberts Mountain allochthon contain significant populations of zircons with Grenville affinity (Smith and Gehrels, 1994; Gehrels and Dickinson, 1995; Gehrels et al., 2000), and Grenville-derived zircons are a major component in many Neoproterozoic to Cambrian quartz arenites of the western Laurentian margin (Rainbird et al., 1992; Stewart et al., 2001). The Scotty Wash Sandstone is part of the Antler foreland basin that received siliciclastic sediment shed from the Roberts Mountain allochthon, although input from the craton to the east is a possible contributor based on compositional maturity and some west-directed paleocurrent indicators (Trexler et al., 1995). The ultimate source for 1.0 to 1.3 Ga populations is the eastern Laurentian Grenville/Marathon belt, with Neoproterozoic to Cambrian cross-continental fluvial transport and successive reworking responsible for wide redistribution (Rainbird et al., 1992; Stewart et al., 2001).

The Scotty Wash Sandstone also contains significant Mesoproterozoic peaks at 1.48 Ga, 1.65 Ga, and 1.82 Ga, and a Paleoproterozoic peak at 2.52 Ga. Detrital zircon age peaks of 1.43, 1.60 and 1.80 Ga have been recorded in the Ordovician Vinnini Formation of the Roberts Mountain allochthon, and peaks of 2.30 to 2.80 Ga similarly derived from the Roberts Mountain allochthon are common within the Antler overlap sequence (Gehrels et al., 2000). Within the Newark Canyon Formation, peaks of 1.42 Ga and 1.85 Ga represent the remaining significant Precambrian peaks. A compilation of Precambrian zircon ages from the Sheep Pass Formation (Fig. 9A) similarly reveals major peaks at 1.51 Ga, 1.66 Ga, 1.86 Ga, 2.73 Ga, and 2.87 Ga.

Previous workers have asserted that no clasts older than Devonian are present within conglomerates of the Sheep Pass Formation type section (Winfrey, 1958, 1960; Kellogg, 1964). However, our study has identified clasts of the highly distinctive Ordovician Eureka Quartzite within Member A in the type section, indicating that source areas containing lower Paleozoic strata did contribute to the Sheep Pass basin. A shift toward older Precambrian ages relative to Grenville-sourced grains within the Sheep Pass type section, as well as an upward trend toward greater textural and compositional sandstone maturity, suggests an unroofing signal involving increased input from lower Paleozoic sources following Paleocene to Eocene widening of the Sheep Pass basin.

A trend toward older Precambrian ages is seen within the Lowry Spring section, and also within the Duckwater Mountain, Sawmill Canyon and Kinsey Canyon sections. Within many of the "tuffaceous" Sheep Pass sections, this trend correlates with a greater proportion of Cambrian to Devonian clasts within conglomeratic beds, as compared to dominantly upper Paleozoic clasts within the Sheep Pass Formation type section. The Precambrian peaks within the Stinking Spring Conglomerate are more similar to those seen within the Sheep Pass Formation type section, although the Stinking Spring Conglomerate contains a large number of clasts derived from recycling of the underlying Sheep Pass Formation type section. The relatively small Precambrian population of the Murphy Wash section is also dominated by Grenville grains, likely derived from sandy interbeds within the underlying Mississippian Chainman Formation.

The final significant peaks within the Scotty Wash Sandstone are 426 and 412 Ma (Silurian), obtained from typically moderately abraded, subhedral zircons. Similar Late Ordovician to Silurian peaks are present in the Newark Canyon Formation (449 and 437 Ma, n=9), and a 424 Ma peak represents the single largest peak within Member A of the Sheep Pass Formation type section (n=22 or 13%). Smaller ca. 420 Ma peaks occur in Member C and E of the Sheep Pass Formation type section, the Stinking Spring Conglomerate, and the Lowry Spring section. Relatively minor populations of Devonian zircons are also present in Sheep Pass Formation Member A (363 Ma, n=5) and in the Stinking Spring Conglomerate (377 Ma, n=6). Lower Paleozoic population ages of 420 to 350 Ma are recognized within Triassic strata of eastern Nevada (Gehrels and Dickinson, 1995), although major Silurian peaks are not recognized within the Roberts Mountain allochthon. Major detrital zircon age peaks of 410 to 445 Ma are, however, recognized within Devonian to Triassic miogeoclinal strata of Alaska and British Columbia (Ross et al., 1997, Gehrels and Ross, 1998, Gehrels et al., 1999). A compilation of Paleozoic detrital zircon U-Pb ages from the Sheep Pass Formation and "tuffaceous" Sheep Pass Formation indicate that the principle Paleozoic age peaks are Silurian (423 and 442 Ma) (Fig 9B). The existence of a Silurian age peak in the Mississippian Scotty Wash Sandstone and incorporation into a majority of the Sevier hinterland sections analyzed suggests that this may be a more important age peak for upper Paleozoic strata in Nevada than previously recognized. Silurian detrital zircons were likely derived from lower Paleozoic volcanic arc terranes such as the Klamath Mountains where Silurian volcanism is documented (Metcalf et al., 2000), and subsequently incorporated into backarc basin strata of the Roberts Mountain allochthon.

Our studies indicate that Sevier hinterland strata contain significant populations of Mesozoic zircons, despite the fact that previous studies of the Newark Canyon Formation (Nolan et al., 1956; Vandervoort, 1987) and the Sheep Pass Formation type section (Winfrey, 1958, 1960; Kellogg, 1964; Fouch, 1979) (Fig. 9C) indicate the lack of a discernable volcaniclastic component. Petrographic sections of Sample 07NW2 from the Newark Canyon Formation type section however, indicate that altered lithic volcanic grains are a common sandstone constituent (Fig. 10A). The Newark Canyon Formation contains both volcanic-derived zircons (TuffZirc age of 120.6 ± 3.2 Ma) and a previously unrecognized water-lain tuff (116.1 ± 1.6 Ma) within the upper portion of the type section. The Newark Canyon Formation type section also contains a small Barremian population (129 Ma, n=3), a single grain of 141.5 ± 1.4 Ma age (Berriasian), and a single Middle Jurassic grain (171.1 ± 1.7 Ma).

The Sheep Pass Formation type section contains a significant population of Mesozoic zircons (n=62, or 13%), the age population of which changes markedly upsection. Nineteen Mesozoic grains were recovered from Member A (11% of the total) with peaks at 103 (n=8) and 110 Ma (n=4). Two Maastrichtian grains (with ages of 67.8 ± 1 Ma and 70 ± 1.3 Ma) were obtained from the uppermost sample within Member A (06SP20). The remaining Mesozoic grains within Member A display a wide spread of Early Cretaceous to Late Triassic ages, none of which define a robust population. Member C contains the largest component of Mesozoic grains with 35 grains (23%), but contains relatively few Cretaceous grains. The major Mesozoic age peak within Member C is Late Jurassic at 155 Ma (Kimmeridgian), with a minor Early Jurassic population at 186 Ma. Member E contains the smallest percentage of Mesozoic grains (n=7 or 8%), and these grains fall within a single 112 Ma age peak (Aptian). The overlying Stinking Spring Conglomerate also contains a relatively small Mesozoic population which defines an Aptian peak at 118 Ma (n=7) and two additional grains with ages of 92.1 ± 3.2 Ma and 97.7 ± 2.8 Ma. Thin-sections of sandstone cobbles within Member A of the Sheep Pass Formation type section indicate the reworking of older (Cretaceous?) volcaniclastic strata (Fig. 10B); while sandstones within the Sheep Pass Formation are dominated by grains of quartz, chert, and detrital carbonate (Fig. 10C), altered lithic volcanic grains are discernable as a minor component.

Sections of the "tuffaceous" Sheep Pass Formation typically contain no major Mesozoic detrital zircon populations, although relatively small populations or individual grains of Mesozoic age are common and worth noting. The Lowry Spring section yielded only one Mesozoic grain, which was of Late Jurassic age (154 ± 1.5 Ma, Kimmeridgian), while the overlying Sawmill Canyon section yielded a total of three mid- to Late Cretaceous grains (99.8 ± 1.1 Ma, 82.9 Ma ± 2.0 Ma, and 69.8 ± 2.3 Ma). Grains from the Duckwater Mountain section produced a small Cretaceous peak at 112 Ma (Albian), while the Kinsey Canyon section yielded only two Mesozoic grains with ages of 81.3 ± 2.1 Ma and 238.7 ± 5.2 Ma (Middle Triassic). The Murphy Wash section of the southern Snake Range yielded a single Late Cretaceous zircon with an age of 94.9 ± 3.5 Ma.

A compilation of geochronologic data from Mesozoic intrusions in north-central and east-central Nevada indicates a bimodal age distribution, with the Late Jurassic (145-175) and mid-to Late Cretaceous (65-110 Ma) representing two major intrusive pulses within the Sevier hinterland (du Bray, 2007). A bimodal age distribution is also apparent from a compilation of Mesozoic grains within the Sheep Pass Formation type section and "tuffaceous" Sheep Pass Formation, with major peaks at 154 Ma and 111 Ma (Fig 9C). Although the Sheep Pass Formation type section lacks identifiable volcanic clasts within conglomerate beds, cobbles of litharenitic sandstone not derived from local Paleozoic strata are present, suggesting that the ultimate source for many of the Mesozoic zircons present may have been from reworking of older Cretaceous volcaniclastic sedimentary strata such as the Newark Canyon Formation. Aptian to Barremian (116 to 129 Ma) zircons present in the Newark Canyon type section are also present in the Sheep Pass Formation type section, and widely scattered sections assigned to the Newark Canyon Formation have been assigned Albian-Aptian ages based on biostratigraphy (Nolan et al., 1956; Fouch et al., 1979). While few localities of Cretaceous or Jurassic volcanic strata are known in east-central Nevada, erosion during the Cretaceous and early Paleogene may have removed extrusive volcanic strata linked to currently exposed intrusions (du

Bray, 2007). Successive recycling of older hinterland strata as seen in the Sheep Pass Formation type section and the overlying Stinking Spring Conglomerate illustrates that intervals of hinterland deposition were separated by widespread erosion and reworking. Late Cretaceous plutons of 95-65 Ma are relatively common in eastern Nevada (du Bray, 2007), but lack of corresponding age peaks in Sevier hinterland strata suggest that intrusions during this period were dominantly deep-seated and were unroofed following the Eocene.

Sections of the "tuffaceous" Sheep Pass Formation are distinct from the Sheep Pass Formation type section in that thin-sections reveal abundant lithic volcanic fragments (Fig. 10D), detrital biotite, and abundant feldspar. Detrital zircon separates contain distinctly elongated, volcanic-sourced zircons that range in age from 35 to 38 Ma. A compilation of Eocene detrital zircon ages indicate a peak in magmatic activity in east-central Nevada at 36 Ma (Fig. 9D). The TuffZirc age determination of 37.7 ± 0.6 Ma from the upper portion of the Stinking Spring Conglomerate invalidates the "tuffaceous" Sheep Pass Formation correlation of Fouch (1979), indicating instead that the Duckwater Mountain, Sawmill Canyon, and Kinsey Canyon sections are younger than or coeval with the deposition of the basal member of the Garrett Ranch Group which unconformably overlies the Sheep Pass Formation type section. The Oligocene ZircTuff age of 31.9 ± 0.6 Ma obtained from the Murphy Wash section overlaps with K-Ar and $^{40}Ar/^{39}Ar$ ages obtained from volcanic strata within the Garrett Ranch Group (Hose et al., 1976; Best et al., 1993).

A small number of zircons indicate ages from 39 to 49 Ma, however none of the sections analyzed contain statistically robust populations older than 37 Ma. Volcanic strata ranging in age from 43-39 Ma have been documented in northeastern Nevada and adjacent Utah (Brooks et al., 1995). Ages of 39-40 Ma have also been obtained from volcanic strata and granitic dikes of the Kern and Deep Creek Ranges northeast of the study area (McKee et al., 1976; Gans et al., 1989) and from tuffs overlying the White Sage Formation of west-central Utah (Dubiel et al., 1996).

Results of (U-Th)/He detrital zircon dating of the Mississippian Scotty Wash Sandstone, Sheep Pass Formation type section, and Stinking Spring Conglomerate indicate mid-to late Permian cooling ages (ca. 265-313 Ma) derived largely from zircons with Precambrian crystallization ages. These new data corroborate interpretations based on previous conodont alteration studies which suggest that neither deep thrust burial nor accumulation of a thick Mesozoic sedimentary succession have affected large regions of upper Paleozoic strata in east-central Nevada (Gans et al., 1990). The preservation of Permian cooling ages coeval with the Permian to Early Triassic Sonoma orogeny also support the hypothesis that following Early Cretaceous contraction along the central Nevada fold-thrust belt, eastward propagation of the Sevier foreland fold-thrust belt occurred without the development of major surface-breaking thrust faults in east-central Nevada, at least locally (Armstrong, 1972; Gans and Miller, 1983; Gans et al., 1989; Miller and Gans, 1989).

Mesozoic cooling ages preserved in the Sheep Pass Formation type section reveal three distinct peaks at 135 Ma (Berriasian), 106 Ma (Albian), and 80 Ma (Campanian). While Albian cooling ages overlap with 104 Ma and 111 Ma U-Pb crystallization peaks, the largest cooling age peak occurring at 80 Ma does not correspond with any U-Pb crystallization ages from the Sheep Pass Formation type section, and a 135 Ma crystallization peak is similarly unrepresented. The principle cooling age peak of the Stinking Spring Conglomerate is 40 Ma, although the fact that zircons with Eocene cooling ages are euhedral may indicate a genetic link with ca. 38 Ma tuff-sourced U-Pb crystallization ages.

Tectonic and Paleogeographic Implications

Distributions of detrital zircon populations within the Newark Canyon Formation and Sheep Pass Formation suggest that sediment was derived primarily from local sources, with little evidence of long-range Cretaceous to Paleogene transport. Detrital zircon studies of the volcaniclastic Pine Nut, Luning and Lovelock assemblages of western Nevada contain Triassic populations with ages ranging from 218 to 243 Ma (Manuszek et al., 2000), while upper Paleozoic to lower Mesozoic terranes of the northern Sierra Nevada have yielded detrital zircons ranging from 370 to 185 Ma (Permian to Early Jurassic) (Spurlin et al., 2000) (Fig. 11). Geochronological studies within the Sierra Nevada magmatic arc indicate that pluton emplacement occurred over protracted intervals during the Triassic to Jurassic (206-155 Ma) and Cretaceous (125-88 Ma) (Evernden and Kistler, 1970; Stern et al., 1981; Bateman, 1983; Saleeby et al., 1989), and volcaniclastic sediments within the Cretaceous Great Valley forearc basin similarly display a wide range of Triassic to Late Cretaceous zircon populations reflecting sediment derivation primarily from the Sierra Nevada magmatic arc (DeGraaf-Surpless et al., 2002). Lack of significant populations of Triassic, Early to Middle Jurassic, and Late Cretaceous zircons within Sevier hinterland deposits of east-central Nevada suggest geographic isolation from lower Mesozoic terranes of western Nevada and the Sierra Nevada magmatic arc. Geographic isolation is also reflected in late Eocene Sevier hinterland strata of east-central Nevada, which lack discernable populations derived from the Middle Eocene (43-39 Ma) northern Nevada volcanic field (Brooks et al., 1995).

The deposition of the Newark Canyon Formation was intimately linked with motion along the central Nevada fold-thrust belt in Albian-Aptian time (Vandervoort and Schmitt, 1990; Carpenter et al., 1993). The central Nevada fold-thrust belt largely involved east-vergent deformation of Cambrian-Pennsylvanian strata (Speed et al., 1988; Allmendinger, 1992; Carpenter et al., 1993; Taylor et al., 2000), with the Newark Canyon Formation deposited as a piggyback basin system (Vandervoort and Schmitt, 1990). Lack of significant zircon populations with a clear link to lower Mesozoic volcaniclastic sources of western Nevada suggests that local Paleozoic strata involved in fold-thrust belt deformation served as the principle sediment source for the Newark Canyon Formation. This observation suggests that the mid-Jurassic Luning-Fencemaker belt (Oldow, 1984; Wyld et al., 2001; Wyld, 2002) was not a major contributor of sediment to the Newark Canyon Formation, contrary to previous paleogeographic reconstructions (DeCelles, 2004, his fig. 10). Geographic isolation of the Newark Canyon Formation basin system from fluvial systems draining the Sierra Nevada and Early Mesozoic terranes of western Nevada was likely the result of intervening topographic lows represented by the King Lear Formation basin system of western Nevada (Martin et al., in press), as well as by the creation of high-standing topography within the central Nevada fold-thrust belt (Fig. 12A).

Extension and deposition of the Sheep Pass Formation type section was initiated in Campanian to Maastrichtian times (Vandervoort and Schmitt, 1990; Druschke et al., in press) following the onset of the Late Cretaceous amagmatic gap (Dickinson and Snyder,

1978) and the initiation of hinterland mid-crustal extension (Wells et al., 1990; Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; McGrew and Snee, 2000; Wells and Hoisch, 2008). Stratigraphic patterns and paleoflow indicators within the Sheep Pass Formation type section indicate that proximal source highlands lay to the east (Winfrey, 1958, 1960, Kellogg, 1964; Fouch, 1979, Druschke et al., in press) (Fig. 12B). The presence of Albian-Aptian detrital zircon populations and reworked volcaniclastic sandstone clasts within the Sheep Pass Formation type section suggest that Early Cretaceous strata partially coeval with the Newark Canyon Formation were once relatively extensive in the Sevier hinterland, and were subsequently eroded during the Late Cretaceous to Paleogene. However, the preservation of Permian cooling ages within upper Paleozoic strata of the Sevier hinterland indicates that post-Permian sedimentary sequences did not exceed 4 km in thickness.

The absence of significant detrital zircon populations younger than 103 Ma within the Sheep Pass Formation implies that topography was sufficient during the Late Cretaceous and Paleogene to isolate depocenters within the Sevier hinterland from the high-standing Sierra Nevada arc (Fig. 10B). Indications that west-flowing Late Cretaceous paleodrainages extended well into the interior of the Sierra Nevada (House et al., 2001) suggest that the majority of arc-related detritus was shed west into the Great Valley forearc basin. Peripheral antecedent river systems and interior extensional basins exhibiting internal drainage patterns are features common within the modern Tibetan, Turkish and Iranian plateau systems (Dilek and Moores, 1999). Internal drainage was initiated within portions of the Puna-Altiplano in the Miocene (Vandervoort et al., 1995). Similar conditions may have been widespread within the latest Cretaceous and Paleogene

Sevier hinterland of east-central Nevada. Width and configuration of the Sevier plateau varied substantially along the length of the orogen, allowing post-Early Cretaceous direct drainage connections between the magmatic arc and the Sevier foreland basin system to exist elsewhere, as in the case of the McCoy basin (Fig 10A, Barth et al., 2004).

The presence of abundant clasts derived from Ordovician to Neoproterozoic lithologies within the Stinking Spring Conglomerate (Kellogg, 1964) and sections of "tuffaceous" Sheep Pass Formation (Drewes, 1967; Gans et al., 1989) point to progressively deeper stratigraphic levels of unroofing during the middle to late Eocene. The late Eocene (ca. 35-38 Ma) marks a period of widespread extension and volcanism in east-central Nevada (Gans et al., 1989; Armstrong and Ward, 1991; Axen et al., 1993; Gans et al., 2001), however the existence of Late Cretaceous to middle Eocene alluvial and lacustrine deposits suggests that the initiation of upper crustal extension significantly predated volcanism within the Sevier hinterland. In this interpretation, the 7 km of structural unroofing interpreted by Gans et al. (1989) from the presence of Neoproterozoic quartzite and Jurassic volcanic clasts within late Eocene conglomerates of the Schell Creek Range may represent the combination of late Eocene and earlier episodes of Late Cretaceous to middle Eocene extension within the Sevier hinterland.

Conglomerate clast provenance (Drewes, 1967; Gans et al., 1989) and paleocurrents within late Eocene sections of the Schell Creek and central Egan Ranges indicate that sediment was largely derived from the east, similar to paleodispersal patterns of the Sheep Pass Formation type section. These observations suggest that the Snake Range formed a long-lived highland and potential drainage divide, as proposed by Christiansen et al. (1992, their fig. 15). Previous studies have suggested that the Grouse Creek-Raft

River-Albion core complex may represent a major ramp anticline related to the Sublett synclinorium, and that topographic uplift occurred as a result of hanging wall displacement over the ramp (Wells, 1997). The Confusion Range synclinorium (Hose, 1977) of east-central Utah lies along strike with the Sublett synclinorium, and is located east of the Snake Range core complex. The Snake Range core complex may therefore represent a southern continuation of this anticlinal ramp structure, which potentially contributed to its high relief relative to Late Cretaceous to Eocene depocenters of east-central Nevada.

Extensional basin deposits of latest Cretaceous to early Eocene age are widely distributed in the Sevier hinterland and have been identified within the Fish Creek Mountains, Grant Range, Egan Range and adjacent subsurface of Railroad and White River Valleys of east-central Nevada (Winfrey, 1958, 1960; Kellogg, 1964; Fouch, 1979; Vandervoort and Schmitt, 1990; Fouch et al., 1991; Druschke et al., in press), and the vicinity of Gold Hill in western Utah (Potter et al., 1995; Dubiel et al., 1996). Contrary to reconstructions that imply that the Sheep Pass Formation represents a single large lake basin (Winfrey, 1958, 1960), distribution of megabreccia and coarse alluvial deposits of variable Late Cretaceous to Paleocene age over a wide area of east-central Nevada suggests a number of discrete sedimentary basins. Middle to late Eocene extensional deposits are generally more abundant within east-central Nevada than latest Cretaceous to early Eocene deposits, potentially due to greater extensional fragmentation of the Sevier hinterland, or due to preservational bias of younger deposits. In many cases (i.e., the Sheep Pass Formation type section) middle to late Eocene deposits overlie older Sevier hinterland strata, which suggests that structural reactivation controlled long-lived depocenters.

Conclusions

Over 1300 LA-ICP-MS U-Pb detrital zircon analyses of strata within east-central Nevada record evolving tectonics and paleogeography throughout the transition from Early Cretaceous contraction to latest-Cretaceous-through-Eocene extension in the Sevier hinterland. Analyses from the Mississippian Scotty Wash Sandstone reveals major age peaks at 426 and 412 Ma, 1.1 Ga, 1.48 Ga, 1.65 Ga, 1.82 Ga, and 2.52 Ga, reflecting derivation primarily from the Roberts Mountain allochthon. Detrital zircon analyses of the Newark Canyon Formation type section and Sheep Pass Formation type section reveal that the majority of the zircons present were derived from recycling of upper Paleozoic strata found throughout east-central Nevada, and contain Silurian, Grenville (1.0 to 1.3 Ga), and mid-Mesoproterozoic to Archean age peaks similar to those in the Scotty Wash Sandstone.

The Newark Canyon Formation type section contains a previously unrecognized Aptian volcaniclastic component as revealed by a 120.6 ± 3.2 Ma U-Pb age within the Upper Conglomerate Member, and a 116.1 ± 1.6 Ma U-Pb age from a water-lain tuff within the Upper Carbonaceous Member. These new data indicate that the Newark Canyon Formation type section is Aptian or older. Absence of significant Jurassic or Triassic detrital zircons suggests that the Newark Canyon basin system was isolated from terranes to the west by high-standing topography within the central Nevada fold-thrust belt. Early Cretaceous volcaniclastic input to the Newark Canyon Formation type section may have been deposited as airfall from the coeval arc to the west, but was more likely the product of local volcanic sources within the Sevier hinterland today represented by scattered occurrences of coeval plutonic rocks.

The Sheep Pass Formation type section contains a relatively minor Mesozoic detrital zircon component comprising roughly 15% of the zircons analyzed, and displays a distinctly bimodal distribution of Early Cretaceous (111 Ma) and Late Jurassic (154 Ma) ages. This pattern resembles the bimodal age distribution of intrusions within east-central and north-central Nevada (du Bray, 2007); the lack of older Mesozoic populations and Late Cretaceous populations within the Sheep Pass Formation indicate continued geographic isolation of the Sevier hinterland from source areas of western Nevada and the Sierra Nevada. Mesozoic detrital zircon populations within the Sheep Pass Formation type section were likely derived from widespread Early Cretaceous volcaniclastic strata and hinterland volcanic centers that were subsequently eroded during the Late Cretaceous to Eocene. Geographic isolation of the Sevier hinterland during the Late Cretaceous to Paleogene from the high-standing Sierra Nevada to the west was likely due to the combination of 1) antecedent river systems on the periphery of the plateau to the west that transported arc-derived detritus primarily to the Great Valley forearc basin, 2) internal drainage within the interior plateau following a Late Cretaceous transition from regional shortening to extension, and 3) locally rugged topography within the plateau interior recorded by widespread coarse fanglomerate and block-slide deposits.

The ca. 25-30 m.y. gap between the deposition of Late Cretaceous-Paleocene extensional deposits of the Sheep Pass Formation type section, and more widespread middle to late Eocene sedimentary deposits suggest that two distinct extensional events occurred within the Sevier hinterland. Detrital zircon analyses of the Stinking Spring Conglomerate and the "tuffaceous" Sheep Pass Formation of Fouch (1979) reveal an up-section increase of late Eocene volcanic-derived zircons, defining a peak in magmatic activity at 36 Ma in east-central Nevada. In many cases, thick intervals of coarse conglomeratic strata lacking a tuffaceous component form the base of "tuffaceous" Sheep Pass Formation sections. This pattern suggests that extension preceded late Eocene magmatism in east-central Nevada and potentially initiated as early as the middle Eocene (Bridgerian, ca. 50.5-45.4 Ma) based on biostratigraphic age correlations. The overlap of late Eocene TuffZirc ages in the Stinking Spring Formation with sections of the "tuffaceous" Sheep Pass Formation invalidates the correlation of Fouch (1979) and indicates that late Eocene volcaniclastic strata variously assigned to the Sheep Pass Formation and basal Garrett Ranch Group are coeval.

