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Structural, stratigraphic, and geochronologic evidence for extension predating Palaeogene volcanism in the Sevier hinterland, east-central Nevada

P. Druschke*, A.D. Hanson and M.L. Wells

Department of Geoscience, University of Nevada, Las Vegas, NV, 89154, USA

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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 of the tectonic and palaeogeographic 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 Palaeocene motion along the Ninemile fault is suggested by widespread soft-sediment 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 Palaeocene 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 ca. 38–35 Ma volcanism across a wide swath of east-central Nevada, renewed extension may have begun as early as the middle Eocene. Palaeocurrent data from uppermost Cretaceous to upper Eocene alluvial fanglomerates of the Egan and Schell Creek ranges record westward palaeoflow 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 latest Cretaceous–Palaeogene time. Late Cretaceous to Palaeocene 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 Palaeogene Sevier hinterland.

Keywords: the Sevier hinterland; ^{40}Ar/^{39}Ar dating, Sheep Pass Formation; syncovergent extension

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*Corresponding author. Email: druschke@unlv.nevada.edu

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Introduction

The Sevier hinterland is regarded by many 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 Palaeogene palaeogeography and tectonics of the Sevier plateau remain controversial. The current prevailing palaeogeographic model for the Sevier hinterland was advanced by Armstrong (1968, 1972); he concluded that the unconformity separating upper Cretaceous and Palaeogene sedimentary deposits of eastern Nevada from underlying upper Palaeozoic strata displays generally $<10^\circ$ of angular discordance, and therefore represents a widespread low-relief erosional surface. Similarly, later regional models have proposed that the Late Cretaceous to Palaeogene 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 2009; Druschke *et al.* 2009). 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 million years 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.* 2009).

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 Palaeogene 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. Palaeocene 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 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

Palaeogene 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.* 2009). 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 Palaeogene 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 $>15{,}000\,\mathrm{km}^2$ of modern-day east-central Nevada (Fouch *et al.* 1991; Figure 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.* 2009). 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 2009). These data indicate that deposition of Upper Cretaceous to Eocene Sevier hinterland strata within east-central Nevada occurred in response to at least two separate episodes of extension.

This study presents new 1:12,000 scale geologic mapping from the southern Egan Range, as well as new ^{40}Ar/^{39}Ar geochronology, stratigraphic observations, and palaeocurrent data from additional sections of the Sheep Pass Formation and correlative units located throughout the Egan and Schell Creek Ranges of east-central Nevada. These data provide evidence for active, surface breaking normal faults of latest Cretaceous to Palaeocene age in east-central Nevada, and evidence for subsequent middle to late Eocene extension. Regional age relations and stratigraphic correlations demonstrate that at least two discrete episodes of extension affected the latest Cretaceous to Eocene Sevier hinterland of east-central Nevada, and were associated with rugged topography and high relief locally.

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

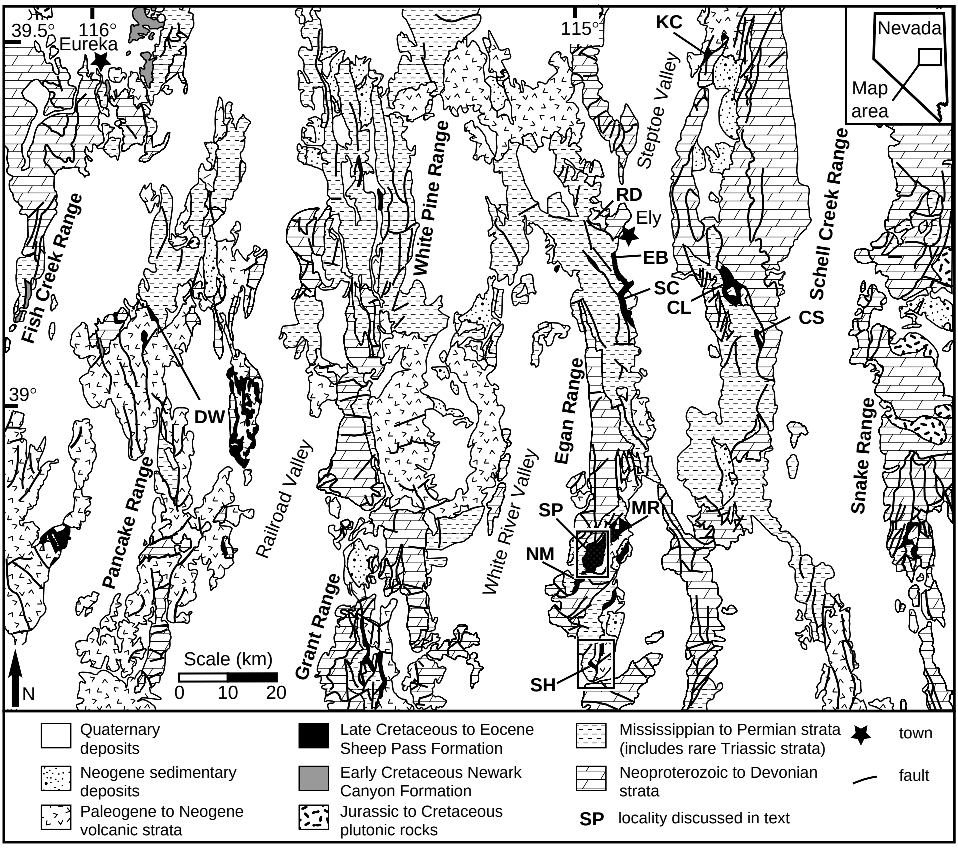

Figure 1. General geologic map of east-central Nevada modified from Stewart and Carlson (1977). Localities discussed in text include DW, Duckwater Mountain section of the Sheep Pass Formation; SP, Sheep Pass Canyon type section of the Sheep Pass Formation (SPF; box corresponds to area of Figure 6); MR, Milk Ranch Canyon; SH, Shingle Pass (box corresponds to area of Figure 8); 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 and CS, Cooper Summit section of the KCF.

et al. 1993, 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 2009). 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 Palaeozoic units prior to the onset of late Eocene (ca. 38–35 Ma) volcanism (Druschke 2009). 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 2009). 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 Palaeogene due to sustained high elevation and initiation of hinterland extensional basins (Druschke 2009).

Detrital zircon (U–Th)/He 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 2009). 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 2009; Druschke *et al.* 2009). 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 north western 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 (Figure 2) in the southern Egan Range. The basal member of the Sheep Pass Formation (A) is composed of coarse conglomerate and breccia that generally fines upward and are interpreted as proximal alluvial fan deposits (Winfrey 1958, 1960; Kellogg 1964; Fouch 1979). Member B is composed of microbially laminated limestone that locally interfingers with the uppermost beds of member A, and is interpreted as deposits from a shallow freshwater lake (Winfrey 1958, 1960; Fouch 1979). Member C is