(U-Th)/He detrital zircon thermochronommetry of the Scotty Wash Sandstone, Sheep Pass Formation type section, and Stinking Spring Conglomerate reveal that middle to late Permian cooling ages are preserved in zircons derived from local upper Paleozoic strata. These data corroborate earlier interpretations based on conodont alteration studies that upper Paleozoic strata were not buried under a thick Mesozoic section (Gans et al., 1990). Cretaceous cooling ages of 80 Ma (Campanian) are preserved within the Sheep Pass Formation type section, and no crystallization ages correspond to this Late Cretaceous cooling age peak. This suggests that 5-6 km of unroofing has occurred between Campanian cooling through 180° C, to Maastrichtian redeposition in the Sheep Pass Formation, a period of 10-15 m.y.

Figure Captions

Figure 1. Map of the western U.S. Cordillera showing the location of major Paleozoic to Mesozoic tectonic elements and potential detrital zircon source areas for Sevier hinterland strata. Box corresponds to area of Figure 2. GA = the Permo-Triassic Golconda Allochthon, RMA = the Devonian to Mississippian Roberts Mountain Allochthon, CNTB = the Early Cretaceous Central Nevada fold-thrust belt, GRA = the Grouse Creek/Raft River/Albion core complex, RH = the Ruby/East Humboldt core complex, SR = the Snake Range core complex. Modified from Smith and Gehrels (1994); Wyld, (2002); Wells and Hoisch, (2008); and Dickinson, (2008).

Figure 2. General geologic map of east-central Nevada modified from Stewart and Carlson, (1977). NW = Newark Canyon type section of the Newark Canyon Formation, DW = Duckwater Mountain section of the Sheep Pass Formation, SP = Sheep Pass Canyon type section of the Sheep Pass Formation, EB = Elderberry Canyon section of the Sheep Pass Formation, SC = Sawmill Canyon section of the Sheep Pass Formation, KC = Kinsey Canyon type section of the Kinsey Canyon Formation, MW = Murphy Wash section.

Figure 3. Stratigraphic columns for Cretaceous to Eocene hinterland deposits within east-central Nevada, including the Newark Canyon Formation type section (after Nolan et al., 1956, Vandervoort, 1987), Sheep Pass Formation type section (after Winfrey, 1958, 1960; Fouch, 1979, and the Sawmill Canyon section of the “tuffaceous” Sheep Pass

Formation. Additional age control for the Sheep Pass Formation type section from Good (1987) and Druschke et al. (in press).

Figure 4. A). A plain light image of detrital zircon separates from sample 06SP29, illustrating the dominant well-abraded zircon population, and subordinate euhedral to subhedral zircon population typical of the Sheep Pass Formation type section. B). A plain light image of an abraded, sub-rounded grain (from 06SP29). Generally grains displaying similar morphologies reveal Precambrian crystallization ages. C). Plain light image of a typical euhedral grain (from 06SP29), euhedral grains within the Sheep Pass Formation type section typically reveal Mesozoic crystallization ages. Grains B and C were sampled for (U-Th)/He dating.

Figure 5. Concordia diagrams of selected U/Pb detrital zircon age analyses from Cretaceous to Eocene hinterland strata of east-central Nevada. Sample 06NW1 (top center) is a tuff with a 116.1 ± 3.0 Ma eruptive age. Error ellipses are 1σ sigma.

Figure 6. Probability density plots of U-Pb detrital zircon data from the complete suite of Sevier hinterland deposits reported in this study, and the Mississippian Scotty Wash Sandstone (06SP30). The histogram and scale at left indicate the number of single grain U-Pb analyses corresponding to the probability curve. Mesoproterozoic and older peak determinations are given in Ga.

Figure 7. TuffZirc age extraction analyses (Ludwig and Mundil, 2002) for samples containing a single-source tuffaceous component. A). Sample 07NW2 from the Newark Canyon Formation type section; B). Sample 06SP22 from the uppermost Stinking Spring Conglomerate in Sheep Pass Canyon; C). Sample 05SM2 from the Sawmill Canyon section of the central Egan Range; D). Sample 05DW1 from the Duckwater Mountain section of the Pancake Range; E). Sample 05KC1 from the Kinsey Canyon section of the Schell Creek Range; F). Sample 07SR1 from Murphy Wash in the southern Snake Range.

Figure 8. Probability density plots of (U-Th)-He detrital zircon data from the: A). Mississippian Scotty Wash Sandstone , B). the Sheep Pass Formation type section, and C). the Stinking Spring Conglomerate. The histogram and scale at left depicts the number of single grain (U-Th)/He age analyses corresponding to probability curve peaks.

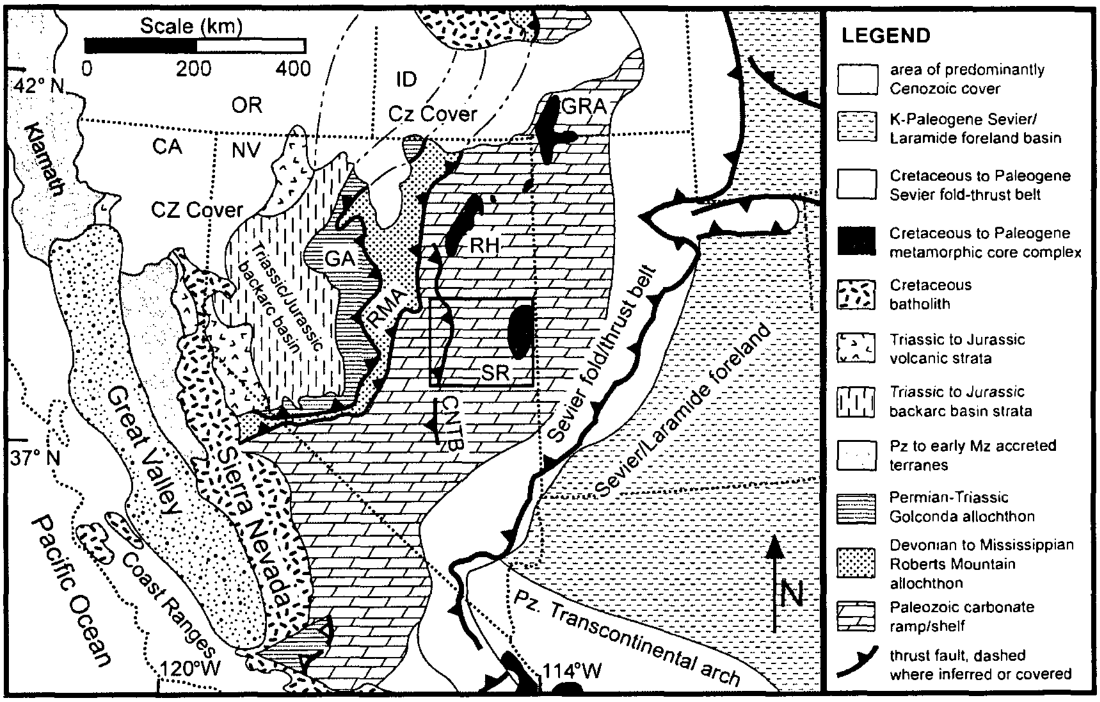
Figure 9. Probability density plots for Precambrian, Paleozoic, Mesozoic, and Eocene zircon populations compiled from the Sheep Pass Formation type section, Stinking Spring Conglomerate and 'tuffaceous" Sheep Pass Formation. Analyses from the Mississippian Scotty Wash Sandstone, Early Cretaceous Newark Canyon Formation, and Oligocene Murphy Wash section are not included in these plots.

Figure 10. Thinsections from Sevier hinterland strata: A). Sample (07NW2) from the Newark Canyon Formation with crossed nichols displaying lithic volcanic fragments (Lv) and monocrystalline quartz grains (Qm). B). Reworked Cretaceous(?) sandstone cobble from Member A of the Sheep Pass Formation type section in plain-polarized light

displaying mainly silicified volcanic lithic fragments (Lv). Circular structures within volcanic lithic grains are spherulites (sp) formed from devitrification of the originally glassy volcanic groundmass. C). Sample (06SP18) from Member C of the Sheep Pass Formation type section. Relatively well-sorted, fine sand grains are dominantly composed of monocrystalline quartz (Qm) and detrital carbonate (Ls), although sparse, altered lithic volcanic fragments (Lv) are discernable. D). Sample 05KC1 from the Kinsey Canyon Formation type section. Unaltered volcanic lithic fragments (Lv), feldspar and detrital biotite books (not shown) in addition to monocrystalline quartz (Qm) and detrital carbonate (Ls) grains are common sandstone constituents of stratigraphic sections grouped within the "tuffaceous" Sheep Pass Formation by Fouch (1979). Arrows are .25 mm in length.

Figure 11. Normalized age probability density plots for detrital zircon data including from the bottom up; the Sheep Pass Formation type section, Mississippian Scotty Wash Sandstone, and the Upper Conglomeratic Member of the Newark Canyon Formation type section. These are plotted against previously published U-Pb detrital zircon ages for the Golconda allochthon (Riley et al., 2000), Robert's Mountain allochthon (Gehrels et al., 2000), upper Paleozoic to Jurassic terranes of the northern Sierra Nevada (Spurlin et al., 2000), Cambrian to Devonian miogeoclinal reference for Nevada (Gehrels and Dickinson, 1995), and the upper Triassic Lovelock/Luning assemblages of western Nevada (Manuszek et al., 2000).

Figure 12. A). Schematic reconstruction of elements of the Early Cretaceous (Barremian-Albian) Sevier orogen (modified from DeCelles, 2004). Deposition of Newark Canyon Formation-correlative units within the Sevier hinterland likely occurred within localized, discrete sub-basins (Vandervoort and Schmitt, 1990) MSNI = Mojave-Snowlake-Nevada-Idaho dextral transform fault (after Wyld and Wright, 2001), KLB = King Lear basin system (location and paleocurrent data after Martin et al., in press), LFTB = Luning-Fencemaker fold and thrust belt which was inactive following the Middle Jurassic (after Wyld, 2002); CNTB = Central Nevada fold and thrust belt). Schematic reconstruction of the Sevier orogen during Maastrichtian to Early Eocene time including locations of developing core complexes (adapted from DeCelles, 2004). Potential Late Cretaceous reactivation of the McCoy basin is based on interpretations by Welle (2008) and T. Lawton (written comm.). During the middle to late Eocene, renewed extension led to the establishment of more widely distributed extensional basins that partially overlapped elements of the Maastrichtian to middle Eocene Sheep Pass basin. GRA = Grouse Creek-Raft River-Albion metamorphic core complex, RH = Ruby-East Humboldt core complex, SR = Snake Range core complex, SPB = Sheep Pass basin system, WSB = White Sage basin. Location of the zone of Late Cretaceous peraluminous granite intrusions is after Miller and Bradfish (1980). This zone generally corresponds to areas that experienced Late Cretaceous to Paleogene mid-crustal extension.


Scale (km)
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200
400
42° N
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CZ Cover
Klamath
Triassic/Jurassic backarc basin
GA
RMA
RH
GRA
SR
CNTB
Great Valley
Sierra Nevada
Coast Ranges
Pacific Ocean
Sevier fold/thrust belt
Sevier/Laramide foreland
Pz. Transcontinental arch
N
LEGEND
area of predominantly Cenozoic cover
K-Paleogene Sevier/ Laramide foreland basin
Cretaceous to Paleogene Sevier fold-thrust belt
Cretaceous to Paleogene metamorphic core complex
Cretaceous batholith
Triassic to Jurassic volcanic strata
Triassic to Jurassic backarc basin strata
Pz to early Mz accreted terranes
Permian-Triassic Golconda allochthon
Devonian to Mississippian Roberts Mountain allochthon
Paleozoic carbonate ramp/shelf
thrust fault, dashed where inferred or covered

Figure 1.

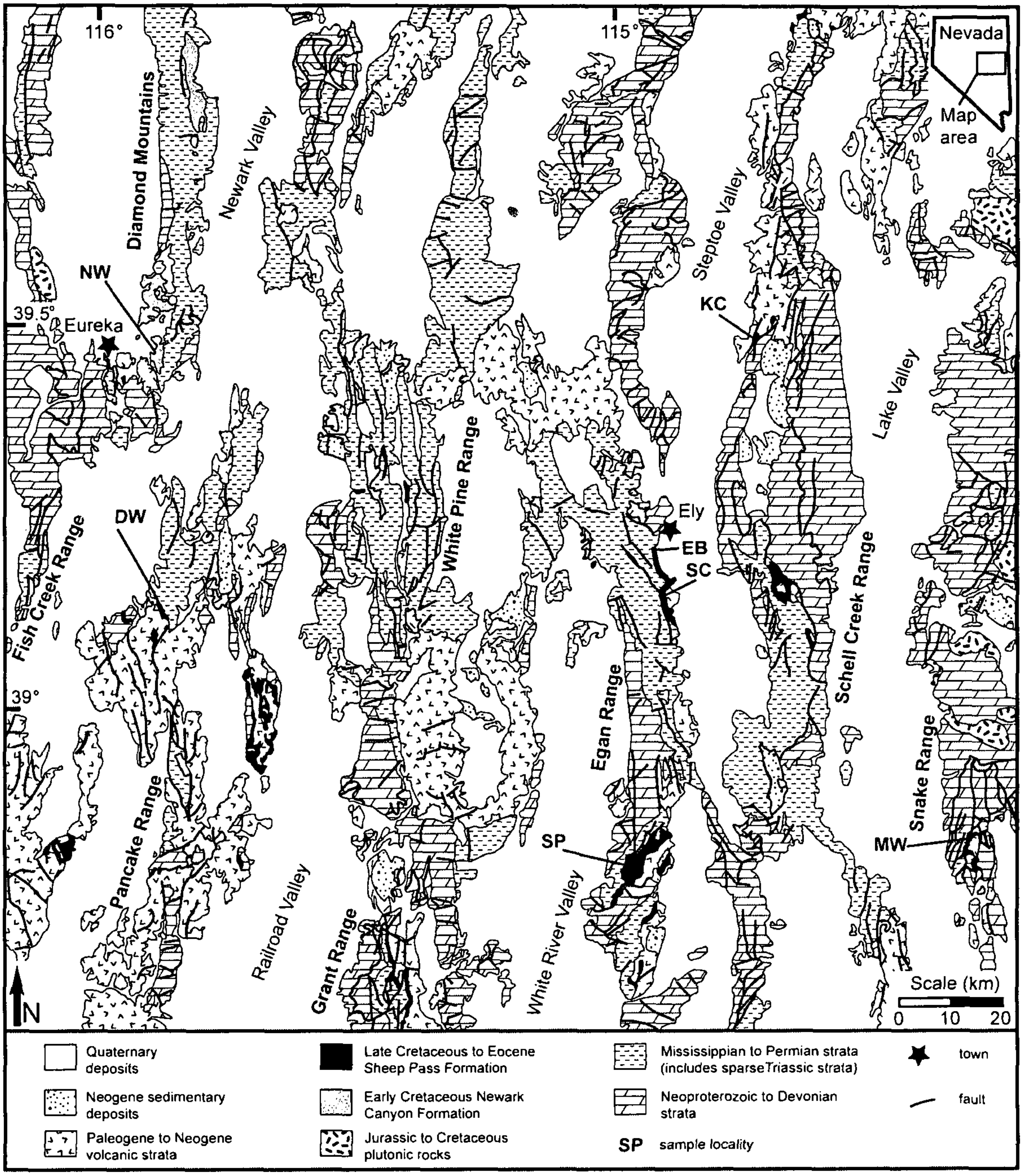

116°
115°
Nevada
Map area
Diamond Mountains
Newark Valley
NW
39.5°
Eureka
Steptoe Valley
KC
Lake Valley
White Pine Range
Ely
EB
SC
DW
Fish Creek Range
Schell Creek Range
39°
Egan Range
Snake Range
Pancake Range
SP
MW
Railroad Valley
White River Valley
Grant Range
N
Scale (km)
0 10 20
Quaternary deposits
Neogene sedimentary deposits
Paleogene to Neogene volcanic strata
Late Cretaceous to Eocene Sheep Pass Formation
Early Cretaceous Newark Canyon Formation
Jurassic to Cretaceous plutonic rocks
Mississippian to Permian strata (includes sparseTriassic strata)
Neoproterozoic to Devonian strata
SP sample locality
town
fault

Figure 2.

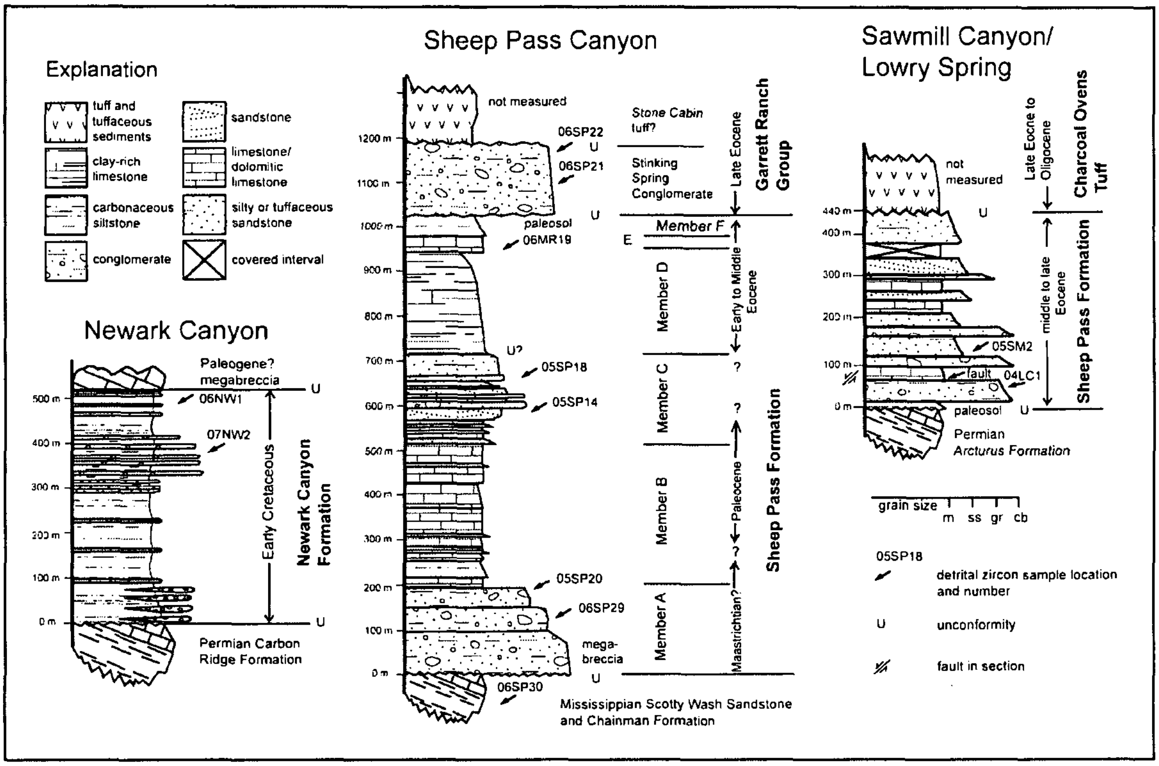


Figure 3.

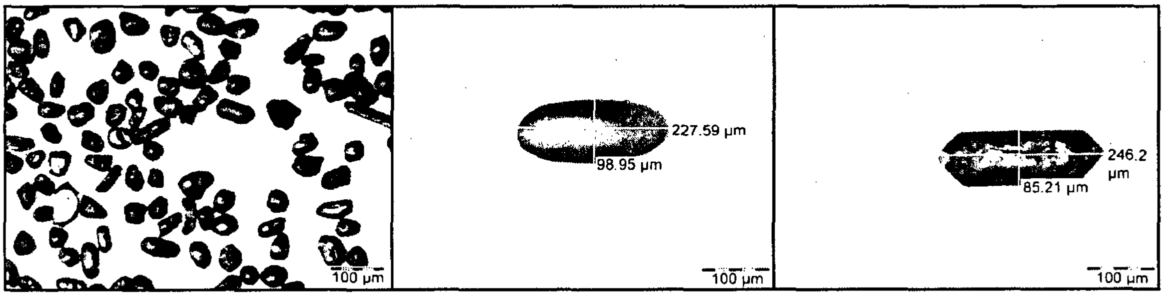


Figure 4.

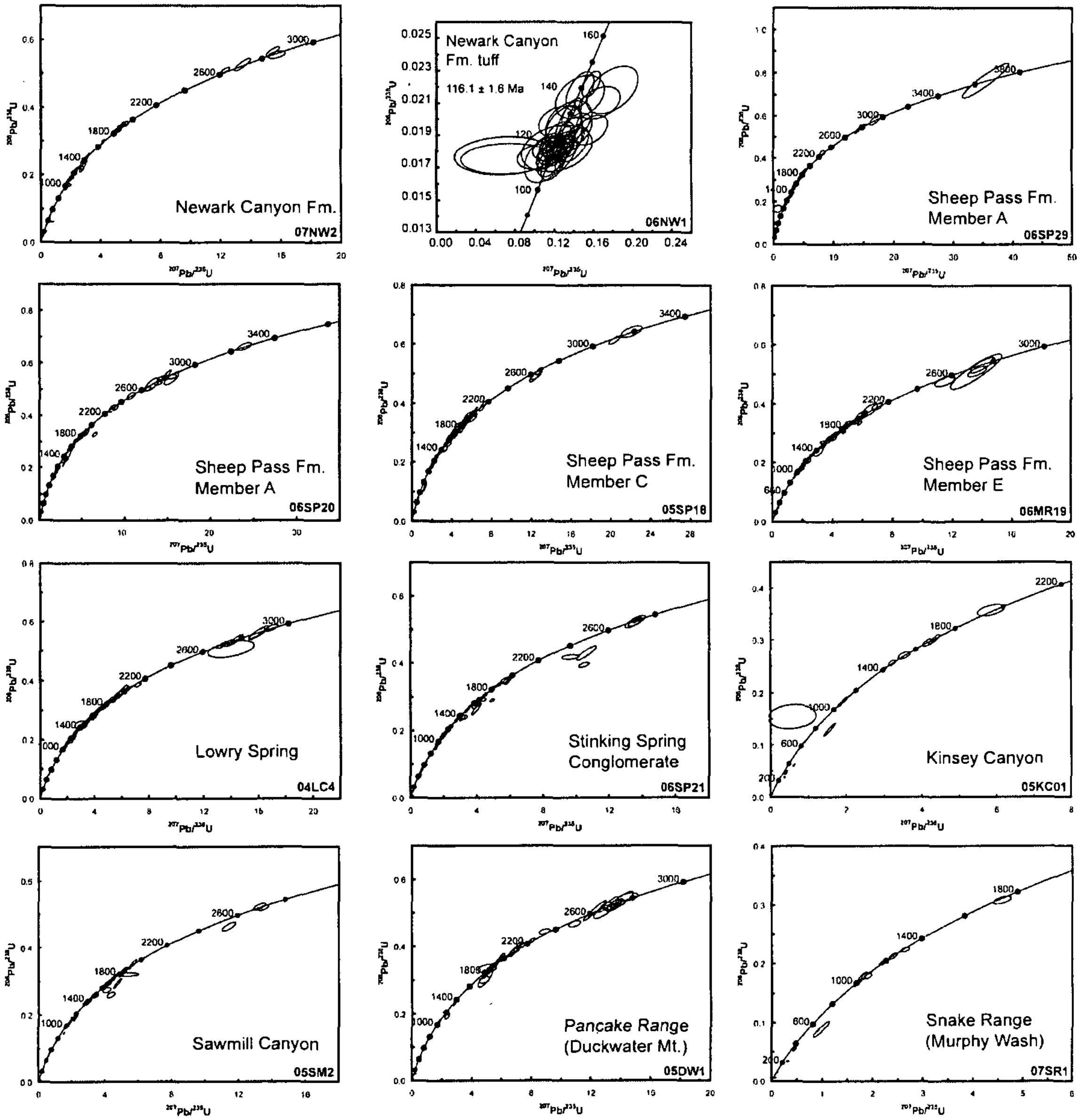
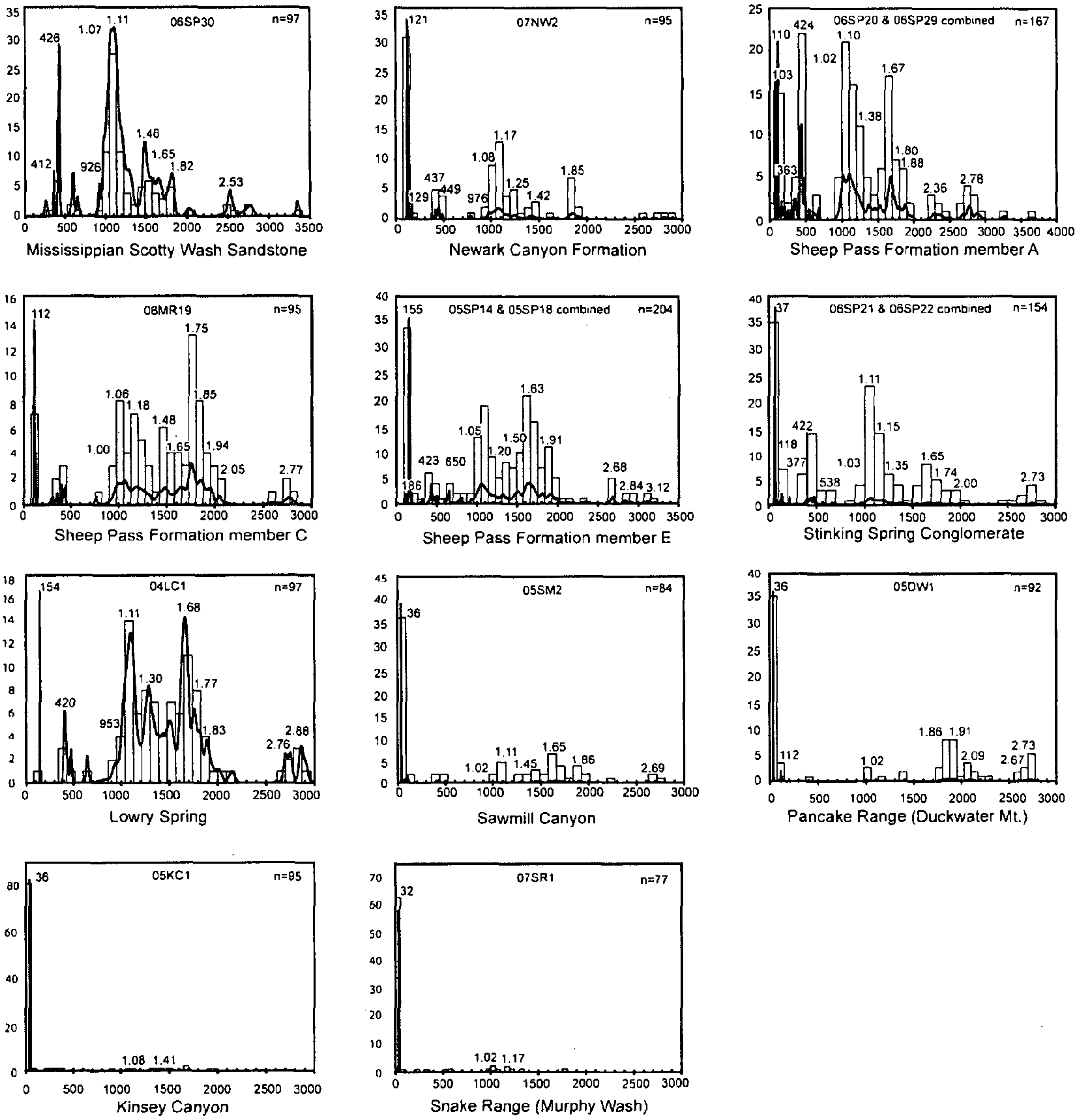

Newark Canyon Fm.
07NW2
Newark Canyon Fm. tuff
116.1 ± 1.6 Ma
06NW1
Sheep Pass Fm. Member A
06SP29
Sheep Pass Fm. Member A
06SP20
Sheep Pass Fm. Member C
05SP18
Sheep Pass Fm. Member E
06MR19
Lowry Spring
04LC4
Stinking Spring Conglomerate
06SP21
Kinsey Canyon
05KC01
Sawmill Canyon
05SM2
Pancake Range (Duckwater Mt.)
05DW1
Snake Range (Murphy Wash)
07SR1
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

Figure 5.



06SP30 n=97
426
1.07
1.11
412
926
1.48
1.65
1.82
2.53
0 500 1000 1500 2000 2500 3000 3500
Mississippian Scotty Wash Sandstone
07NW2 n=95
121
437
449
129
976
1.08
1.17
1.25
1.42
1.85
0 500 1000 1500 2000 2500 3000
Newark Canyon Formation
06SP20 & 06SP29 combined n=167
110
424
103
1.02
1.10
1.67
1.38
363
1.80
1.88
2.36
2.78
0 500 1000 1500 2000 2500 3000 3500 4000
Sheep Pass Formation member A
08MR19 n=95
112
1.75
1.06
1.18
1.85
1.48
1.00
1.65
1.94
2.05
2.77
0 500 1000 1500 2000 2500 3000
Sheep Pass Formation member C
155
05SP14 & 05SP18 combined n=204
1.63
1.05
1.50
1.20
1.91
423
650
186
2.68
2.84
3.12
0 500 1000 1500 2000 2500 3000 3500
Sheep Pass Formation member E
37
06SP21 & 06SP22 combined n=154
1.11
422
118
377
1.15
1.03
538
1.35
1.65
1.74
2.00
2.73
0 500 1000 1500 2000 2500 3000
Stinking Spring Conglomerate
154
04LC1 n=97
1.11
1.68
1.30
1.77
420
953
1.83
2.88
2.76
0 500 1000 1500 2000 2500 3000
Lowry Spring
05SM2 n=84
36
1.11
1.65
1.02
1.45
1.86
2.69
0 500 1000 1500 2000 2500 3000
Sawmill Canyon
36
05DW1 n=92
112
1.86
1.91
1.02
2.09
2.73
2.67
0 500 1000 1500 2000 2500 3000
Pancake Range (Duckwater Mt.)
36
05KC1 n=95
1.08
1.41
0 500 1000 1500 2000 2500 3000
Kinsey Canyon
07SR1 n=77
32
1.02
1.17
0 500 1000 1500 2000 2500 3000
Snake Range (Murphy Wash)

Figure 6.

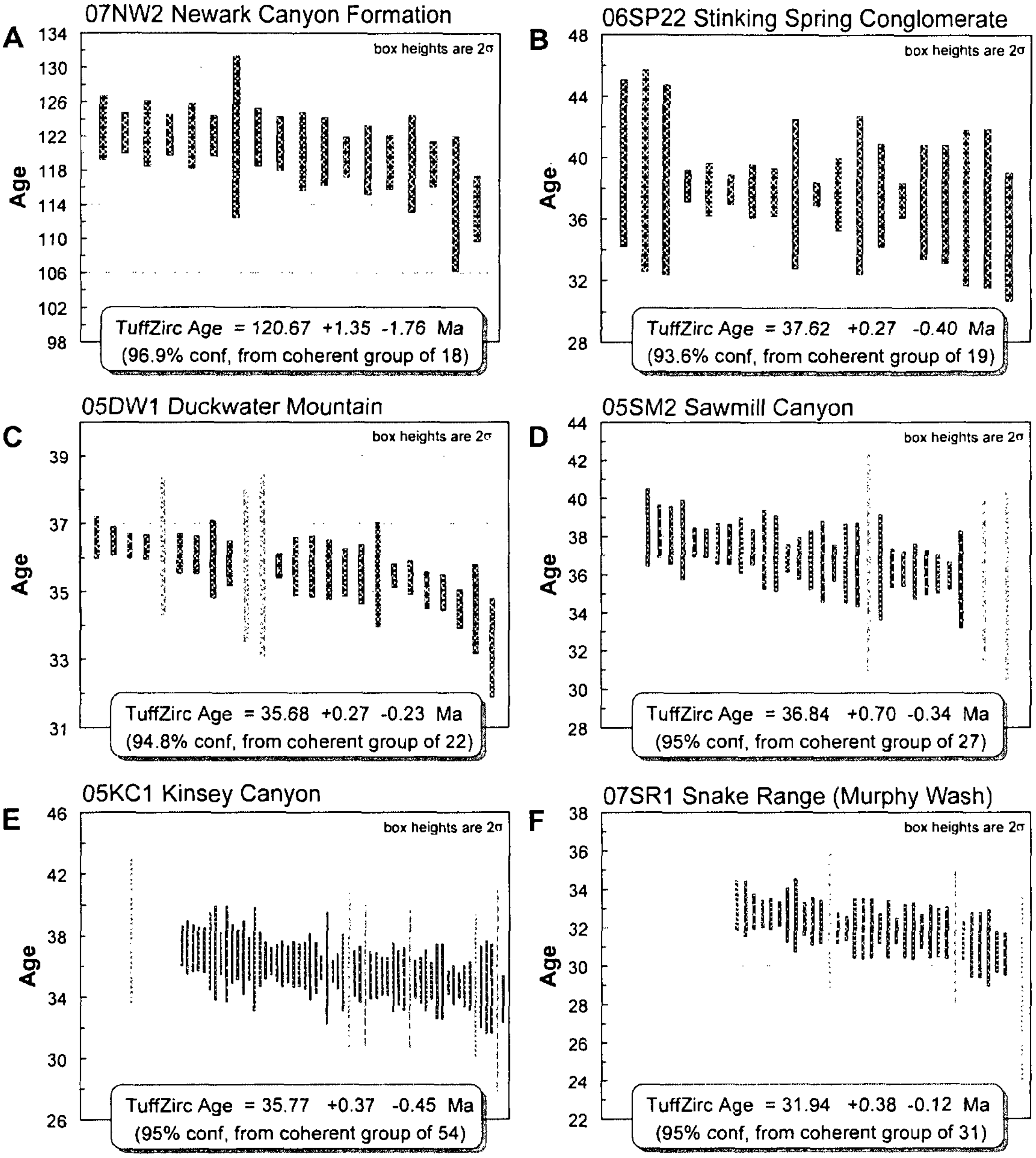

A
07NW2 Newark Canyon Formation
box heights are 2σ
Age
134
130
126
122
118
114
110
106
102
98
TuffZirc Age = 120.67 +1.35 -1.76 Ma
(96.9% conf, from coherent group of 18)
B
06SP22 Stinking Spring Conglomerate
box heights are 2σ
Age
48
44
40
36
32
28
TuffZirc Age = 37.62 +0.27 -0.40 Ma
(93.6% conf, from coherent group of 19)
C
05DW1 Duckwater Mountain
box heights are 2σ
Age
39
37
35
33
31
TuffZirc Age = 35.68 +0.27 -0.23 Ma
(94.8% conf, from coherent group of 22)
D
05SM2 Sawmill Canyon
box heights are 2σ
Age
44
42
40
38
36
34
32
30
28
TuffZirc Age = 36.84 +0.70 -0.34 Ma
(95% conf, from coherent group of 27)
E
05KC1 Kinsey Canyon
box heights are 2σ
Age
46
42
38
34
30
26
TuffZirc Age = 35.77 +0.37 -0.45 Ma
(95% conf, from coherent group of 54)
F
07SR1 Snake Range (Murphy Wash)
box heights are 2σ
Age
38
36
34
32
30
28
26
24
22
TuffZirc Age = 31.94 +0.38 -0.12 Ma
(95% conf, from coherent group of 31)

Figure 7.

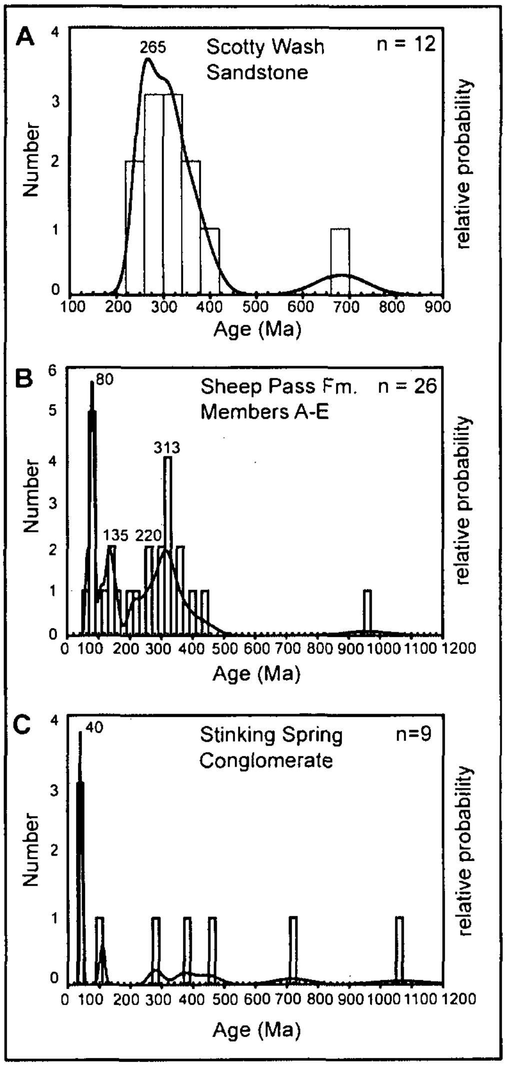

A
Scotty Wash
Sandstone
n = 12
265
Number
relative probability
0
1
2
3
4
100 200 300 400 500 600 700 800 900
Age (Ma)
B
Sheep Pass Fm.
Members A-E
n = 26
80
313
135 220
Number
relative probability
0
1
2
3
4
5
6
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
Age (Ma)
C
Stinking Spring
Conglomerate
n=9
40
Number
relative probability
0
1
2
3
4
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
Age (Ma)

Figure 8.

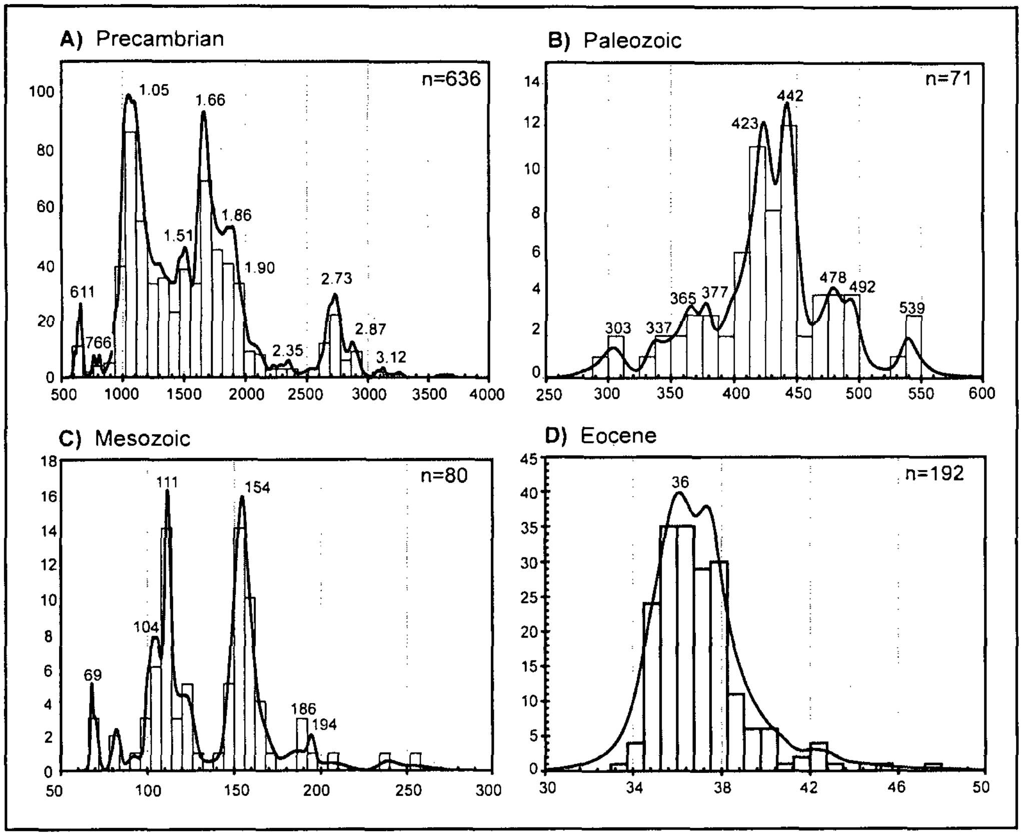

A) Precambrian
n=636
1.05
1.66
1.51
1.86
1.90
611
766
2.35
2.73
2.87
3.12
0
20
40
60
80
100
500
1000
1500
2000
2500
3000
3500
4000
B) Paleozoic
n=71
442
423
365
377
303
337
478
492
539
0
2
4
6
8
10
12
14
250
300
350
400
450
500
550
600
C) Mesozoic
n=80
111
154
104
69
186
194
0
2
4
6
8
10
12
14
16
18
50
100
150
200
250
300
D) Eocene
n=192
36
0
5
10
15
20
25
30
35
40
45
30
34
38
42
46
50

Figure 9.

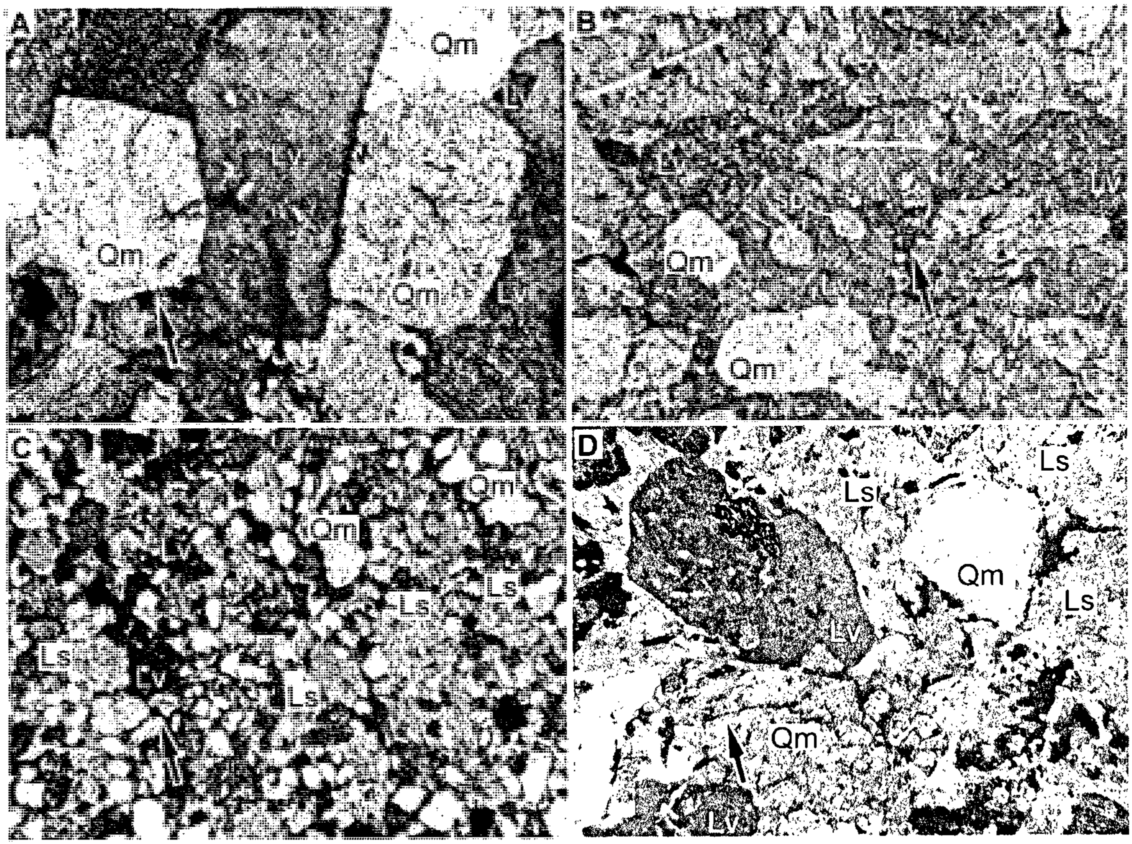

A
Qm
Lv
Qm
Qm
Lv
B
Lv
Lv
Qm
Qm
Lv
C
Qm
Qm
Lv
Ls
Ls
Ls
Lv
Ls
D
Ls
Ls
Qm
Ls
Lv
Qm
Lv

Figure 10.

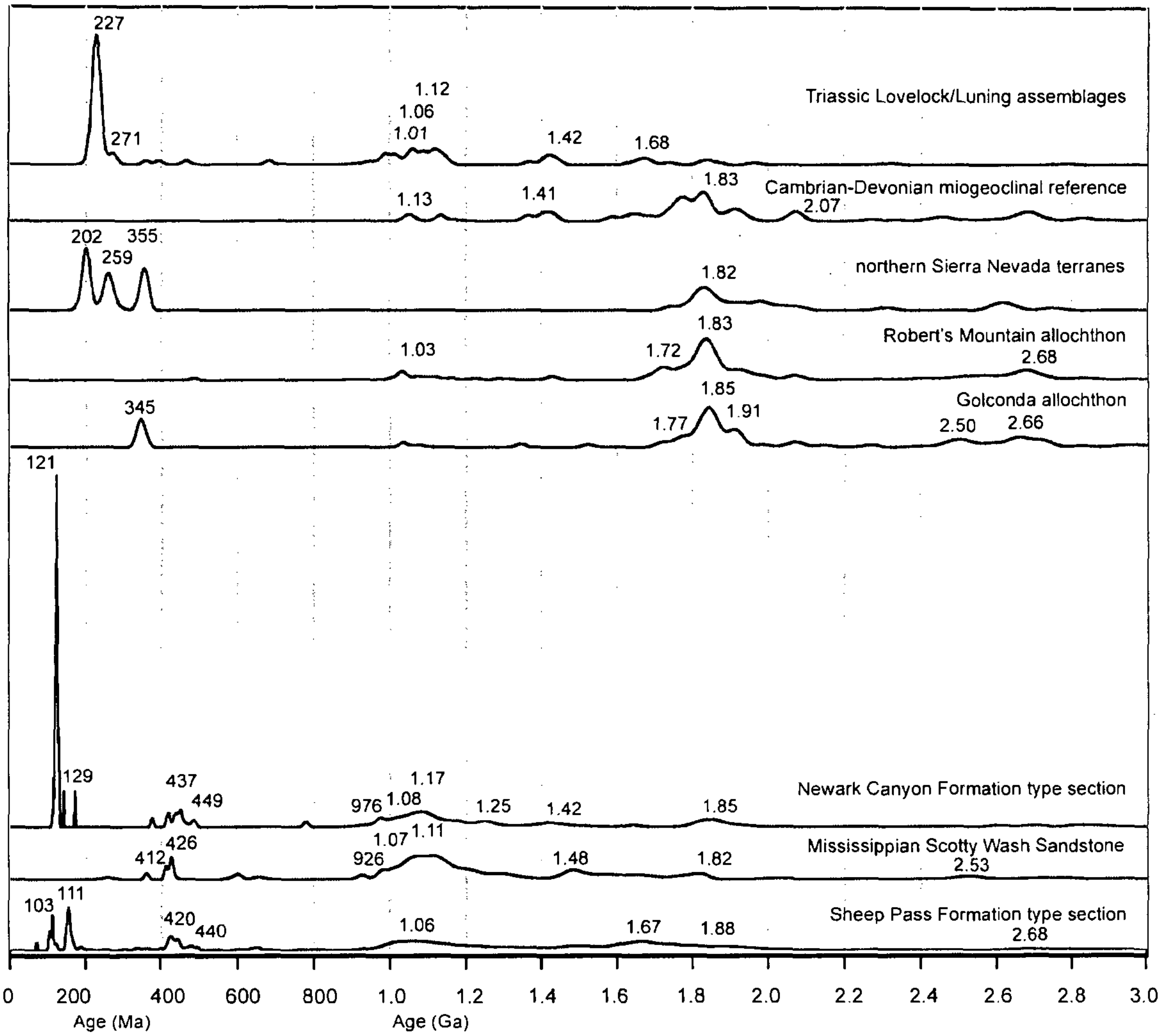

227
271
1.12
1.06
1.01
1.42
1.68
Triassic Lovelock/Luning assemblages
1.13
1.41
1.83
2.07
Cambrian-Devonian miogeoclinal reference
202
355
259
1.82
northern Sierra Nevada terranes
1.03
1.72
1.83
Robert's Mountain allochthon
2.68
345
1.77
1.85
1.91
Golconda allochthon
2.50
2.66
121
129
437
449
976
1.08
1.17
1.25
1.42
1.85
Newark Canyon Formation type section
412
426
926
1.07
1.11
1.48
1.82
Mississippian Scotty Wash Sandstone
2.53
103
111
420
440
1.06
1.67
1.88
Sheep Pass Formation type section
2.68
0
200
400
600
800
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Age (Ma)
Age (Ga)

Figure 11.

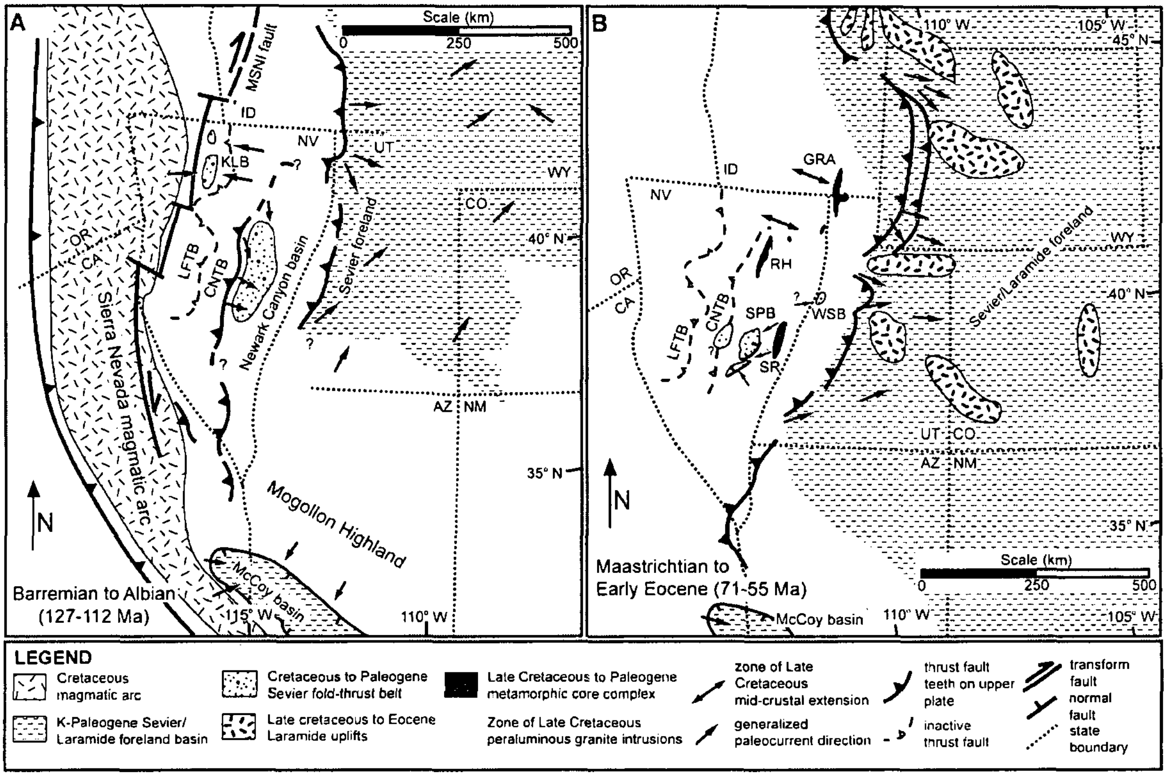

A
Scale (km)
0
250
500
MSNI fault
ID
NV
UT
WY
CO
40° N
KLB
OR
CA
LFTB
CNTB
Newark Canyon basin
Sevier foreland
Sierra Nevada magmatic arc
AZ
NM
35° N
N
Mogollon Highland
McCoy basin
Barremian to Albian
(127-112 Ma)
115° W
110° W
B
110° W
105° W
45° N
GRA
RH
SPB
SR
WSB
Sevier/Laramide foreland
UT
CO
AZ
NM
Maastrichtian to
Early Eocene (71-55 Ma)
McCoy basin
LEGEND
Cretaceous magmatic arc
K-Paleogene Sevier/ Laramide foreland basin
Cretaceous to Paleogene Sevier fold-thrust belt
Late cretaceous to Eocene Laramide uplifts
Late Cretaceous to Paleogene metamorphic core complex
Zone of Late Cretaceous peraluminous granite intrusions
zone of Late Cretaceous mid-crustal extension
generalized paleocurrent direction
thrust fault teeth on upper plate
inactive thrust fault
transform fault
normal fault
state boundary

Figure 12.

CHAPTER 4

STRUCTURAL, STRATIGRAPHIC, AND GEOCHRONOLOGICAL EVIDENCE FOR EXTENSION PREDATING PALEOGENE VOLCANISM IN THE SEVIER HINTERLAND OF EAST-CENTRAL NEVADA

Abstract

Alluvial and lacustrine deposits of the > 1 km thick, uppermost Cretaceous to middle Eocene Sheep Pass Formation of east-central Nevada provide a unique opportunity to test models pertaining to the tectonic and paleogeographic evolution of the Sevier hinterland. Within the south Egan Range, new 1:12,000 geologic mapping and stratigraphic observations reveal that latest Cretaceous initiation of the Sheep Pass basin was marked by megabreccia deposition, growth faults, and fanning dips that formed in response to down-to-the-northwest motion along the Ninemile fault, a presently low-angle normal fault displaying 4 km of stratigraphic throw. Continued Maastrichtian to late Paleocene motion along the Ninemile fault is suggested by widespread soft-sedimentary deformation within the Sheep Pass Formation, interpreted as seismites. Located 20 km to the south of the Sheep Pass Formation type section, the Shingle Pass fault similarly shows evidence for late Paleocene motion.

A subsequent episode of Eocene extension is recorded within the Sevier hinterland by a series of normal faults that repeat the Sheep Pass Formation type section, but are overlapped by the upper Eocene to Oligocene Garrett Ranch Group. These faults are

interpreted as splays related to reactivation of the Ninemile fault system. Megabreccia deposits of middle to late Eocene age in the hanging wall of the Shingle Pass fault also record this younger event. New ^{40}Ar/^{39}Ar ages of Eocene volcanic strata in the Egan and Schell Creek Ranges presented here indicate that while this later period of extension overlapped with ca. 38-35 Ma volcanism across a wide swath of east-central Nevada, renewed extension may have begun as early as the middle Eocene. Paleocurrent data from uppermost Cretaceous to upper Eocene alluvial fanglomerates of the Egan and Schell Creek Ranges record westward paleoflow away from the foreland and suggest that the area of the central Nevada/Utah borderlands formed a series of long-lived highlands bounded to the west by west-dipping normal faults. These data indicate that the Sevier hinterland of east-central Nevada was topographically more rugged than generally envisioned and experienced episodic extension throughout the latest Cretaceous and Paleogene. Late Cretaceous to Paleocene extensional basins overlapped temporally with previously documented mid-crustal extension within the Sevier hinterland, and with shortening within the Sevier foreland to the east. Orogen-top, synconvergent extensional basins are documented in both the modern Puna-Altiplano and Tibetan plateaus, and our new data strengthen their comparison with the Late Cretaceous to Paleogene Sevier hinterland.

Introduction

The Sevier hinterland is regarded by some as an ancient high-altitude orogenic plateau generally analogous to the modern Andean Puna-Altiplano or Tibetan Plateau (e.g., Coney and Harms, 1984, Jordan and Alonso, 1987; Jones et al., 1998; Dilek and

Moores, 1999; House et al., 2001; DeCelles, 2004), but many aspects of Late Cretaceous to Paleogene paleogeography and tectonics of the Sevier plateau remain controversial. The current prevailing paleogeographic model for the Sevier hinterland was advanced by Armstrong (1968, 1972); he concluded that the unconformity separating upper Cretaceous and Paleogene sedimentary deposits of eastern Nevada from underlying upper Paleozoic strata displays generally less than 10° of angular discordance, and therefore represents a widespread low-relief erosional surface. Similarly, later regional models have proposed that the Late Cretaceous to Paleogene Sevier hinterland was a region of low-relief, and experienced either tectonic quiescence or only minor contractional deformation (Gans and Miller, 1983). These conditions are hypothesized to have ended with the onset of southward migrating volcanism and extension that affected northeastern Nevada beginning in the middle Eocene (ca. 43-41 Ma) (Armstrong and Ward, 1991; Brooks et al., 1995; Mueller et al., 1999; Rahl et al., 2002; Haynes, 2003), and east-central Nevada beginning in the late Eocene (ca. 38-35 Ma) (Gans et al., 1989; Armstrong and Ward, 1991; Axen et al., 1993; Gans et al., 2001).

In contrast with models that advocate a contractional or quiescent tectonic setting for the Late Cretaceous to early Eocene Sevier hinterland, numerous studies have proposed that coeval hinterland sedimentary deposits of east-central Nevada and west-central Utah were deposited in extensional basins (Winfrey, 1958, 1960; Kellogg, 1959, 1964; Newman, 1979; Vandervoort and Schmitt, 1990; Fouch et al., 1991, Potter et al., 1995; Dubiel et al., 1996; Druschke et al., in press; Druschke et al., in review). The timing for the transition from contraction to extension in the Sevier hinterland is critical for determining the driving mechanisms of extension, and understanding long-term tectonic processes affecting orogenic plateaus. Previous models have hypothesized that volcanism was the driver of coeval middle to late Eocene extension in eastern Nevada through thermal weakening of the upper crust (Coney and Harms, 1984; Gans et al., 1989; Armstrong and Ward, 1991). However, evidence for upper crustal extension predating volcanism by 5-25 m.y. within the Sevier hinterland (between the latest Cretaceous and middle Eocene) suggests instead a potential link with coeval mid-crustal extension (Vandervoort and Schmitt, 1990, Druschke et al., in press).

Regardless of uncertainties concerning the timing for the onset of upper crustal extension, studies of the Grouse Creek-Raft River-Albion and Ruby-East Humboldt core complexes have established that the Sevier hinterland underwent ~14 km of mid-crustal extensional thinning during Late Cretaceous to Paleogene time based on thermochronology and thermobarometry of Barrovian mineral assemblages (Wells et al., 1990; Hodges and Walker; 1992; Camilleri and Chamberlain; 1997; McGrew et al., 2000; Harris et al., 2007; Wells and Hoisch, 2008). Within the Snake Range, Late Cretaceous mid-crustal extension is not recognized in most studies, although Lewis et al. (1999) speculated on the possibility of Late Cretaceous tectonic unroofing within the Snake Range core complex based on U-Pb monazite ages and a post ca. 75 Ma lowering of metamorphic temperature gradients. Paleocene to middle Eocene (57-41 Ma) motion along the northern Snake Range decollement is suggested by $^{40}Ar/^{39}Ar$ muscovite and K-spar cooling ages (Lee and Sutter, 1991; Lee et al., 1995).

The previous hypothesis of Hodges and Walker (1992) postulates that the upper crust of the Sevier hinterland was effectively decoupled during Late Cretaceous to early Paleogene mid-crustal extension, and behaved either passively, or experienced compression. This model is challenged by recent evidence documenting surface-breaking normal faults of latest Cretaceous age within east-central Nevada (Druschke et al., in press). Synconvergent extensional basins are features documented in the modern Andean Puna-Altiplano (Dalmayrac and Molnar, 1981; Allmendinger et al., 1997) and Tibetan Plateau (Molnar and Chen, 1983; Kapp et al., 2008). Extension preceding the onset of volcanism within the high-elevation Sevier plateau may have been driven by gravitational spreading toward the foreland (e.g. Axen et al., 1993; Jones et al., 1998, Sonder and Jones, 1999). Lithospheric delamination and mid-crustal thermal weakening during the transition to flat-slab subduction at the onset of the Laramide orogeny also have been proposed as mechanisms for Late Cretaceous to early Paleogene hinterland extension (e.g. Platt, 2007; Wells and Hoisch, 2008). In contrast, middle to late Eocene extension which affected both the hinterland and foreland regions of the Sevier orogen was likely the product of a decrease in plate convergence rates between North American and the Farallon/Kula plates, and subsequent slab rollback/foundering (Engebretson et al., 1985; Humphreys, 1995; Constenius, 1996; Dickinson, 2002).

The > 1 km thick Sheep Pass Formation type section comprises one of the most complete sedimentary sections within the Sevier hinterland, and strata correlative to the Sheep Pass Formation are scattered over an area of > 15,000 km^2 of modern-day east-central Nevada (Fouch et al., 1991) (Fig. 1). A Maastrichtian to middle Eocene age has been established for the Sheep Pass Formation type section based on biostratigraphy (Fouch, 1979; Good, 1987; Swain, 1999) as well as U-Pb detrital zircon and carbonate dating (Druschke et al., in press). Additional sections containing strata as young as Oligocene have been correlated to the Sheep Pass Formation on the basis of lithostratigraphy and proposed similarity in depositional age (Brokaw, 1967, Hose et al., 1976; Fouch, 1979, Good, 1987; Emry, 1990). Recent U-Pb detrital zircon studies indicate that the depositional age of many sections previously correlated to the Sheep Pass Formation overlap with deposition of the basal members of the Eocene to Oligocene Garrett Ranch Group (Druschke et al., in review). These data indicate that deposition of Upper Cretaceous to Eocene Sevier hinterland strata within east-central Nevada occurred in response to at least two discrete episodes of extension.

This paper presents new 1:12,000 scale geologic mapping from the southern Egan Range, in addition to new stratigraphic and paleocurrent data from sections correlated to the Sheep Pass Formation throughout the Egan and Schell Creek Ranges. Previous studies have documented latest Cretaceous (Druschke et al., in press) and late Eocene (Gans et al., 1989; Axen et al., 1993; Gans et al., 2001) normal faults and extensional basin deposits within east-central Nevada. This study presents additional evidence for latest Cretaceous and late Eocene extension in the Sevier hinterland, as well as the intervening interval of the Paleocene to middle Eocene. New $^{40}Ar/^{39}Ar$ geochronology from volcanic strata of the basal Garrett Ranch Group, and volcaniclastic sections previously correlated to the Sheep Pass Formation in the central Egan Range and Schell Creek Range establish that extension predated the ca. 38 to 35 Ma initiation of volcanism throughout east-central Nevada.

Regional Tectonic Framework

Previous studies within the Ruby-East Humboldt and Snake Range core complexes indicate that the earliest Sevier-related deformation, metamorphism and volcanism began locally in the Late Jurassic (Miller et al., 1988; Miller and Gans, 1989; Hudec, 1992, Miller and Hoisch, 1995; DeCelles, 2004, Sullivan and Snoke, 2007). East-vergent shortening deformation associated with the Sevier-related central Nevada fold-thrust belt is widely distributed throughout east-central Nevada (Speed et al., 1988; Allmendinger, 1992; Taylor et al., 1993; Taylor et al., 2000; DeCelles, 2004). The timing of deformation along the central Nevada fold-thrust belt is loosely constrained by deposits of the Aptian-Albian, syn-contractional Newark Canyon Formation (Vandervoort and Schmitt, 1990; Taylor et al., 2000). The Newark Canyon Formation has produced Aptian apatite-fission track exhumation ages (116 ± 13 Ma, Carpenter et al., 1993) and an Aptian U-Pb zircon age (116.1 ± 1.6 Ma) from a water-lain tuff in the uppermost member of the type section (Druschke et al., in review). Contraction along the central Nevada fold-thrust belt had ceased by mid-to Late Cretaceous times as indicated by a series of undeformed or untilted plutons (ca. 100-85 Ma) that cut earlier compressional structures in the Grant Range and adjacent Golden Gate Range (Taylor et al., 2000).

Cretaceous to Eocene strata of east-central Nevada unconformably overlie shallow marine sedimentary deposits of generally Devonian to Permian age (Winfrey, 1958, 1960; Armstrong, 1968, 1972; Fouch, 1979), and contain detritus derived primarily from recycling of local Paleozoic units prior to the onset of late Eocene (ca. 38-35 Ma) volcanism (Druschke et al., in review). Detrital zircon U-Pb ages of Sevier hinterland strata, including the Newark Canyon Formation type section and the Sheep Pass Formation type section, lack significant populations of Triassic, Early to Middle Jurassic, or Late Cretaceous zircons. These results indicate that the Sevier hinterland was geographically isolated from the Sierra Nevada magmatic arc and Triassic to Jurassic arc-related terranes of western Nevada (Druschke et al., in review). Geographic isolation of the Sevier hinterland was likely the result of uplift and rugged topography following initiation of the central Nevada fold-thrust belt in the Early Cretaceous, and continued during the latest Cretaceous and Paleogene due to sustained high elevation and initiation of hinterland extensional basins (Druschke et al., in review).

Detrital zircon (U-Th)/He detrital zircon dating within the Sheep Pass Formation type section, and the underlying Mississippian Scotty Wash Sandstone indicate that Permian cooling ages (representing cooling through ~6 km depths) have been retained (Druschke et al., in review). While these data suggest that source areas for the Sheep Pass basin did not experience deep stratigraphic or thrust burial, the Sheep Pass Formation also contains a significant zircon population of ca. 80 Ma (U-Th)/He cooling ages despite the lack of a corresponding Late Cretaceous U-Pb detrital zircon crystallization age peak (Druschke et al., in press; Druschke et al., in review). These cooling ages indicate significant unroofing occurred locally between Campanian time and Maastrichtian initiation of the Sheep Pass basin.

The only direct record of shortening of Laramide (80-50 Ma) age within the Sevier hinterland is a dated compressional P-T path from upper amphibolite facies metamorphic rocks of the Grouse Creek Range of northwestern Utah (Hoisch et al., 2008), pre-late Eocene recumbent folding of Late Cretaceous low-angle normal faults in the Grouse Creek-Raft River-Albion core complex (Wells, 1997), and post-early Eocene, pre-late Eocene folding of portions of the early Eocene White Sage Formation of west-central Utah (Potter et al., 1995). Folding due to fault-propagation in extensional settings is well established (e.g., Sharp et al., 2000) but studies documenting pre-late Eocene folding of the White Sage Formation do not distinguish between regional contraction and more localized contraction within an extensional setting (Potter et al., 1995; Dubiel et al., 1996). Gans (2000) interpreted folding of the Sheep Pass Formation in the northern White Pine Range to be related to strike-slip faulting in an overall extensional setting. Open, east-plunging folds affecting the Sheep Pass Formation and overlying Garrett Ranch Group were mapped by Kellogg (1959, 1964), who interpreted an extensional basin setting for the affected units. The middle Eocene (ca. 50 Ma) marks the cessation of contraction within the Sevier foreland as recorded by the development of extensional lacustrine basin systems superimposed on elements of the former Sevier contractional wedge in Utah (Constenius, 1996; DeCelles, 2004).

Background: The Sheep Pass Formation

The Sheep Pass Formation was originally named for non-volcaniclastic alluvial, fluvial and lacustrine strata in the Pancake, Grant and southern Egan ranges (Winfrey, 1958, 1960). Six members (A-F) were identified within the > 1 km thick type section at Sheep Pass Canyon (Fig. 2) in the southern Egan Range. A Maastrichtian to middle Eocene age (Bridgerian, 50.5-45.4 Ma) was assigned to the type section based on palynomorphs (Fouch, 1979), mollusks (Good, 1987), and ostracodes (Swain, 1999). A latest Cretaceous fossil age assignment for the basal Sheep Pass Formation type section has recently been corroborated by a Maastrichtian (66.1 ± 5.4 Ma) U-Pb age from lacustrine carbonate at the base of member B, in addition to Maastrichtian zircons (70 ± 1.3 Ma and 68 ± 1 Ma) within the uppermost beds of Member A (Druschke et al., in press). Megabreccia-containing deposits of the Sheep Pass Formation type section

(Member A) are latest Cretaceous age, similar to lacustrine limestone and associated megabreccia deposits of the Fish Creek Range (Vandervoort and Schmitt, 1990). However, megabreccia deposits within the Sheep Pass Formation in the Grant Range (Newman, 1979) are middle Eocene in age (Fouch, 1979), and megabreccia deposits at Shingle Pass (Kellogg, 1959; 1964) in the southern Egan Range overlie strata of late Paleocene to middle Eocene(?) age (Good, 1987).

Kellogg (1959, 1964) interpreted deposition of the Sheep Pass Formation to have been controlled by motion along the Shingle Pass fault, a NW-dipping normal fault approximately 20 km south of the Sheep Pass Formation type section in the southern Egan Range. The 20 km distance of the Shingle Pass fault from the Sheep Pass Formation type section suggests that this hypothesis is unlikely (Newman, 1979). More recently, Druschke et al. (in press) interpreted deposition of the Sheep Pass Formation type section to have been controlled by the Ninemile fault, a presently low-angle, NW-dipping normal fault located 3 km south of Sheep Pass Canyon. The Ninemile fault exhibits approximately 4 km of stratigraphic throw based on the juxtaposition of upper Paleozoic strata against lower Paleozoic strata (Kellogg, 1963, 1964). The Ninemile fault shows evidence for motion during deposition of the basal Sheep Pass Formation, and subsequent reactivation (Druschke et al., in press).

Winfrey (1958, 1960) originally interpreted the Sheep Pass Formation to be deposited in an extensional half-graben, due to westward thinning of exposures and subcrop, although no related normal faults were identified. Subsequent documentation of megabreccia associated with the Sheep Pass Formation in the southern Egan Range (Kellogg, 1959, 1964), Grant Range (Newman, 1979), and the Fish Creek Range

(Vandervoort and Schmitt, 1990), have been cited in support of an extensional basin interpretation. The Sheep Pass Formation type section unconformably overlies sedimentary strata of Mississippian to Pennsylvanian age, and in turn is unconformably overlain by the volcaniclastic Garrett Ranch Group of late Eocene to Oligocene age (Winfrey, 1958, 1960; Kellogg, 1959, 1964; Hose et al., 1976). Locally, the basal member of the Garrett Ranch Group is a >150 m thick conglomerate unit designated the Stinking Spring Conglomerate (Kellogg, 1959, 1964). A reworked tuff within the upper portion of the Stinking Spring Conglomerate in Sheep Pass Canyon has produced a U-Pb age of 37.7 ± 0.6 Ma (Druschke et al., in review), indicating a late Eocene maximum depositional age. The Stinking Spring Conglomerate in turn is unconformably overlain by approximately 400 m of rhyolitic ashflow tuff, reworked tuff, and localized basalt flows of the Garrett Ranch Group in Sheep Pass Canyon (Winfrey 1958; Kellogg, 1964; Hose et al., 1976) (Fig. 2). The basal rhyolitic tuff unit of the Garrett Ranch Group within Sheep Pass Canyon has been correlated to the Stone Cabin Formation, a welded tuff member of the Garrett Ranch Group in the Grant Range, based on phenocryst mineralogy (Hose et al., 1976). Radke (1992) reported a ^{40}Ar/^{39}Ar sanidine age of 35.3 ± 0.8 Ma from the Stone Cabin Formation.

The Sheep Pass Formation was expanded to include alluvial, fluvial and lacustrine strata within the central Egan Range (Ely Quadrangle) that is in part volcaniclastic (Brokaw, 1967; Hose et al., 1976; Fouch et al., 1979) (Fig. 2). Sheep Pass Formation deposits in the central Egan Range contain fossil assemblages that indicate a Bridgerian age (50.5-45.4 Ma) (Fouch, 1979; Good, 1987; Emry, 1990; Emry and Korth, 1990), but grade upward into tuffaceous alluvial and lacustrine strata. Sections of the Sheep Pass

Formation within the Ely Quadrangle are unconformably overlain by the Charcoal Ovens Tuff, which has produced a K-Ar age of 32.8 ± 1.1 Ma (McKee et al., 1976). On the basis of potential age overlap with the Sheep Pass Formation type section, Fouch (1979) designated these deposits "type 2" Sheep Pass Formation to denote the presence of a volcaniclastic component that is lacking in the type section. Fouch (1979) also correlated tuffaceous alluvial and lacustrine strata of the Schell Creek Range, originally designated the Kinsey Canyon Formation (Young, 1960) (Fig. 2), to the Sheep Pass Formation. However, recent U-Pb detrital zircon analyses of "type 2" Sheep Pass Formation deposits in the central Egan Range, and the Kinsey Canyon Formation type section indicate a substantial contribution from ca. 37-36 Ma volcanic sources (Druschke et al., in review).

At Cooper Summit in the Schell Creek Range (Fig. 1), a sequence of intercalated conglomerate, ashflow tuffs, and minor lacustrine limestone are interpreted to have been deposited in the hanging wall of a west-dipping normal fault (Gans et al., 1989). K-Ar dating of the intercalated tuffs indicates eruptive ages of ca. 38 to 35 Ma (McKee, 1976). Based on the presence of characteristic Jurassic granitic clasts derived from the Snake Range to the east, and Neoproterozoic quartzite within the conglomerates at Cooper Summit, Gans et al. (1989) concluded that 7 km of structural unroofing had occurred within the Snake Range by the late Eocene. The late Eocene age for the strata at Cooper Summit is similar to the eruptive ages of a series of synextensional tuff units within the Robinson District west of Ely, Nevada that bracket a period of rapid extension between 37.56 ± 0.03 Ma and 36.68 ± 0.04 Ma ($^{40}Ar/^{39}Ar$ sanidine) (Gans et al., 2001). Upper Eocene tuffs in the Robinson District overlie lacustrine limestone of the Sheep Pass Formation that locally are middle Eocene based on biostratigraphy (Good, 1987). In the northern White Pine Range, conglomerate and lacustrine limestone correlated to the Sheep Pass Formation are overlain by flows of basaltic andesite of late Eocene age ($^{40}Ar/^{39}Ar$ age of 38.2 ± 0.2 Ma) (Gans, 2000).

$^{40}Ar/^{39}Ar$ Geochronology Methods

At numerous localities within the Egan and Schell Creek ranges of east-central Nevada, the Sheep Pass Formation and correlative strata are unconformably overlain by, or intercalated with, volcanic units that are either undated or were dated using methods less precise than $^{40}Ar/^{39}Ar$ geochronology. In order to provide a more robust geochronologic framework for Paleogene strata of east-central Nevada, five samples were collected from volcanic units capping the Sheep Pass Formation in the Egan Range, and four samples were collected from upper Eocene deposits of the Schell Creek Range (sample locations are depicted on Fig. 1). Eight of the samples were composed of rhyolitic tuff containing abundant sanidine, while the ninth sample was aphanitic basalt (see Table 1 for sample descriptions). For each sample, 2-5 kg of freshly broken material was collected based on stratigraphic position within previously undated sections, in order to provide a series of bracketing ages across angular unconformities. Thin sections were made to assess the suitability for dating, and only samples displaying little to no alteration were selected for final processing.

Samples were crushed following standard procedures and sieved to varying size fractions based on average phenocryst dimensions for the individual samples, typically 100 to 300 μm. For the rhyolitic tuff samples, approximately 100 mg of sanidine crystals were hand-picked, and 300 mg of fresh glassy groundmass was hand-picked for the basalt sample. Separates were ultrasonically bathed in acetone and rinsed in deionized water. The sanidine fractions were briefly bathed in HF acid solution to remove any remaining glass. Samples were irradiated at the Oregon State University Radiation Center. Following irradiation, samples were analyzed at the Nevada Isotope Geochemistry Laboratory (NIGL). K-glass and CaF_2 correction factors from neutron induced reactions were determined using single crystal laser fusions. J factors for each sample were determined by laser fusion of 5-10 single crystals of neutron fluence monitors (FCT, Fish Canyon Tuff sanidine) (Cebula et al., 1986). Discrimination and sensitivity of the mass spectrometer was verified by repeated atmospheric argon analyses. Standard step-heating procedures (see Staudacher et al., 1978) for the basalt groundmass ages were performed using a resistance furnace. Single crystal age determinations for the sanidine samples were carried out using a 20 W CO_2 laser. Automation and age calculations were performed using LabSpec software (Lehigh University). Data used to construct age determination plots are presented in the appendices (Appendix IV).

$^{40}Ar/^{39}Ar$ Geochronology Results

The Egan Range

The type section of the Sheep Pass Formation is unconformably overlain by the Garrett Ranch Group of late Eocene to Oligocene age (Winfrey 1958, 1960; Kellogg, 1959, 1964; Hose et al., 1976; Best et al., 1993). Previous dating of the Garrett Ranch Group has largely been performed on members located in the Grant Range to the east (Hose et al., 1976; Radke, 1992; Best et al., 1993), and members present in the Egan Range have largely been correlated based on lithology and phenocryst mineralogy.

However, while the thickness of the Garrett Ranch Group in the Grant and Pancake Ranges to the west is > 1 km (Hose et al., 1976), the thickness of the Garrett Ranch Group where it overlies the Sheep Pass Formation type section is approximately 500 m (Kellogg, 1959; 1964). In addition, Kellogg (1959, 1964) identified a >150 m thick carbonate-clast conglomerate, the Stinking Spring Conglomerate, as the basal member of the Garrett Ranch Group in Sheep Pass Canyon. The Stinking Spring Conglomerate has not been identified in exposures of the Garrett Ranch Group elsewhere.

The Stinking Spring Conglomerate in Sheep Pass Canyon is unconformably overlain by a series of thin, local basalt flows, which are in turn overlain by non-welded rhyolitic ashflow tuffs. $^{40}Ar/^{39}Ar$ groundmass analyses of basalt (Sample 06SP10) overlying the Stinking Spring Conglomerate indicate a pseudo plateau age of 35.7 ± 0.3 Ma (Fig. 3). Sample 04SP18 was collected from basal exposures of the overlying ashflow tuff, and indicates a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 35.43 ± 0.11 Ma (Fig. 3). While the basalt pseudo plateau age indicates disturbance, possibly due to weathering or alteration, results are consistent with the overlying tuff age, and with the U-Pb detrital zircon maximum depositional age of the uppermost Stinking Spring Conglomerate. Sample 06MR2 was collected from a welded tuff comprising the uppermost member of the Garrett Ranch Group in Milk Ranch Canyon, located just below the contact with Miocene(?) siliciclastic deposits of the Milk Ranch section (Kellogg, 1959, 1964). Exposures of the Sheep Pass Formation and Garrett Ranch Group in Milk Ranch Canyon are contiguous with exposures in Sheep Pass Canyon. Results indicate a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 26.68 ± 0.04 Ma (Oligocene) (Fig. 3).

Approximately 20 km to the south of Sheep Pass Canyon at Shingle Pass (Fig. 1), 150 m of conglomerate and lacustrine limestone of the Sheep Pass Formation unconformably overlie Permian strata. At this locality, biostratigraphic correlations indicate that the Sheep Pass Formation is late Paleocene in age, similar to the basal strata of Member C within the type section (Good, 1987). The Sheep Pass Formation at Shingle Pass is overlain by megabreccia derived from the Pennsylvanian Ely Limestone extending for > 1 km to the north (Kellogg, 1959; 1964). Megabreccia deposits are in turn overlain by rhyolitic tuff, reworked tuff, and conglomerate of the Garrett Ranch Group. Sample 05SH1 was collected from basal exposures of the Garrett Ranch Group consisting of interbedded tuff, and conglomerate, and yielded a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 35.52 ± 0.08 Ma (Fig. 3).

Within the central Egan Range near Ely Nevada, the Sheep Pass Formation crops out continuously for a distance of approximately 20 km (Brokaw, 1967) (Fig. 1). Biostratigraphic correlations based on mammalian fossils from the basal beds of the Sheep Pass Formation within the central Egan Range (Elderberry Canyon) indicate a middle Eocene age (Bridgerian ca. 50.5-44.5 Ma) (Emry, 1990; Emry and Korth, 1990). Beds of middle Eocene age are, however, overlain by as much as 300 m of lacustrine limestone, and fluvial sandstone and conglomerate containing tuffaceous interbeds. U-Pb detrital zircon dating of tuffaceous sandstone and conglomerate at Sawmill Canyon indicate a 36.8 ± 1.1 Ma maximum depositional age (Druschke et al., in review). This sequence of non-tuffaceous and volcaniclastic strata equivalent to the Sheep Pass Formation (Brokaw, 1967; Hose et al., 1976; Fouch, 1979) is in turn unconformably overlain by the Charcoal Ovens Tuff, which displays approximately 10° of angularity with respect to the underlying Sheep Pass Formation.

Sample 05SM1 was collected from the base of the Charcoal Ovens Tuff in Sawmill Canyon. Results indicate a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 36.17 ± 0.08 Ma (Fig. 4). This late Eocene age is significantly older than the previously reported K-Ar age of 32.8 ± 1.1 Ma for the Charcoal Ovens Tuff (McKee et al., 1976). A late Eocene rather than Oligocene age is supported by correlation of the sphene-bearing Charcoal Ovens Tuff to the Cooper Summit Tuff of the central Schell Creek Range based on phenocryst mineralogy (Hose and Blake; 1976). The Cooper Summit Tuff has produced a K-Ar biotite age of 38.0 ± 3.8 Ma (Drewes, 1967). Additional data used for age determinations are presented in the appendices (Appendix IV).

The Schell Creek Range

The Kinsey Canyon Formation is named for discontinuous exposures of lacustrine limestone, conglomerate and interbedded tuffaceous sandstone within the central Schell Creek Range (Young, 1960). The type Kinsey Canyon Formation consists of approximately 140 m of thinly laminated lacustrine limestone, unconformably overlain by the Kalamazoo Tuff. Based on compaction foliation, the Kalamazoo Tuff displays approximately 20° of dip discordance with respect to the underlying Kinsey Canyon Formation The Kinsey Canyon Formation is visibly truncated by the planar erosional surface below the Kalamazoo Tuff. The Kalamazoo Tuff has produced a K-Ar age of 35.5 ± 0.5 Ma (Hagstrum and Gans, 1989), and K-Ar biotite age of 37.8 ± 1.0 Ma has been reported from exposures of rhyolite lava interbedded with the Kinsey Canyon Formation several km south of the type section (Gans et al., 1989). U-Pb detrital zircon dating of conglomerate beds at the base of the Kinsey Canyon Formation type section indicate a 35.8 ± 0.5 Ma maximum depositional age (Druschke et al., in review).

Previous studies have described beds of tuffaceous sandstone within the Kinsey Canyon Formation type section (Young, 1960; Fouch, 1979). We have concluded that these beds are in fact a series of water-lain tuffs based on their composition of crudely graded euhedral phenocrysts within a glassy groundmass in sharp, planar contact with thinly laminated lacustrine carbonate. A tuff bed approximately 30 cm thick, located 75 m above the base of the section (sample 05KC6) has produced a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 35.29 ± 0.12 Ma (Fig. 4). A new $^{40}Ar/^{39}Ar$ sanidine age determination of the overlying Kalamazoo Tuff (sample 06KZ1) yielded a weighted mean age of 35.30 ± 0.12 Ma, and a resulting isochron age of 35.39 ± 0.07 Ma (Fig. 4).

Located 40 km to the south of the Kinsey Canyon Formation type section, the Cave Lake section of the Kinsey Canyon Formation consists of approximately 350 m of conglomerate, stromatolite-bearing lacustrine limestone, and interbedded tuff (Fig. 2). Thickness must be considered approximate due to poor exposure within the upper portion of the section, although scattered exposures high within the section display bedding attitudes that are concordant with lower portions of the section. The Cave Lake section unconformably overlies the Mississippian Chainman Formation and brecciated, discontinuous blocks of the Pennsylvanian Ely Limestone. The Cave Lake section in turn is overlain by a sequence of rhyolite vitrophyre, rhyolitic tuff, rhyolite lavas and dacite lavas (Drewes, 1967). The volcanic sequence unconformably overlies the Kinsey Canyon Formation with 30° of angularity. Tuff interbedded with conglomerate in the upper Cave Lake section (sample 04CL12) yielded a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 36.38

± 0.11 Ma (Fig. 4). The overlying rhyolite vitrophyre (sample 04CL13) yields a $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 35.97 ± 0.10 Ma (Fig. 4).

Paleocurrent Analysis Methods and Results

Previous workers have inferred paleotransport directions for the Sheep Pass Formation based on conglomerate clast provenance, and the thickness and distribution of lithostratigraphic members, although no paleocurrent analyses of the Sheep Pass Formation have previously been published. A westward direction of transport has been inferred for alluvial and fluvial facies of the Sheep Pass Formation type section, based on thinning of conglomerate and sandstone-dominated Members A and C to the west (Winfrey, 1958, 1960; Fouch, 1979). A westward direction of transport has similarly been inferred for conglomeratic intervals of the Cooper Summit and Cave Lake sections of the Kinsey Canyon Formation based on the presence of Jurassic granite clasts exotic to the Schell Creek Range. Given the presence of Jurassic granitoids and the potential for significant unroofing by late Eocene time, the Snake Range to the east has been proposed as the likely source area (Drewes, 1967; Gans et al., 1989).

Alluvial and fluvial facies of the Sheep Pass Formation contain conglomerate and coarse-grained sandstone that preserve abundant unidirectional current ripples and pebble imbrication. Paleocurrent measurements, principally from pebble imbrications within alluvial fanglomerates, were collected from numerous intervals of Member A and C of the Sheep Pass Formation type section, and from the overlying Stinking Spring Conglomerate. Additional paleocurrent measurements were recorded from several fanglomerate intervals of the Sawmill Canyon section in the central Egan Range, and from the Cave Lake section of the Kinsey Canyon Formation in the Schell Creek Range. In total, 215 paleocurrent measurements were measured (Appendix V). Following restoration of original horizontality through use of a stereonet, results confirm previous inferences of a dominantly westward direction of transport for the Sheep Pass Formation (Fig. 5). A mean azimuth paleotransport direction of 278° was obtained from the Sheep Pass Formation type section, and a similar mean paleotransport direction of 265° was obtained from the overlying Stinking Spring Conglomerate. The Sawmill Canyon section and the Cave Lake section, separated by 20 km of the intervening Steptoe Valley, record mean paleotransport directions of 262° and 264° respectively. Previous paleomagnetic analyses of the Kalamazoo Tuff suggest that 28° ± 12° of clockwise rotation have affected the northern Schell Creek Range since late Eocene time (Hagstrum and Gans, 1989). Restoration of approximately 15-40° of clockwise vertical-axis rotation would not significantly alter the dominantly westward paleoflow direction indicated by pebble imbrication of the Cave Lake section.

Late Cretaceous to Eocene Structure and Stratigraphy of the Egan and Schell Creek Ranges

The Blue Spring Fault System

Located 3-5 km to the south and east of Sheep Pass Canyon, the presently low-angle Ninemile fault served as the basin-bounding normal fault during latest Cretaceous initiation of the Sheep Pass basin (Druschke et al., in press). Additional structural and stratigraphic evidence in the vicinity of Sheep Pass Canyon indicates that the Ninemile fault was reactivated in Eocene time. At Blue Spring approximately 3 km south of Sheep

Pass Canyon (Fig. 6), a series of exposures of Mississippian Chainman Shale and Scotty Wash Sandstone, Pennsylvanian Ely Limestone and Cretaceous to Paleocene Member B of the Sheep Pass Formation are juxtaposed against late Paleocene to middle Eocene Members C-F of the Sheep Pass Formation type section.

This previously unrecognized stratigraphic repetition is best explained by the presence of a series of two or more poorly exposed, NE-trending, down-to the west normal faults, here designated as the Blue Spring fault system. The inferred trace of the Blue Spring fault system extends from the Ninemile fault for approximately 3 km to the NE based on the outcrop pattern of repeated strata, and thereafter is overlapped by the Garrett Ranch Group. The basal member of the Garrett Ranch Group, the Stinking Spring Conglomerate, displays no apparent offset where it overlaps the trace of the Blue Spring fault system. In the footwall of the Blue Spring fault system, the Stinking Spring Conglomerate and overlying volcanic strata of the Garrett Ranch Group were deposited unconformably upon repeated beds of the Sheep Pass Formation Member B, as well as the underlying Pennsylvanian Ely Limestone. In the hanging wall of the Blue Spring fault system, the Stinking Spring Conglomerate unconformably overlies the Sheep Pass Formation type section with approximately 10° of angular discordance, locally truncating middle Eocene Members E and F.

Structural repetition along the inferred trace of the Blue Spring fault system is interpreted to represent up to 1 km of stratigraphic throw along the Blue Spring fault system based on the juxtaposition of the upper members of the Sheep Pass Formation with the basal Sheep Pass Formation and underlying upper Paleozoic strata. Motion on the Blue Spring fault system occurred following deposition of the Sheep Pass Formation, and preceded deposition of the Garrett Ranch Group. South of Blue Spring, the exposed trace of the Ninemile fault is not offset along the inferred trend of the Blue Spring fault system. A series of similar NE trending, down-to-the-northwest, normal faults repeat lower Paleozoic strata within the footwall of the Ninemile fault, but are not contiguous with the Blue Spring fault system.

The Blue Spring fault system is interpreted to represent a series of fanning-upward fault splays that merge with the through-going Ninemile fault at depth (Fig. 7). A similar relationship between presently low-angle normal faults and upward fanning splays of late Eocene age has been documented within the northern Egan Range (Gans and Miller, 1983). Motion on the Blue Spring fault splays was accompanied by motion along the Ninemile fault, an interpretation that is supported by the following observations: 1) the inferred trace of the Blue Spring fault splays are sub-parallel to the overall trend of the Ninemile fault, 2) the sense of down-to-the-northwest transport is the same as that of the Ninemile fault, and 3) the approximately 1 km of stratigraphic throw exhibited by the Blue Spring fault system is far less than the approximate 4 km stratigraphic throw along the Ninemile fault. While the present dip of the Ninemile fault averages 25° to the west, an original orientation of approximately 50° may be inferred if 25° of Neogene eastward rotation of the southern Egan Range block is restored.

Tectonic significance of the basal Garrett Ranch Group in the southern Egan Range

The Stinking Spring Conglomerate forms the basal member of the Garrett Ranch Group in Sheep Pass Canyon (Kellogg, 1959; 1964) and is composed of dominantly carbonate-cobble conglomerate, but contains scattered boulders of 0.5 m to >1 m diameter. In comparison with the conglomeratic Sheep Pass Formation Member A, the

Stinking Spring Conglomerate contains a more diverse clast assemblage, with clasts of Devonian to Ordovician lithologies being much more abundant (Druschke et al., in review). The Stinking Spring Conglomerate also contains abundant clasts recycled from the underlying Sheep Pass Formation type section Members A-E (Kellogg, 1959, 1964). These clasts are recognizable as gray-to-beige, ostracodal lacustrine limestone, tan sandstone and reworked conglomerate. Clasts of the Sheep Pass Formation indicate uplift and locally deep erosion prior to deposition of the Stinking Spring Conglomerate.

Timing of motion on the Blue Spring fault system is bracketed between the Bridgerian age (ca. 50.5 to 45.4 Ma) fossil assemblages within the upper members of the Sheep Pass Formation type section (Good, 1987), and a maximum depositional age of 37.7 ± 0.6 Ma from the uppermost Stinking Spring Conglomerate (Druschke et al., in review). However, the Stinking Spring Conglomerate overlaps the Blue Spring fault system with no apparent offset, suggesting that potential topography created by motion along the fault system was beveled by erosion prior to deposition of the Stinking Spring Conglomerate. The incorporation of clasts of the Sheep Pass Formation within the Stinking Spring Conglomerate may represent erosion of the Sheep Pass Formation within the footwall of the Blue Spring fault system or other potential and as-yet-unidentified, upward-fanning fault splays associated with the Ninemile fault. A number of unnamed fault splays repeating portions of the Sheep Pass Formation in Ninemile Canyon to the south have been identified (Druschke et al., in press).

In map view (Fig. 6), the outcrop pattern of the Stinking Spring Conglomerate largely mirrors Sheep Pass Formation Member A, and similarly thins to the northeast. The Stinking Spring Conglomerate is interpreted to have formed in an alluvial fan environment (Kellogg, 1959; 1964) similar to Member A and portions of Member C within the underlying Sheep Pass Formation type section (Fouch, 1979). The Stinking Spring Conglomerate is unconformably overlain by ashflow tuffs of the lower Garrett Ranch Group in Sheep Pass Canyon. Exposures of tuff within the lower Garrett Ranch Group along the southern flanks of Blue Mountain contain thick, interbedded conglomeratic intervals. Conglomeratic intervals thin rapidly to the north, away from the direction of the Ninemile fault, and are interpreted to represent a series of footwall-derived alluvial fans. Bedding dips within the basal Sheep Pass Formation range from 45° to as high as 65° to the east, although dips within the upper members average 35° to the east. The Stinking Spring Conglomerate displays bedding dips that average 25° to the east, continuing a pattern of fanning dips related to progressive rotation of hanging wall strata along the Ninemile fault. These stratigraphic relationships strongly suggest that deposition of the Garrett Ranch Group in the vicinity of Sheep Pass Canyon was related to motion along the Ninemile fault.

The Shingle Pass fault

The Sheep Pass Formation and Garrett Ranch Group at Shingle Pass (Fig. 1) are preserved within the hanging wall of the Shingle Pass fault (Kellogg, 1959, 1964). The Shingle Pass fault strikes E/W with a 55° dip to the north, and exhibits approximately 4 km of stratigraphic throw based on the juxtaposition of Cambrian to Ordovician strata in its footwall against Devonian to Permian strata in its hanging wall (Fig. 8). The Sheep Pass Formation at Shingle Pass consists of coarse fanglomerate (Member A) which undergoes a facies change to lacustrine limestone (Member B) approximately 1 km north of the Shingle Pass fault. Megabreccia derived from the Pennsylvanian Ely Limestone and Mississippian Scotty Wash Sandstone overlies the Sheep Pass Formation at Shingle Pass, which is locally truncated along an unconformity displaying 10° of angular discordance (Kellogg, 1959; 1964). This megabreccia deposit thins to the north and is overlain by conglomerate, tuff, and reworked tuff of the Garrett Ranch Group. A series of conglomerate bodies are interbedded with the lower Garrett Ranch Group at Shingle Pass; they thin to the north similar to exposures of the basal Garrett Ranch Group adjacent to the Ninemile fault in Sheep Pass Canyon.

Megabreccia deposits at Shingle Pass are interpreted to represent a series of block-slide deposits derived from the footwall of the Shingle Pass fault. Given that the megabreccia deposits consist of multiple coherent blocks estimated to exceed 30 m in width based on current exposures, and extend over 3 km to the north, the footwall of the Shingle Pass fault is inferred to have possessed considerably steep topography. Late Paleocene motion on the Shingle Pass fault is inferred from the fact that exposures of the Sheep Pass Formation consist of coarse fanglomerate (Member A) that undergoes a facies change to lacustrine limestone (Member B) abruptly 1 km to the north. Megabreccia deposits at Shingle Pass are assumed to be generally age correlative to the Stinking Spring Conglomerate, and to record middle to late Eocene reactivation of the Shingle Pass fault prior to deposition of the Garrett Ranch Group.

The Schell Creek Range

Sections of the Kinsey Canyon Formation within the central Schell Creek Range have previously been interpreted as extensional basin deposits related to motion on a west-dipping normal fault or series of faults of late Eocene age (Gans et al., 1989). The Cave Lake and Kinsey Canyon sections bracket major angular unconformities between the deposition of the Kinsey Canyon Formation and eruption of overlying late Eocene volcanic strata. Interbedded conglomerate, tuff and sandstone within the Cave Lake section dip approximately 45° to the east, and $^{40}Ar/^{39}Ar$ dating of Sample 04CL12 within the upper portion of this sequence indicates a depositional age of 36.38 ± 0.11 Ma. The unconformity separating the Cave Lake section from the overlying rhyolite vitrophyre is a planar erosional surface, indicating significant beveling. The overlying rhyolite vitrophyre has produced a $^{40}Ar/^{39}Ar$ age of 35.97 ± 0.10 Ma, and displays a dip of approximately 15° to the east based on compaction foliation of fiameé. The implications of these new data are that approximately 30° of structural tilting of the Cave Lake section, erosional beveling, and eruption of the overlying rhyolite vitrophyre occurred over the span of a maximum of 620 k.y., and potentially as little as 200 k.y.

The Kinsey Canyon Formation type section displays gentle eastward dips of approximately 25°, although the overlying Kalamazoo tuff displays approximately 45° of eastward dip based on compaction foliation of flattened pumice. The unconformity separating the Kinsey Canyon Formation from the Kalamazoo Tuff is a planar erosional surface that visibly truncates the underlying Kinsey Canyon Formation type section. This relationship implies that the Kinsey Canyon Formation was tilted 20° to the east and erosionally beveled prior to eruption of the Kalamazoo Tuff. New $^{40}Ar/^{39}Ar$ age constraints indicate that deposition of the upper Kinsey Canyon Formation, 20° of tilting, erosional beveling and eruption of the Kalamazoo Tuff took place between 35.29 ± 0.12 Ma (Sample 05KC6) and 35.39 ± 0.07 Ma (Sample 06KZ1). These $^{40}Ar/^{39}Ar$ ages bracket an interval of 290 k.y or less.

Seismites within the Sevier hinterland?

The Sheep Pass Formation type section is dominated by lacustrine limestone members deposited within shallow, permanent freshwater lakes spanning the latest Cretaceous to middle Eocene (Fouch, 1979; Good, 1987) (Fig. 2). Despite the low-energy setting implied by these fine-grained deposits, Members B and C of the Sheep Pass Formation contain previously undocumented, abundant, large-scale soft-sedimentary slump deposits and de-watering structures. Member B consists of > 250 m of predominantly thinly-bedded, microbially-laminated carbonate and carbonaceous siltstone. This monotonous succession is interrupted by intervals of complexly folded carbonate beds (Fig. 9A). These soft-sedimentary structures are encased within planar, undeformed strata, and contain rip-up clasts (Fig. 9B), pebble lags (Fig. 9C), and load casts (Fig. 9D) found locally in association with deformed intervals. Slump-folded lacustrine limestone beds are common throughout Member B; they include tabular, deformed intervals < 1 m thick that are laterally traceable for up to 100 m along strike, to lenticular intervals > 5 m thick (Figs. 9E) that are laterally traceable for several hundred meters before pinching out into thinly-bedded, undeformed strata.

Interbedded fluvial sandstone and lacustrine limestone of Member C similarly display evidence for widespread soft-sedimentary deformation. In additional to slump-folds (Fig. 9F), sandy beds of Member C commonly display flame structures, fluidization pipes and ball-and-pillar structures (Fig. 9G). The vergence of sigmoidal soft-sedimentary folds and deflected flame structures within Members B and C of the Sheep Pass Formation type section indicate transport to the west, consistent with westward paleoflow indicators within alluvial facies of Members A and C. Large-scale slump deposits demonstrate that low-energy lacustrine deposition within the Maastrichtian to Paleocene (Fouch, 1979; Good, 1987; Druschke, in press) Member B of the Sheep Pass Formation type section was interrupted repeatedly by mass-movements that transported sediment westward into the deeper portions of the lake system. Interbedded alluvial and lacustrine facies of the late Paleocene to Eocene(?) Member C (Fouch, 1979; Good, 1987) were similarly affected, although widespread examples of soft-sedimentary deformation are lacking in the uppermost members of the Sheep Pass Formation (D-F).

Soft-sedimentary deformation is also present within the Kinsey Canyon Formation type section in the Schell Creek Range. Here, a series of intensely folded intervals of thinly laminated carbonate mudstone are laterally traceable across the available exposures (Fig. 9H). Three intervals of intensely deformed beds are observable ranging from 1 to 5 dm in thickness, and separated by 5-10 m intervals of planar, undeformed beds. Deformed strata at Kinsey Canyon occur in laminated low-energy, shallow lacustrine carbonate mudstone and siltstone that preserve grazing trails, agglutinated caddis fly larval casings, root casts, and are not in close proximity to thicker or coarser-grained beds.

Water escape and fluidization structures are common where fine-grained deposits are rapidly loaded by turbidites, slumps and debris flows (Lowe, 1975). Within the Sheep Pass Formation type section, dewatering structures occur in association with slump deposits, but also occur in the absence of obvious causes for loading, as in the case of folded intervals of the Kinsey Canyon Formation type section. Numerous studies within tectonically active sedimentary basins have interpreted a seismic trigger for widespread and abundant soft-sedimentary deformation, particularly in lacustrine facies (Leeder, 1987; Rodríguez-Pascua et al., 2000; Montenat et al., 2007; Singh and Jain, 2007). Sedimentary features formed in response to seismic shocks are termed seismites (Seilacher, 1969) and may include slump folds, debris flows, megabreccia, injection structures, dewatering pipes and sand volcanoes.

Widespread soft-sedimentary deformation in the Sheep Pass Formation and Kinsey Canyon Formation are interpreted as potential seismites based on: 1) their occurrence within basins where normal faulting is indicated by fanning of dips, growth faults, and angular unconformities; 2) abundance and scale of structures within shallow lacustrine facies that lack evidence for significant bathymetric lows; 3) and morphological resemblance to published examples of seismites. Folded intervals within the Kinsey Canyon Formation type section strongly resemble the convex-up "mushroom-shaped structures" within Miocene silty lacustrine laminates in Spain interpreted as seismites (Rodríguez-Pascua et al., 2000, their figs. 7 and 10). Ruptured and overturned bedding in sandstone of the Sheep Pass Formation type section (Fig. 9G) resemble examples of sand volcanoes caused by seismically induced dewatering (Montenat et al., 2007, their figs. 13 and 15). Laterally traceable intervals of folded carbonate mudstones within Member B of the Sheep Pass Formation may represent "seismoslumps" caused by fluidization, which may occur within settings with very low slope gradients (Montenat et al., 2007). The occurrence of potential seismites within widely scattered lacustrine deposits of the Paleogene Sevier hinterland has not previously been documented.

Discussion

Paleogene extension in the Sevier hinterland of east-central Nevada

Previous workers have suggested that the earliest surface-breaking extension within the Sevier hinterland of east-central Nevada coincided with, and was driven by late Eocene volcanism ca. 38-35 Ma (Gans and Miller, 1983; Coney and Harms, 1984; Gans et al., 1989; Armstrong and Ward, 1991). Additional studies have documented poorly dated normal faults within east-central Nevada that offset Paleozoic units, but are overlapped by late Eocene (ca. 35-34 Ma) volcanic strata (Taylor et al., 1989; Axen et al., 1993). Within the Pequop Mountains of northeastern Nevada, Camilleri (1996) identified the Pequop fault as a low-angle normal fault that juxtaposes unmetamorphosed upper Paleozoic strata in its hanging wall against rocks exhumed from 11 km mid-crustal depths in its footwall. This fault is overlapped by ca. 41-39 Ma volcanic strata, indicating significant Late Cretaceous to early Paleogene extension and subsequent erosion prior to the onset of local Eocene volcanism (Camilleri, 1996). Normal faults associated with the lower Eocene (ca. 55-50.5 Ma) White Sage Formation of west-central Utah are similarly overlapped by upper Eocene volcanic strata (ca. 39-37 Ma) (Potter et al., 1995). Our documentation of surface-breaking normal faults coeval with deposition of Sheep Pass Formation Member A in the type section demonstrates that upper crustal extension affected the latest Cretaceous Sevier hinterland (Druschke et al., in press). In many cases, the lack of available age control for latest Cretaceous to Paleogene normal faults, possible subsequent reactivation, and widespread erosion within the high-elevation Sevier hinterland have combined to obscure this earlier extensional history.

Structural and stratigraphic evidence from the southern Egan Range indicates that continued extension following the latest Cretaceous initiation of the Sheep Pass basin affected the Sevier hinterland during Paleocene time. Within the Sheep Pass Formation type section, widespread evidence for large-scale soft-sedimentary slumping, liquefaction, and dewatering in Maastrichtian to upper Paleocene members suggests that unlithified sediments within the Sheep Pass basin were subjected to seismic shocks related to motion along the basin-bounding Ninemile fault system. At Shingle Pass, upper Paleocene (Good, 1987) beds of the Sheep Pass Formation coarsen toward the Shingle Pass fault, an indication that fault motion was coeval with deposition of the Sheep Pass Formation (Kellogg, 1959, 1964). Upper Cretaceous to Paleocene deposits of the Sheep Pass Formation are documented mainly to the west of the southern Egan Range, and have been identified in the Grant Range, Fish Creek Range, and subsurface areas of the adjacent valleys (Fouch, 1979; Vandervoort and Schmitt, 1990, Fouch et al., 1991; Carpenter et al., 1993).

Sections of middle to upper Eocene strata comprising the Elderberry/Sawmill Canyon sections in the central Egan Range were interpreted to have been originally contiguous with the Sheep Pass Formation type section based on potential middle Eocene age overlap (Fouch, 1979). Accordingly, correlative volcaniclastic strata were interpreted to have been present in the Sheep Pass Formation type section, but subsequently eroded along the unconformity separating the Sheep Pass Formation type section from the overlying Garrett Ranch Group (Fouch, 1979). Detrital zircon U-Pb ages from the Sheep Pass Formation type section, Stinking Spring Conglomerate, and Sawmill Canyon section (Druschke et al., in review) in addition to new $^{40}Ar/^{39}Ar$ ages presented in this paper invalidate the direct correlation of the Sheep Pass Formation type section with the Elderberry/Sawmill Canyon sections. This newly established geochronologic framework demonstrates that volcaniclastic strata of the Sawmill Canyon, Cave Lake and Kinsey Canyon sections are age correlative with the basal Garrett Ranch Group in Sheep Pass Canyon (Fig. 10). The presence of a regional unconformity separating a distinct sequence of uppermost Cretaceous to middle Eocene non-volcaniclastic sedimentary strata from a sequence of middle to upper Eocene deposits that are in part volcaniclastic suggests that extension within the Sevier hinterland occurred in two distinct phases (Fig. 11).

Middle Eocene timing for renewed extension is supported by structural and stratigraphic relationships in the Egan Range. In Sheep Pass Canyon, the initiation of the Blue Spring fault system and related reactivation of the Ninemile fault is bracketed by middle Eocene Members E-F of the Sheep Pass Formation type section, and upper Eocene strata (ca. 38-35.5) of the basal Garrett Ranch Group. At Shingle Pass, deposition of megabreccia upon an angular unconformity separating the Sheep Pass Formation from the Garrett Ranch Group similarly suggests reactivation of the Shingle Pass fault in middle(?) to late Eocene time, and the rejuvenation of considerable local topography. In the Elderberry Canyon section, > 40 fossil mammalian taxa of Bridgerian age (ca. 50.5 to 44.5 Ma) (Emry, 1990; Emry and Korth, 1990) are preserved within a sequence of coarse fanglomerate and lacustrine limestone conformably overlain by strata containing reworked tuff (Fouch, 1979). The observation that middle Eocene strata of the central Egan Range grade upward into strata containing late Eocene volcaniclastic input (Fouch, 1979) is the strongest indicator that renewed Eocene extension began in the middle Eocene prior to the onset of local volcanism. We interpret that deposition of the

Elderberry/Sawmill Canyon sections in the central Egan Range in the middle Eocene post-dated deposition of the uppermost members of the Sheep Pass Formation type section, which is permissible given the > 5 m.y. age range of previous biostratigraphic correlations (Fouch, 1979; Good, 1987; Emry, 1990; Emry and Korth, 1991).

Structural, stratigraphic and geochronologic data from the Cave Lake and Kinsey Canyon sections of the Schell Creek Range are consistent with evidence for rapid extension (ca. 37.56 ± 0.03 Ma to 36.68 ± 0.04 Ma) in the Robinson District near Ely, Nevada (Gans et al., 2001). The ca. 38-35 Ma ages encompassed by synextensional deposits of the Schell Creek Range (Drewes, 1967; McKee et al., 1976; Gans et al., 1989) are coeval with development of the 10° angular unconformity separating the Sheep Pass Formation from the Charcoal Ovens Tuff in the central Egan Range, and possibly coeval with the 10° angular unconformity separating the Sheep Pass Formation from upper Eocene strata in Sheep Pass Canyon and Shingle Pass in the southern Egan Range. The Duckwater Mountain section of the northern Pancake Range, approximately 100 km west of the southern Egan Range, has been correlated to the Sheep Pass Formation (Fouch, 1979). As described by Druschke et al. (in review), a > 140 m thick sequence of boulder fanglomerate at Duckwater Mountain interfingers with lacustrine limestone to the south, and is unconformably overlain by the Stone Cabin Formation. U-Pb detrital zircon ages derived from the basal Duckwater Mountain section indicate a 35.7 ± 0.7 Ma maximum depositional age (Druschke et al., in review), while the overlying Stone Cabin Formation has produced a $^{40}Ar/^{39}Ar$ sanidine age of 35.3 ± 0.8 Ma (Radke, 1992). These data suggest that rapid late Eocene extension was widespread across east-central Nevada, and occurred within multiple pulses and in several areas over the interval of 38 to 35 Ma.

Evidence that extension predated volcanism within the latest Cretaceous to Paleogene Sevier hinterland supports the hypothesis that deep-seated, mantle-related processes rather than thermal weakening of the upper crust drove extension (Axen et al., 1993). Deep-seated processes may have included lithospheric delamination coeval with flat-slab subduction during Late Cretaceous to early Paleogene extension (Platt, 2007; Wells and Hoisch, 2008), and subsequent slab rollback/foundering during renewed middle to late Eocene extension (Humphreys, 1995; Dickinson, 2002). However, evidence for rapid deposition and development of major (> 20°) angular unconformities coeval with volcanism in the Kinsey Canyon and Cave Lake sections of the Schell Creek Range, Cooper Summit (Gans et al., 1989) and the Robinson district (Gans et al., 2001) suggest that volcanic-driven upper crustal thermal weakening may have accelerated extension that was already underway. Alternatively, variations in angular discordance along unconformities in the Schell Creek and Egan Ranges may relate more directly to fault proximity and differing kinematics of individual normal faults rather than an overall change in the rate or magnitude of Paleogene extension.

Implications for Paleogeography of the Sevier hinterland

The concept of low-relief for the latest Cretaceous to Eocene Sevier hinterland was based upon the general observation that the Sheep Pass Formation and correlative Cretaceous to Paleogene units of east-central Nevada overlie Paleozoic strata with typically less than 10° of angular discordance (Armstrong, 1968; 1972). The assessment that upper Cretaceous and Paleogene strata display little discordance with underlying upper Paleozoic strata has wide-ranging implications. This conclusion suggests that low-relief and relatively minor tectonic activity affected the region of eastern Nevada for a duration spanning the Permian to Triassic Sonoman orogeny, and the Jurassic to Cretaceous Sevier orogeny. This scenario is unlikely when it is considered that the Sheep Pass Formation and correlative units overlie deformed Paleozoic to lower Cretaceous strata related to the central Nevada fold and thrust belt (Speed et al., 1988; Vandervoort and Schmitt, 1990; Carpenter et al., 1993; Taylor et al., 1993; Taylor et al., 2000), and that the Snake Range core complex to the east records evidence for deep burial in Cretaceous time (Lewis et al., 1999), as well as evidence for significant Jurassic to Cretaceous contractional deformation and metamorphism (Miller et al., 1988; Miller and Gans, 1989).

A more detailed examination of bedding within the Sheep Pass Formation type section (Fig. 6) reveals that the average dip discordance between the Sheep Pass Formation and the underlying Mississippian Chainman Formation is approximately 20°. Only 1 km to the south, the Sheep Pass Formation overlies the Pennsylvanian Ely Limestone with dip discordance that is highly variable, but commonly exceeds 45°. The angularity of this contact is much greater than a simple comparison of dip angles when it is considered that variations in bedding strike across the basal unconformity commonly exceed 90°. Throughout the southern Egan Range, upper Paleozoic strata display numerous faults and folds that predate, and are overlapped by, the Sheep Pass Formation. Similar patterns were mapped by Brokaw (1967) within the Ely Quadrangle of the central Egan Range. Here the Sheep Pass Formation overlies folded and faulted Permian and Pennsylvanian strata, with dip variations across the basal unconformity that average 45° in addition to significant discordance in bedding strike. In the Dry Lake Valley south of the Egan Range, angular discordance across the sub-Tertiary unconformity is 60° (Taylor et al., 1989). Within the northern White Pine Range, agular discordance between the Sheep Pass Formation and underlying Permian units approaches 90° (Gans, 2000). While we do not dispute that areas exist where the angular discordance across the sub-Tertiary unconformity is indeed low, exceptions are too numerous for this to remain a valid characterization of the Sevier hinterland.

A low-relief interpretation for the Late Cretaceous to Paleogene Sevier hinterland may be further called into question when deposits that directly overlie the "sub-Tertiary unconformity" are examined in detail. Within the Sheep Pass Formation type section, the basal Member A is composed of >200 m of matrix-supported boulder breccia, megabreccia blocks derived from Pennsylvanian and Mississippian strata, and cobble to boulder fanglomerate. Alluvial fans, debris flows and block-slide deposits are features common in settings where there is considerable differential relief between source areas and basin. In Milk Ranch Canyon to the east of Sheep Pass Canyon, and in Ninemile Canyon to the south, Member B is locally deposited upon the Ely Limestone, indicating that islands of Paleozoic strata protruded up to several hundred meters from the floor of the Sheep Pass basin. During late Eocene time, fault reactivation rejuvenated steep topographic relief as recorded by deposition of the alluvial fan-dominated Stinking Spring Conglomerate, and block-slide deposits at Shingle Pass. Upper Eocene deposits at Sawmill Canyon and within the Cooper Summit and Cave Lake sections of the Schell Creek Range similarly contain significant thicknesses of cobble to boulder fanglomerates.

Similar stratigraphic features are documented in deposits of varying Late Cretaceous to Eocene age across a wide area of east-central Nevada, suggesting that paleotopography of the Sevier hinterland throughout the Late Cretaceous to Eocene was rugged, and included areas of locally high relief. Within the Fish Creek Range 100 km west of Sheep Pass Canyon, megabreccia derived from Paleozoic strata has been documented in association with Maastrichtian lacustrine deposits correlative to the Sheep Pass Formation type section (Vandervoort and Schmitt, 1990). In the northern Pancake Range, megabreccia is associated with largely undated sections of the Sheep Pass Formation, and blocks of Devonian and Mississippian strata > 2 m in diameter are included in fanglomerate deposits of the upper Eocene Duckwater Mountain section (Druschke et al., in review). Megabreccia blocks derived from Devonian limestone overlie Paleocene limestone and mudstone of the Sheep Pass Formation within the subsurface of Railroad Valley adjacent to the northern Grant Range, but are overlain in turn by the upper Eocene to Oligocene Garrett Ranch Group (Montgomery, 1997). Blocks of megabreccia in the subsurface of Railroad Valley adjacent to the Pancake Range are also contained within the informally named "Troy Basin formation", an up to 120 m thick interval of tuffaceous lacustrine limestone and siltstone underlying the Garrett Ranch Group (Montgomery, 1997). The Troy Basin formation is likely correlative to exposures of the nearby Duckwater Mountain section. Megabreccia derived from recrystallized Paleozoic carbonate has been documented within Paleocene beds of the Sheep Pass Formation in the adjacent northern Grant Range (Newman, 1979). Brecciated masses of the Ely Limestone overlying the Chainman Formation at the base of the Cave Lake section in the Schell Creek Range (Drewes, 1967) are similar to exposures in Sheep Pass Canyon interpreted as megabreccia, and may represent previously unidentified block-slide deposits. Megabreccia is typically deposited within 5 km of significant basin-bounding escarpments (Yarnold and Lombard, 1989), although debris avalanche flow into lakes may significantly increase run-out distances (Yarnold, 1993; Gardner et al., 2000). The wide distribution of megabreccia deposits of varying Late Cretaceous to Eocene age within the Sevier hinterland indicates that deposition occurred in a number of discrete extensional basins in response to two temporally distinct episodes of extension.

Paleocurrent trends for fanglomerate deposits of the Sheep Pass Formation and late Eocene strata of the Egan and Schell Creek Ranges, in addition to conglomerate clast provenance indicating progressively deeper levels of unroofing (Drewes, 1967; Gans et al., 1989, Druschke et al., in review) strongly suggest that the vicinity of the present-day central Nevada and Utah borderlands persisted as a series of long-lived highlands bounded to the west by west-dipping normal faults throughout the Paleogene. This hypothesis is corroborated by previous studies which suggest that core complexes within the Sevier hinterland such as the Snake Range core complex represent formerly high-standing Sevier-related structural culminations (Christiansen et al., 1992; Wells, 1997). It has been suggested that middle to upper Eocene sedimentary deposits of northeastern Nevada represent a series of east-flowing paleocanyons, and that relief within the Ruby-East Humboldt core complex was low in Eocene time (Henry, 2008). However, studies supporting the paleocanyon hypothesis lack paleocurrent analyses (Henry, 2008). In east-central Nevada, no paleocanyons have been identified in association with middle to late Eocene deposits, and 215 paleocurrent measurements from the Egan and Schell Creek ranges overwhelmingly record a westward direction of transport.

Conclusions

Deposition of the Sheep Pass Formation type section was controlled by motion along the Ninemile fault, a presently low-angle, down-to-the-west normal fault with initial movement in latest Cretaceous time. Motion along the Ninemile fault is recorded by megabreccia and growth faults within Maastrichtian Member A of the Sheep Pass Formation type section, and continued motion during deposition of the Maastrichtian to late Paleocene Members B and C of the type section is suggested by widespread, large-scale soft-sedimentary slump deposits, fluidization and dewatering structures interpreted as seismites. Reactivation of the Ninemile fault in middle to late Eocene time is indicated by motion on the Blue Spring fault system, a series of upward fanning splays of the Ninemile fault that repeat the Sheep Pass Formation type section, but are overlapped by the late Eocene Garrett Ranch Group. The Shingle Pass fault located 20 km south of Sheep Pass Canyon similarly shows evidence for motion during the Paleocene, and middle to late Eocene reactivation. New $^{40}Ar/^{39}Ar$ dates derived from volcanic strata of the Garrett Ranch Group indicates that that Eocene fault reactivation occurred prior to ca. 36 Ma.

Deposition of the Sheep Pass Formation within the central Egan Range (Ely Quadrangle—Elderberry/Sawmill Canyon section) began during or prior to the middle Eocene (ca. 50.5-44.5 Ma) but continued into the late Eocene ca. 37-36 Ma. New $^{40}Ar/^{39}Ar$ ages from the Charcoal Ovens Tuff in the central Egan Range, and volcanic strata associated with the Cave Lake section of the Kinsey Canyon Formation in the Schell Creek Range indicate that these sections were coeval, and potentially contiguous when similar paleocurrent trends are considered, and significant post-Eocene east-west extension is restored. Evidence for long-lived, westward paleocurrent trends and progressive unroofing of Paleogene deposits suggests that Late Cretaceous to late Eocene extension, erosion and sedimentation played an important role in the early unroofing history of the Snake Range core complex.

Latest Cretaceous to early Paleogene extension of the Sheep Pass basin temporally overlapped with up to 14 km of mid-crustal extensional thinning within the Sevier hinterland (Wells et al., 1990; Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; McGrew et al., 2000; Harris et al., 2007; Wells and Hoisch, 2008), as well as with continued contraction within the Sevier foreland fold and thrust belt to the east (DeCelles, 2004). More widespread middle to upper Eocene strata related to renewed extension within the Sevier hinterland overlapped temporally with the westward extensional collapse of the Sevier foreland fold and thrust belt (Constenius, 1996). Evidence for active normal faults and rugged relief indicates that the latest Cretaceous to Eocene Sevier hinterland was more structurally and topographically complex than previous models suggest. These features more closely support previous comparisons of the Sevier hinterland to the modern Andean Puna-Altiplano and Tibetan Plateau, where active synconvergent extensional basins have been documented (Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Allmendinger et al., 1997; Kapp et al., 2008). While indications are that latest Cretaceous to Eocene extension-related relief and sedimentation were of much smaller magnitude than Neogene extension within the Basin and Range Province, older extensional structures potentially exerted a strong tectonic inheritance on younger structures given the history of middle to late Eocene reactivation.

Figure captions

Figure 1. General geologic map of east-central Nevada modified from Stewart and Carlson (1977). Localities discussed in text include DW--Duckwater Mountain section of the Sheep Pass Formation, SP--Sheep Pass Canyon type section of the Sheep Pass Formation (SPF), MR—Milk Ranch Canyon, SH--Shingle Pass, NM--Ninemile Canyon, EB--Elderberry Canyon section of the SPF, RD--Robinson District, SC--Sawmill Canyon section of the Sheep Pass Formation, KC--Kinsey Canyon type section of the Kinsey Canyon Formation (KCF), CL--Cave Lake section of the KCF, CS--Cooper Summit section of the KCF. Boxes correspond with the area of geologic maps appearing as figures in this paper.

Figure 2. Stratigraphic column for the Sheep Pass Formation type section (modified from Fouch, 1979), the Sawmill Canyon section of the central Egan Range, and the Kinsey Canyon and Cave Lake sections of the Kinsey Canyon Formation from the Schell Creek Range. Biostratigraphic correlations of members for the Sheep Pass Formation type section are adapted from Fouch (1979) and Good (1987); and from Emry (1990) for the Sawmill Canyon section. U-Pb detrital zircon and (U-Th)/He detrital zircon ages from (from Druschke et al., in press, Druschke et al., in review) indicate maximum depositional ages. A U-Pb carbonate age from the basal portion of Member B indicates a depositional age (Druschke et al., in press).

Figure 3. $^{40}Ar/^{39}Ar$ age results for samples collected from the Garrett Ranch Group within the southern Egan Range. Results from samples 04SP18, 05SH1, and 06MR2 consist of

weighted mean ages of sanidine single crystal fusions. Results for sample 06SP10 consist of a pseudo plateau obtained from step heating of basaltic groundmass. No age isochrons were produced.

Figure 4. $^{40}Ar/^{39}Ar$ age results for samples collected from late Eocene volcanic strata of the central Egan Range (05SM1), and the Schell Creek Range. Results for sample 06KZ1 consist of a weighted mean age of sanidine single crystal fusions, and a resulting age isochron. Results for samples 06KC6, 04CL12, 04CL13 and 05SM01 include weighted mean ages from sanidine single crystal fusions, with no resulting age isochrons.

Figure 5. Equal-area rose diagram plots of paleocurrents from the Sheep Pass Formation type section (Members A and C combined), the overlying Stinking Spring Conglomerate, the Sawmill Canyon section of the Sheep Pass Formation in the central Egan Range, and the Cave Lake section of the Kinsey Canyon Formation in the central Schell Creek Range. Paleocurrents were derived primarily from pebble imbrication, with transport vectors restored to original horizontality using a stereonet.

Figure 6. Geologic map of Sheep Pass Canyon in the southern Egan Range. The Ninemile fault strikes E/W along the southern boundary of the map area, before resuming a NE strike to the east of Sheep Pass Canyon. A series of inferred fault splays trend NE from the Ninemile fault in the vicinity of Blue Spring juxtapose the Sheep Pass Formation type section against the Mississippian Scotty Wash Sandstone and Pennsylvanian Ely

Limestone. These fault splays are overlapped by the Garrett Ranch Group, indicating motion prior to ca. 38-36 Ma (late Eocene).

Figure 7. Schematic cross-section from A to A'(Fig. 7) across the type section of the Sheep Pass Formation, the basal portion of the Garrett Ranch Group, the Blue Spring fault system and the Ninemile fault within the southern Egan Range. Thickness of buried Paleozoic strata adapted from Kellogg (1963).

Figure 8. Geologic map of Shingle Pass within the southern Egan Range, modified from Kellogg (1959). Megabreccia within the hanging wall of the Shingle Pass fault overlies Members A, B and D of the Sheep Pass Formation. Mapped members at Shingle Pass should be considered lithofacies, given that Member B at Shingle Pass is late Paleocene in age based on biostratigraphy, while Member B in the type section is Maastrichtian to early Paleocene (Good, 1987). Member D within the type section is potentially late Paleocene to middle Eocene in age (Fouch, 1979).

Figure 9. (A) Large-scale soft-sedimentary slump fold in Member B of the Sheep Pass Formation type section. (B) Lacustrine limestone rip-up clast associate with a debris slump in Member B. (C) Limestone (intra and extra-basinal), chert and quartzite pebbles incorporated into a dominantly carbonate-mud debris flow in Member B. (D) Load cast associated with a slump fold in Member B. (E) View of a large-scale slump deposit in Member B of the Sheep Pass Formation type section displaying contorted beds. F) Recumbant soft-sedimentary slump fold in medium-grained sandstone beds of Member C

within the Sheep Pass Formation type section. (G) Outcrop of medium-grained sandstone of Member C, displaying an array of dewatering pipes, flame structures, and soft-sedimentary folds. (H) Contorted bedding within lacustrine limestone/siltstone of the Kinsey Canyon Formation type section of the Schell Creek Range. Hammer head in B and C is 20 cm long. Notebook in D is 18 cm tall. Hat in F is 30 cm in diameter. Pencil in G is 15 cm long, pencil in H is 12 cm long.

Figure 10. Correlation diagram for latest Cretaceous to Eocene strata of the Egan and Schell Creek Ranges. In contrast to earlier correlations by Fouch (1979), the latest Cretaceous to middle Eocene (Bridgerian; 50.5-45.4 Ma) Sheep Pass Formation type section predates the deposition of middle to late Eocene strata of the central Egan Range and Schell Creek Range based on age overlap with the basal Garrett Ranch Group in Sheep Pass Canyon. Our new correlations are depicted in gray. The Kinsey Canyon Formation type section is younger than the Stinking Spring Conglomerate, Sawmill Canyon section or Cave Lake section, but overlaps with deposition of the lower Garrett Ranch Group in Sheep Pass Canyon. Detrital zircon U-Pb, (U-Th)/He and U-Pb carbonate ages from Druschke et al., in review.

Figure 11. Diagram comparing age relations of normal faults, associated extensional basin deposits, angular unconformities and megabreccia within the Egan and Schell Creek Ranges. Black arrows depict the potential age span for motion along corresponding normal faults. Inferred normal faulting in the Schell Creek Range is after Gans et al. (1989). Speculative Late Cretaceous unroofing in the Snake Range from Lewis et al.

(1999). ^{40}Ar/^{39}Ar muscovite and Kspar cooling ages along the Snake Range decollement from Lee and Sutter (1991), and Lee (1995)—Paleocene cooling ages are treated as potentially suspect, while middle Eocene cooling ages (46-41 Ma) are considered more robust. Late Eocene extension and volcanism in the Snake Range are after Sullivan and Snoke (2007). Ages for contraction within the Sevier foreland are from from DeCelles, 1994, and timing for initiation of extension in the Sevier foreland from Constensius, 1996. GR—Garrett Ranch Group, CO—Charcoal Ovens, KZ—Kalamazoo, mb—megabreccia U—unconformity.

Table 1: Sample descriptions for volcanic units selected for ^{40}Ar/^{39}Ar dating.

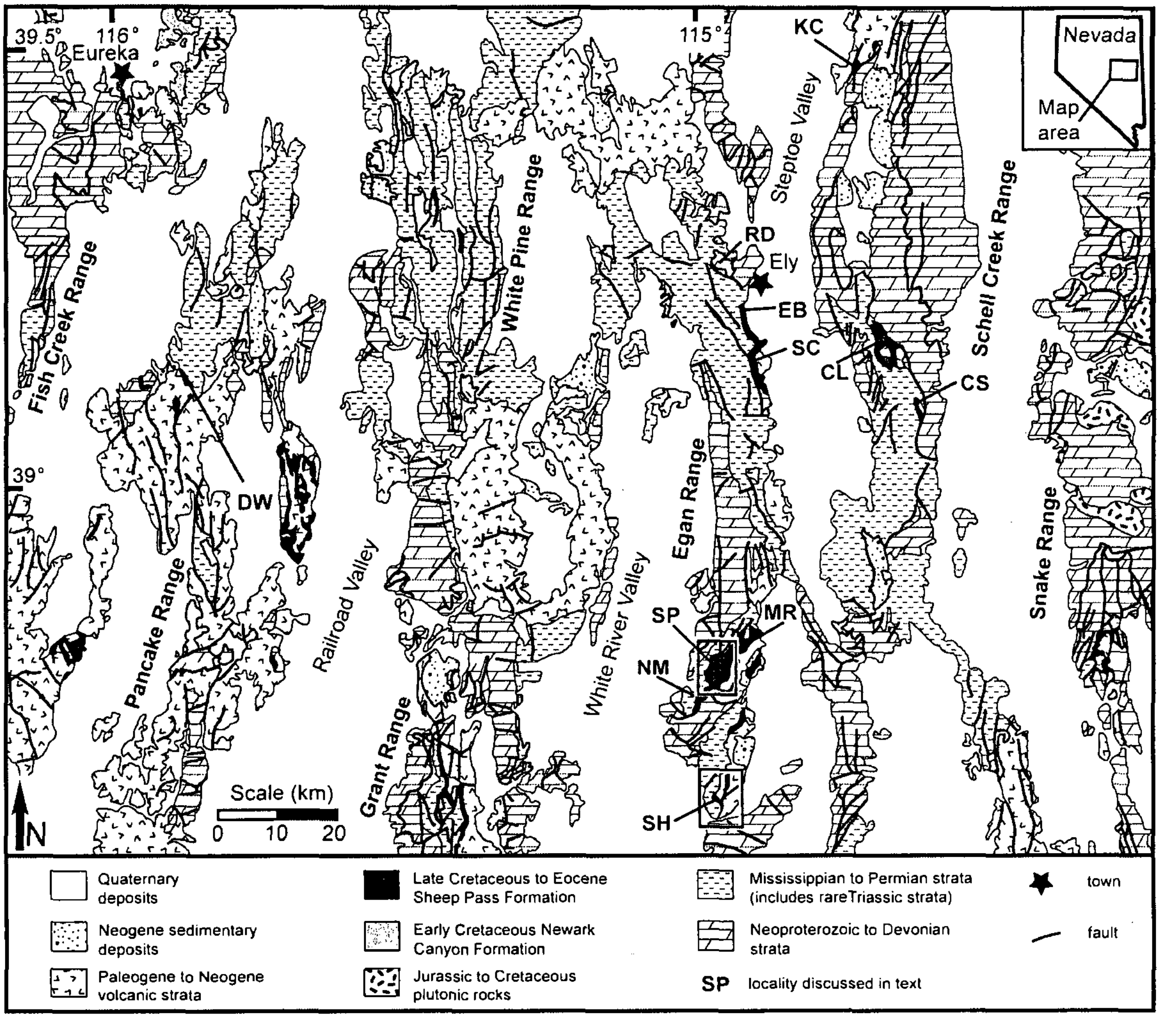

39.5°
116°
Eureka
115°
KC
Nevada
Map area
Steptoe Valley
Schell Creek Range
White Pine Range
Fish Creek Range
RD
Ely
EB
SC
CL
CS
DW
39°
Egan Range
Snake Range
Pancake Range
Railroad Valley
White River Valley
SP
MR
NM
Grant Range
SH
Scale (km)
0
10
20
N
Quaternary deposits
Neogene sedimentary deposits
Paleogene to Neogene volcanic strata
Late Cretaceous to Eocene Sheep Pass Formation
Early Cretaceous Newark Canyon Formation
Jurassic to Cretaceous plutonic rocks
Mississippian to Permian strata (includes rareTriassic strata)
Neoproterozoic to Devonian strata
SP locality discussed in text
town
fault

Figure 1.

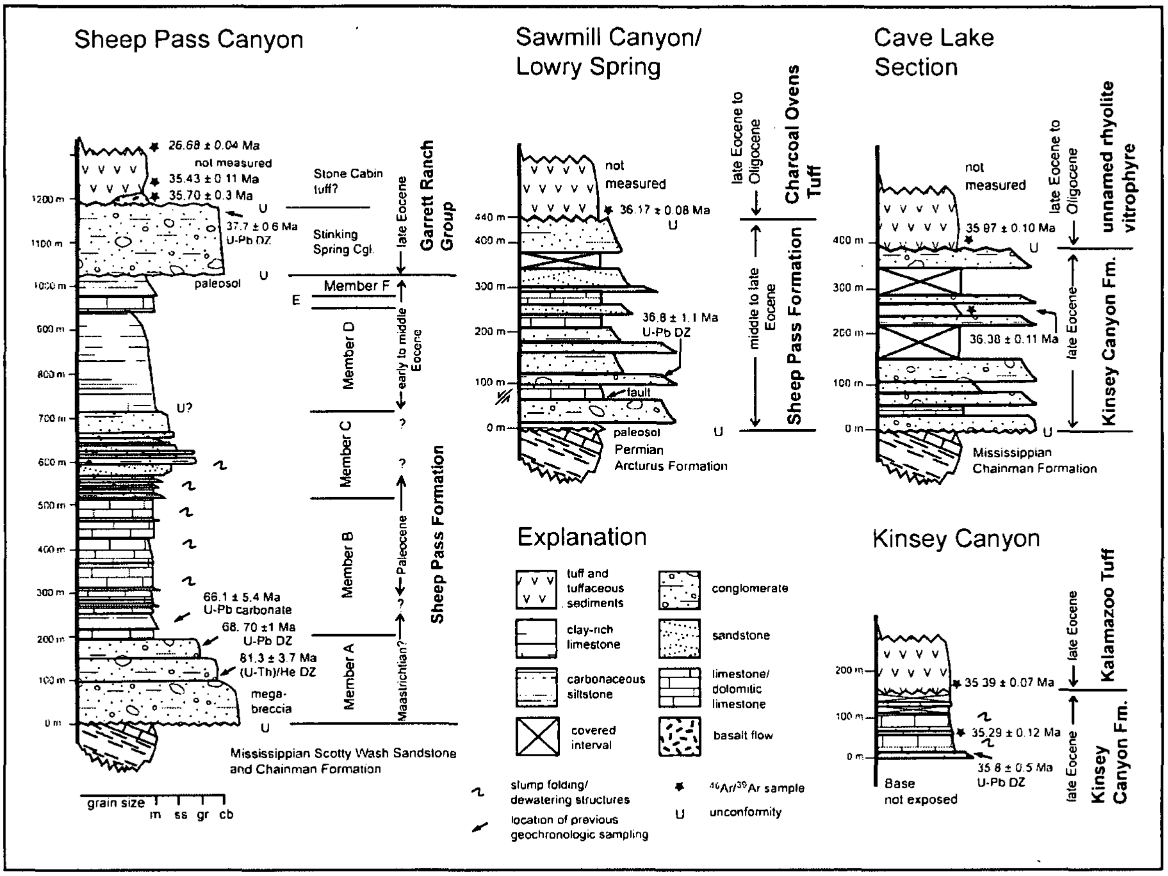

Sheep Pass Canyon
26.68 ± 0.04 Ma
not measured
35.43 ± 0 11 Ma
35.70 ± 0.3 Ma
U
37.7 ± 0 6 Ma
U-Pb DZ
paleosol
U
U?
66.1 ± 5.4 Ma
U-Pb carbonate
68. 70 ±1 Ma
U-Pb DZ
81.3 ± 3.7 Ma
(U-Th)/He DZ
mega-
breccia
U
1200 m
1100 m
1000 m
900 m
800 m
700 m
600 m
500 m
400 m
300 m
200 m
100 m
0 m
Stone Cabin
tuff?
Stinking
Spring Cgl.
Member F
E
Member D
Member C
Member B
Member A
late Eocene
early to middle
Eocene
?
?
Paleocene
?
Maastrichtian?
Garrett Ranch
Group
Sheep Pass Formation
Mississippian Scotty Wash Sandstone
and Chainman Formation
grain size
m ss gr cb
Sawmill Canyon/
Lowry Spring
not
measured
36.17 ± 0.08 Ma
U
440 m
400 m
300 m
200 m
100 m
0 m
36.8 ± 1.1 Ma
U-Pb DZ
fault
paleosol
U
Permian
Arcturus Formation
late Eocene to
Oligocene
middle to late
Eocene
Charcoal Ovens
Tuff
Sheep Pass Formation
Cave Lake
Section
not
measured
35 87 ± 0.10 Ma
U
400 m
300 m
200 m
100 m
0 m
36.38 ± 0.11 Ma
U
Mississippian
Chainman Formation
late Eocene to
Oligocene
late Eocene
unnamed rhyolite
vitrophyre
Kinsey Canyon Fm.
Explanation
tuff and
tuffaceous
sediments
clay-rich
limestone
carbonaceous
siltstone
covered
interval
conglomerate
sandstone
limestone/
dolomitic
limestone
basalt flow
slump folding/
dewatering structures
location of previous
geochronologic sampling
$^{40}Ar/^{39}Ar$ sample
U
unconformity
Kinsey Canyon
200 m
100 m
0 m
35 39 ± 0.07 Ma
35.29 ± 0.12 Ma
35 8 ± 0.5 Ma
U-Pb DZ
Base
not exposed
late Eocene
late Eocene
Kalamazoo Tuff
Kinsey
Canyon Fm.

Figure 2.

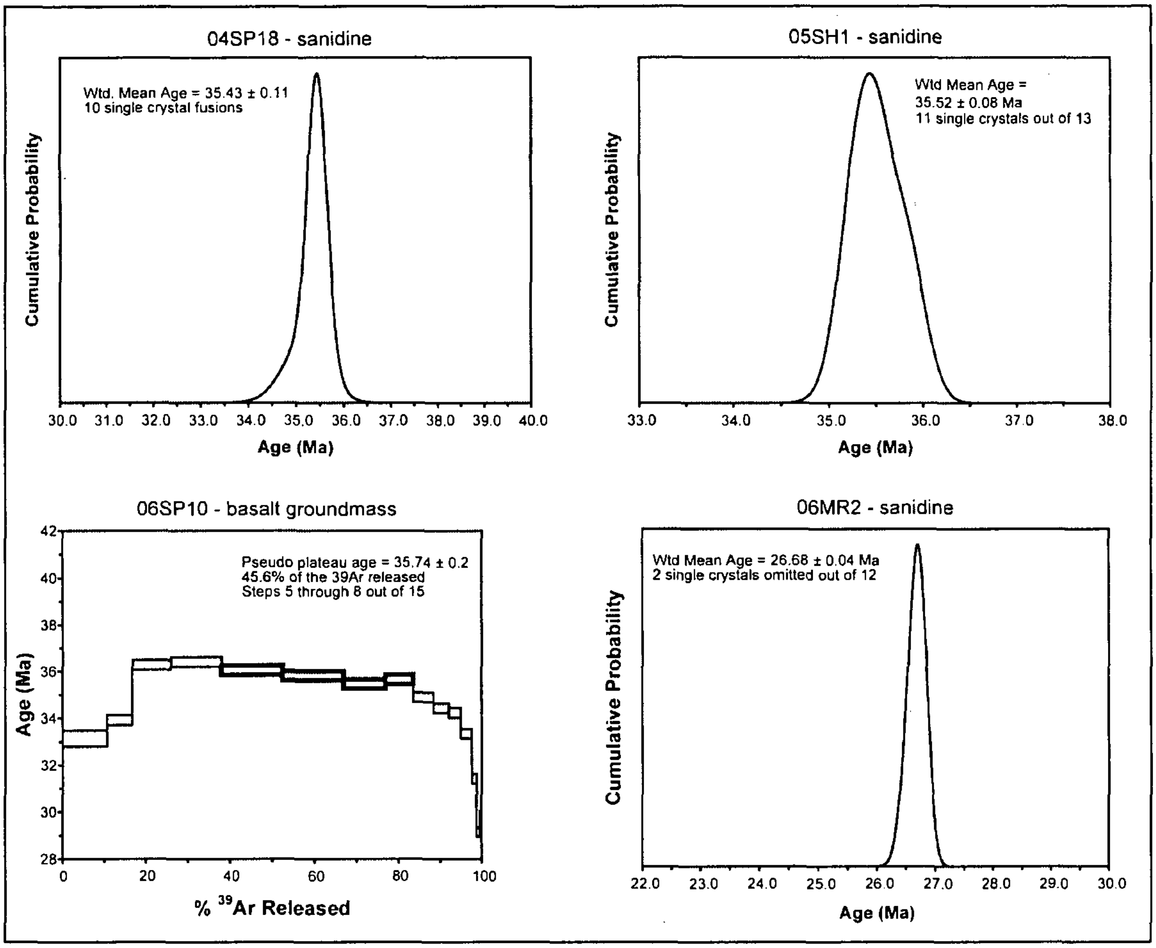

04SP18 - sanidine
Wtd. Mean Age = 35.43 ± 0.11
10 single crystal fusions
Cumulative Probability
30.0 31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 40.0
Age (Ma)
05SH1 - sanidine
Wtd Mean Age =
35.52 ± 0.08 Ma
11 single crystals out of 13
Cumulative Probability
33.0 34.0 35.0 36.0 37.0 38.0
Age (Ma)
06SP10 - basalt groundmass
Pseudo plateau age = 35.74 ± 0.2
45.6% of the 39Ar released
Steps 5 through 8 out of 15
Age (Ma)
42 40 38 36 34 32 30 28
0 20 40 60 80 100
% 39Ar Released
06MR2 - sanidine
Wtd Mean Age = 26.68 ± 0.04 Ma
2 single crystals omitted out of 12
Cumulative Probability
22.0 23.0 24.0 25.0 26.0 27.0 28.0 29.0 30.0
Age (Ma)

Figure 3.

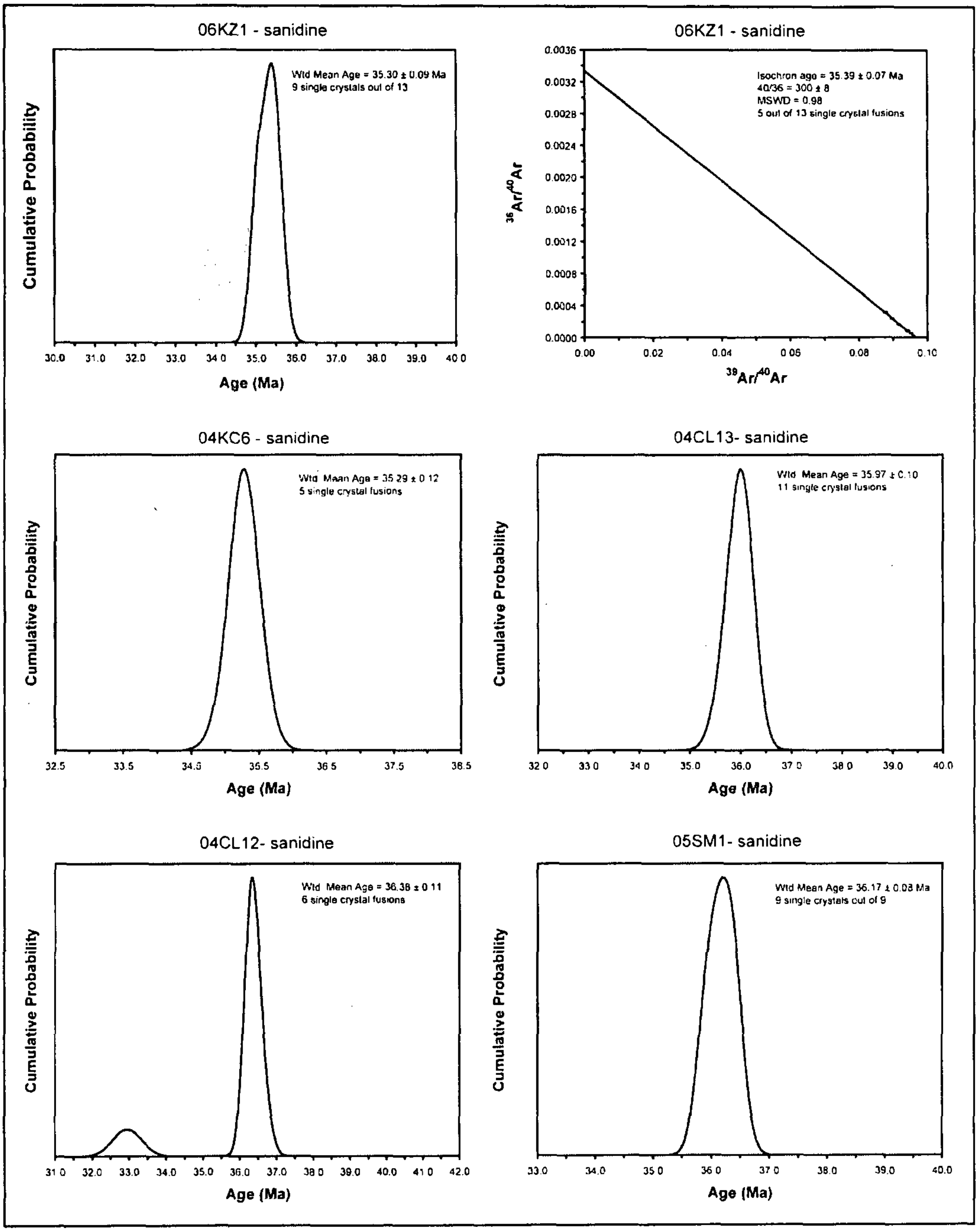

06KZ1 - sanidine
Wtd Mean Age = 35.30 ± 0.09 Ma
9 single crystals out of 13
Cumulative Probability
30.0 31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 40.0
Age (Ma)
06KZ1 - sanidine
Isochron age = 35.39 ± 0.07 Ma
40/36 = 300 ± 8
MSWD = 0.98
5 out of 13 single crystal fusions
0.0036 0.0032 0.0028 0.0024 0.0020 0.0016 0.0012 0.0008 0.0004 0.0000
^{36}Ar/^{40}Ar
0.00 0.02 0.04 0.06 0.08 0.10
^{39}Ar/^{40}Ar
04KC6 - sanidine
Wtd Mean Age = 35.29 ± 0.12
5 single crystal fusions
Cumulative Probability
32.5 33.5 34.5 35.5 36.5 37.5 38.5
Age (Ma)
04CL13- sanidine
Wtd Mean Age = 35.97 ± 0.10
11 single crystal fusions
Cumulative Probability
32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 40.0
Age (Ma)
04CL12- sanidine
Wtd Mean Age = 36.38 ± 0.11
6 single crystal fusions
Cumulative Probability
31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 40.0 41.0 42.0
Age (Ma)
05SM1- sanidine
Wtd Mean Age = 36.17 ± 0.08 Ma
9 single crystals out of 9
Cumulative Probability
33.0 34.0 35.0 36.0 37.0 38.0 39.0 40.0
Age (Ma)

Figure 4.

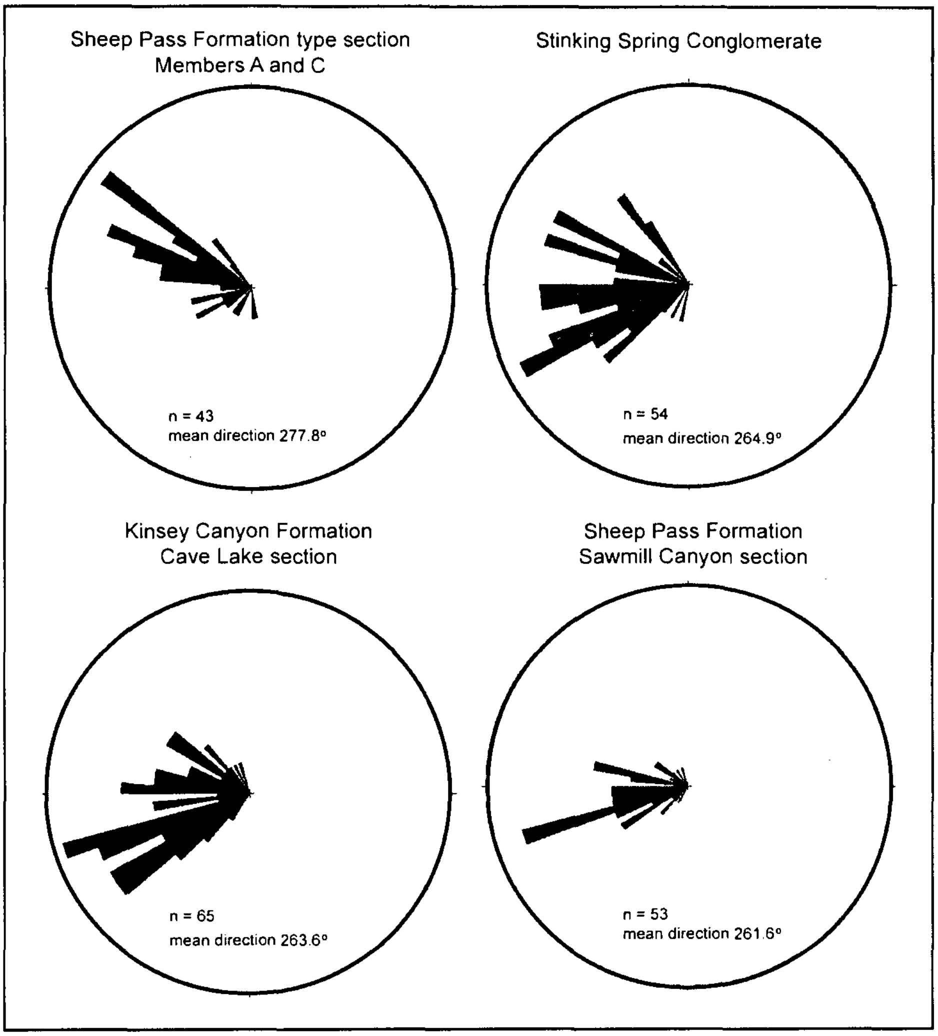

Sheep Pass Formation type section
Members A and C
n = 43
mean direction 277.8°
Stinking Spring Conglomerate
n = 54
mean direction 264.9°
Kinsey Canyon Formation
Cave Lake section
n = 65
mean direction 263.6°
Sheep Pass Formation
Sawmill Canyon section
n = 53
mean direction 261.6°

Figure 5.

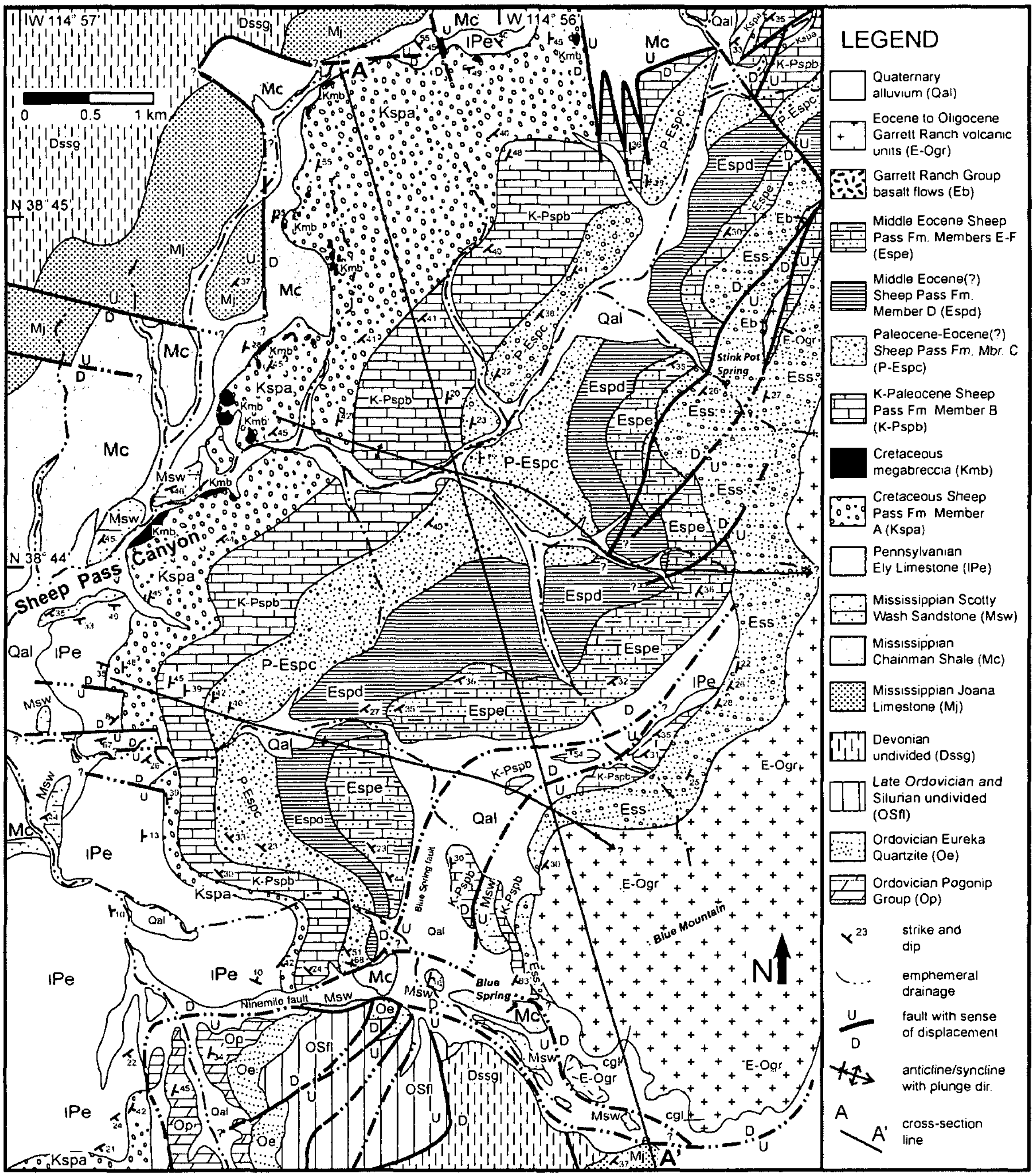

W 114° 57'
W 114° 56'
N 38° 45'
N 38° 44'
0 0.5 1 km
Sheep Pass Canyon
Stink Pot Spring
Blue Spring
Blue Spring fault
Ninemile fault
Blue Mountain
A
A'
N
LEGEND
Quaternary alluvium (Qal)
Eocene to Oligocene Garrett Ranch volcanic units (E-Ogr)
Garrett Ranch Group basalt flows (Eb)
Middle Eocene Sheep Pass Fm. Members E-F (Espe)
Middle Eocene(?) Sheep Pass Fm. Member D (Espd)
Paleocene-Eocene(?) Sheep Pass Fm. Mbr. C (P-Espc)
K-Paleocene Sheep Pass Fm Member B (K-Pspb)
Cretaceous megabreccia (Kmb)
Cretaceous Sheep Pass Fm Member A (Kspa)
Pennsylvanian Ely Limestone (lPe)
Mississippian Scotty Wash Sandstone (Msw)
Mississippian Chainman Shale (Mc)
Mississippian Joana Limestone (Mj)
Devonian undivided (Dssg)
Late Ordovician and Silurian undivided (OSfl)
Ordovician Eureka Quartzite (Oe)
Ordovician Pogonip Group (Op)
strike and dip
emphemeral drainage
fault with sense of displacement
U
D
anticline/syncline with plunge dir.
cross-section line

Figure 6.

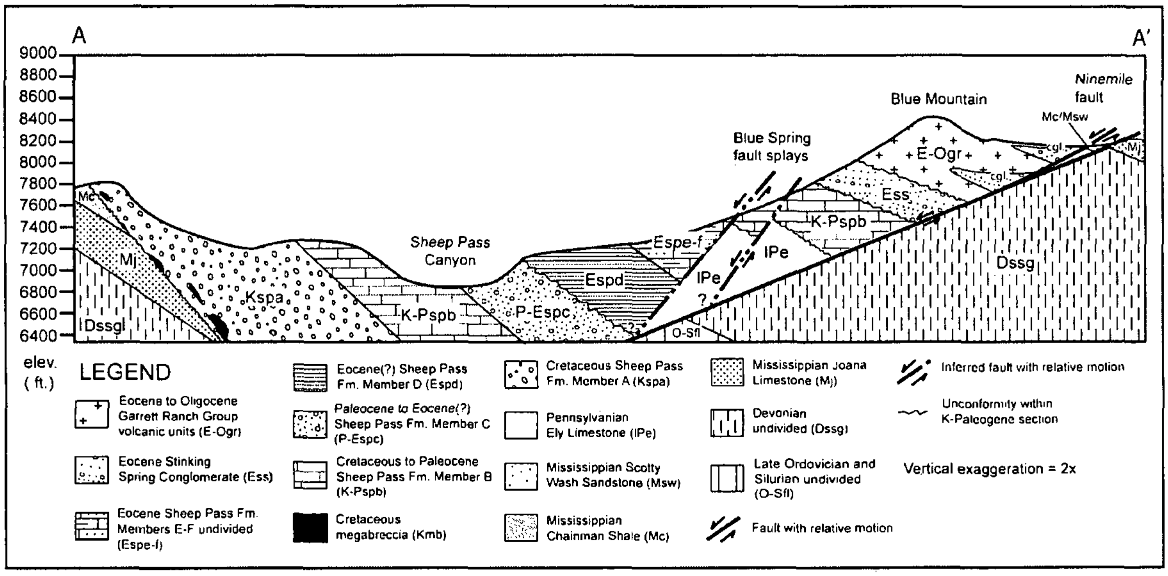

A
A'
9000
8800
8600
8400
8200
8000
7800
7600
7400
7200
7000
6800
6600
6400
elev.
(ft.)
Blue Mountain
Ninemile
fault
Mc/Msw
Blue Spring
fault splays
cgl.
cgl.
E-Ogr
Ess
Mj
K-Pspb
Espe-f
IPe
IPe
?
Dssg
Sheep Pass
Canyon
Mc
Mj
Kspa
K-Pspb
P-Espc
Espd
O-Sfl
Dssgl
LEGEND
Eocene to Oligocene Garrett Ranch Group volcanic units (E-Ogr)
Eocene Stinking Spring Conglomerate (Ess)
Eocene Sheep Pass Fm. Members E-F undivided (Espe-f)
Eocene(?) Sheep Pass Fm. Member D (Espd)
Paleocene to Eocene(?) Sheep Pass Fm. Member C (P-Espc)
Cretaceous to Paleocene Sheep Pass Fm. Member B (K-Pspb)
Cretaceous megabreccia (Kmb)
Cretaceous Sheep Pass Fm. Member A (Kspa)
Pennsylvanian Ely Limestone (IPe)
Mississippian Scotty Wash Sandstone (Msw)
Mississippian Chainman Shale (Mc)
Mississippian Joana Limestone (Mj)
Devonian undivided (Dssg)
Late Ordovician and Silurian undivided (O-Sfl)
Fault with relative motion
Inferred fault with relative motion
Unconformity within K-Paleogene section
Vertical exaggeration = 2x

Figure 7.

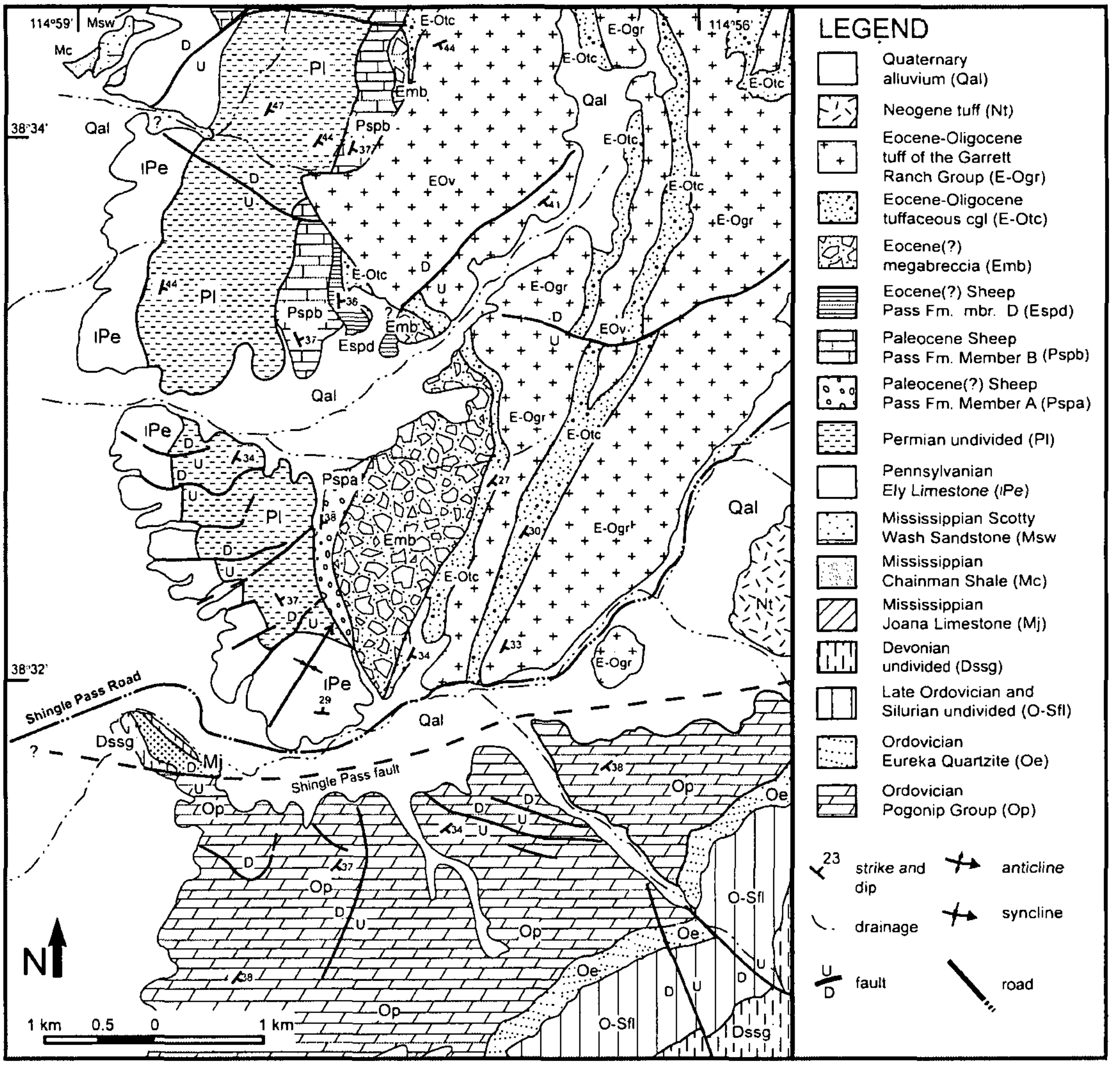

LEGEND
Quaternary alluvium (Qal)
Neogene tuff (Nt)
Eocene-Oligocene tuff of the Garrett Ranch Group (E-Ogr)
Eocene-Oligocene tuffaceous cgl (E-Otc)
Eocene(?) megabreccia (Emb)
Eocene(?) Sheep Pass Fm. mbr. D (Espd)
Paleocene Sheep Pass Fm. Member B (Pspb)
Paleocene(?) Sheep Pass Fm. Member A (Pspa)
Permian undivided (Pl)
Pennsylvanian Ely Limestone (IPe)
Mississippian Scotty Wash Sandstone (Msw
Mississippian Chainman Shale (Mc)
Mississippian Joana Limestone (Mj)
Devonian undivided (Dssg)
Late Ordovician and Silurian undivided (O-Sfl)
Ordovician Eureka Quartzite (Oe)
Ordovician Pogonip Group (Op)
23
strike and dip
anticline
drainage
syncline
U
D
fault
road
114°59'
114°56'
38°34'
38°32'
Msw
Mc
Qal
IPe
Pl
Pspb
Emb
E-Otc
E-Ogr
EOv
Espd
Pspa
Nt
Shingle Pass Road
Shingle Pass fault
Dssg
Mj
Op
Oe
O-Sfl
N
1 km
0.5
0
1 km

Figure 8.

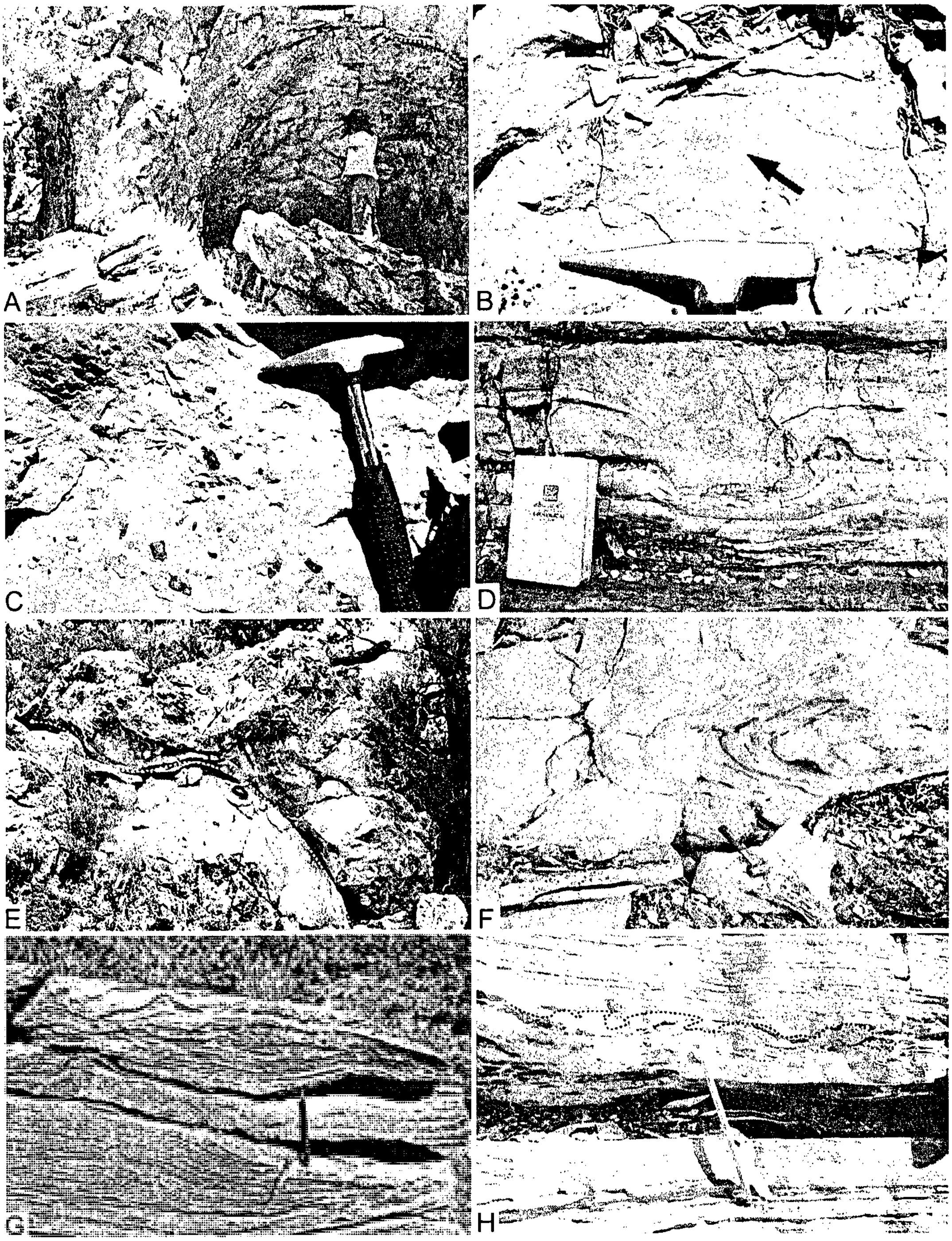


Figure 9.

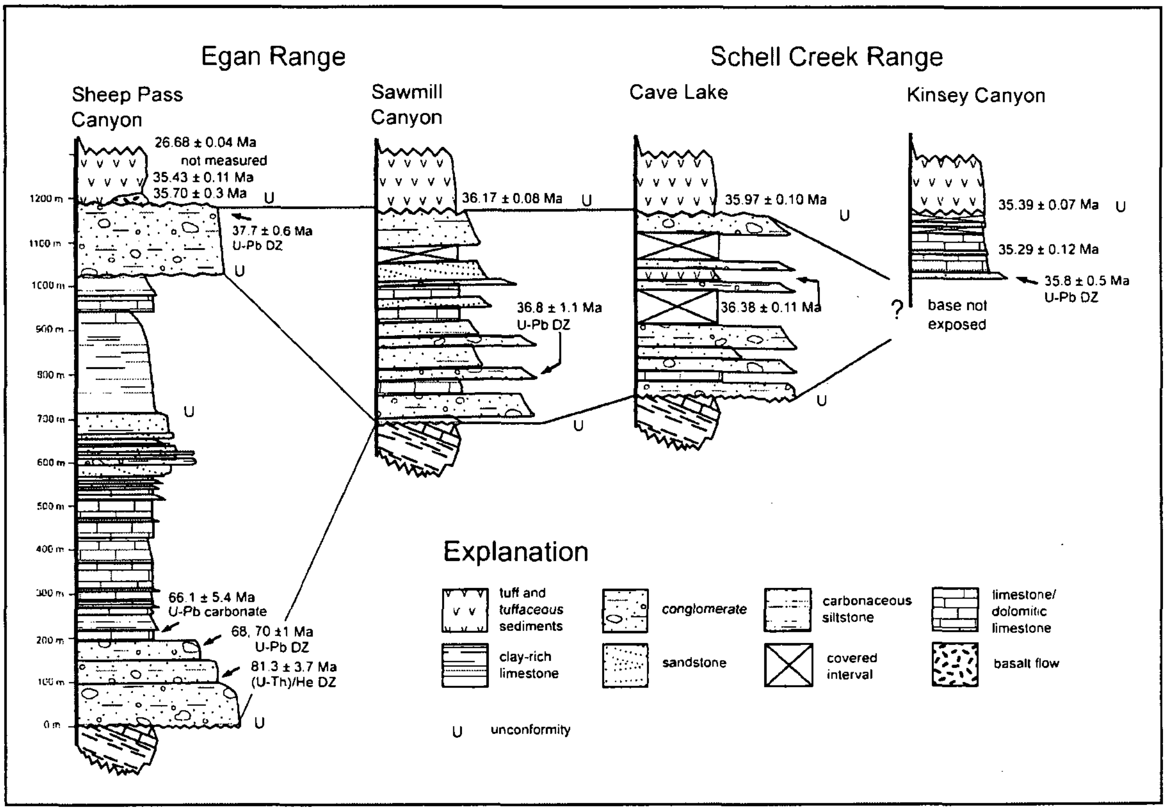

Egan Range
Schell Creek Range
Sheep Pass Canyon
Sawmill Canyon
Cave Lake
Kinsey Canyon
1200 m
1100 m
1000 m
900 m
800 m
700 m
600 m
500 m
400 m
300 m
200 m
100 m
0 m
26.68 ± 0.04 Ma
not measured
35.43 ± 0.11 Ma
35.70 ± 0.3 Ma
U
37.7 ± 0.6 Ma
U-Pb DZ
U
U
66.1 ± 5.4 Ma
U-Pb carbonate
68, 70 ±1 Ma
U-Pb DZ
81.3 ± 3.7 Ma
(U-Th)/He DZ
U
36.17 ± 0.08 Ma
U
36.8 ± 1.1 Ma
U-Pb DZ
U
35.97 ± 0.10 Ma
U
36.38 ± 0.11 Ma
U
?
base not exposed
35.39 ± 0.07 Ma
U
35.29 ± 0.12 Ma
35.8 ± 0.5 Ma
U-Pb DZ
Explanation
tuff and tuffaceous sediments
conglomerate
carbonaceous siltstone
limestone/ dolomitic limestone
clay-rich limestone
sandstone
covered interval
basalt flow
U unconformity

Figure 10.

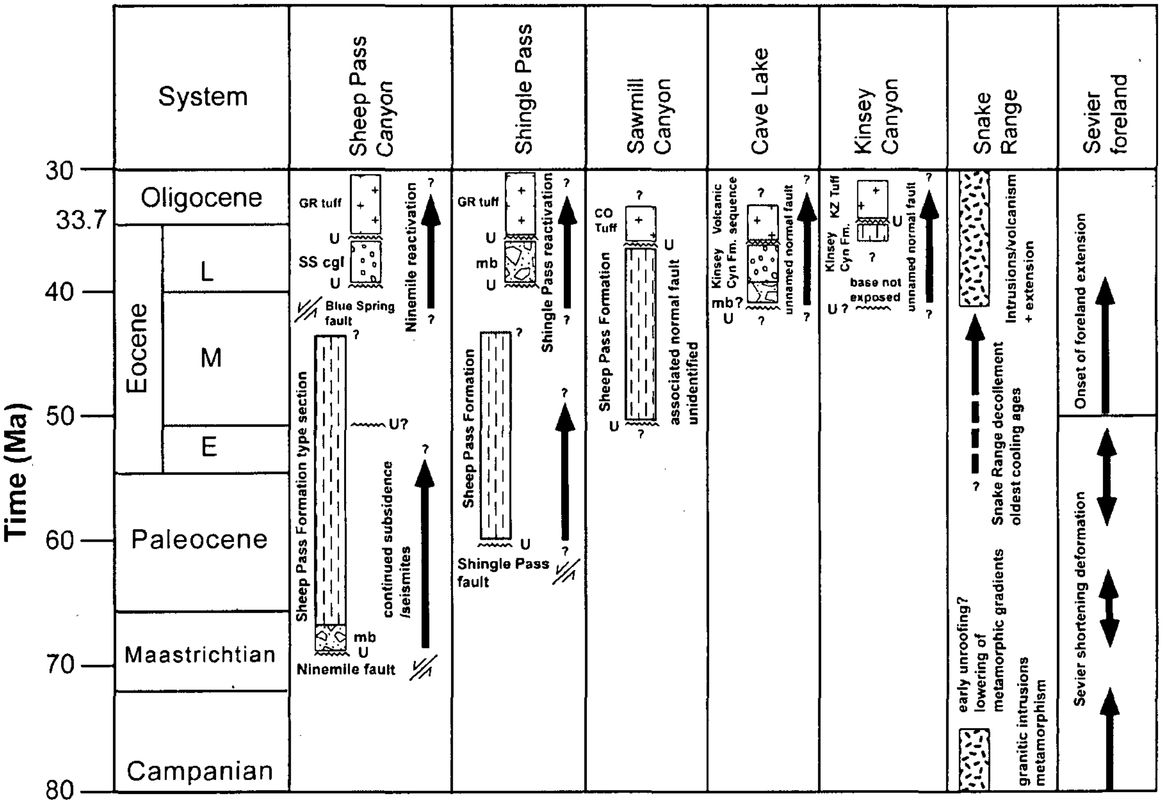

System
Sheep Pass Canyon
Shingle Pass
Sawmill Canyon
Cave Lake
Kinsey Canyon
Snake Range
Sevier foreland
Time (Ma)
30
33.7
40
50
60
70
80
Oligocene
Eocene
L
M
E
Paleocene
Maastrichtian
Campanian
GR tuff
U
SS cgl
U
Blue Spring fault
Ninemile reactivation
?
Sheep Pass Formation type section
U?
continued subsidence /seismites
mb
U
Ninemile fault
GR tuff
U
mb
U
Shingle Pass reactivation
Sheep Pass Formation
U
Shingle Pass fault
CO Tuff
U
Sheep Pass Formation
U
associated normal fault unidentified
Kinsey Cyn Fm. Volcanic sequence
mb?
U
unnamed normal fault
Kinsey Cyn Fm.
KZ Tuff
U
base not exposed
U ?
unnamed normal fault
Intrusions/volcanism + extension
Snake Range decollement oldest cooling ages
early unroofing? lowering of metamorphic gradients
granitic intrusions metamorphism
Onset of foreland extension
Sevier shortening deformation

Figure 11.

Table 1: Sample descriptions for volcanic units from the Egan and Schell Creek Ranges processed for ^{40}Ar/^{39}Ar age analyses at the Nevada Isotope Gechemistry Laboratory (NIGL).

Sample #	Rock	Mineral	Unit	Age (Ma) and 1σ error	Previous age
Egan Range					Stone Cabin Fm? (Hose et al., 1976)
04SP18 Sheep Pass Cyn	af tuff	san	GRG	35.43 ± 0.11	35.3 ± 0.8 (^{40}Ar/^{39}Ar) Stone Cabin Fm. (Radke, 1992)
06SP10 Sheep Pass Cyn	basalt	gm	GRG	35.74 ± 0.21	NA
05SH1 Shingle Pass	af tuff	san	GRG	35.52 ± 0.08	NA
06MR2 Milk Ranch Cyn	wd tuff	san	GRG	26.68 ± 0.04	NA
05SM1 Sawmill Cyn	wd tuff	san	COT	36.17 ± 0.08	32.8 ± 1.1 Ma (K-Ar) (McKee et al., 1976)
Schell Creek Range					
04CL12 Cave Lake	af tuff	san	KCF	36.38 ± 0.11	NA
04CL13 Cave Lake	wd tuff	san	?	35.97 ± 0.10	NA
04KC6 Kinsey Cyn	wl tuff	san	KCF	35.29 ± 0.12	NA
06KZ1 Kinsey Cyn	wd tuff	san	KZT	35.39 ± 0.07	35.5 ± 0.5 Ma (K-Ar) (Hagstrum and Gans, 1989)

af = ash flow; wd = welded; wl = water-lain; san = sanidine, gm = ground mass,
GRG = Garrett Ranch Group; COT = Charcoal Ovens Tuff; KCF = Kinsey Canyon Formation
KZT = Kalamazoo Tuff

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Dissertation Title: The Sheep Pass Formation, a record of Late Cretaceous and Paleogene extension within the Sevier hinterland, east-central Nevada

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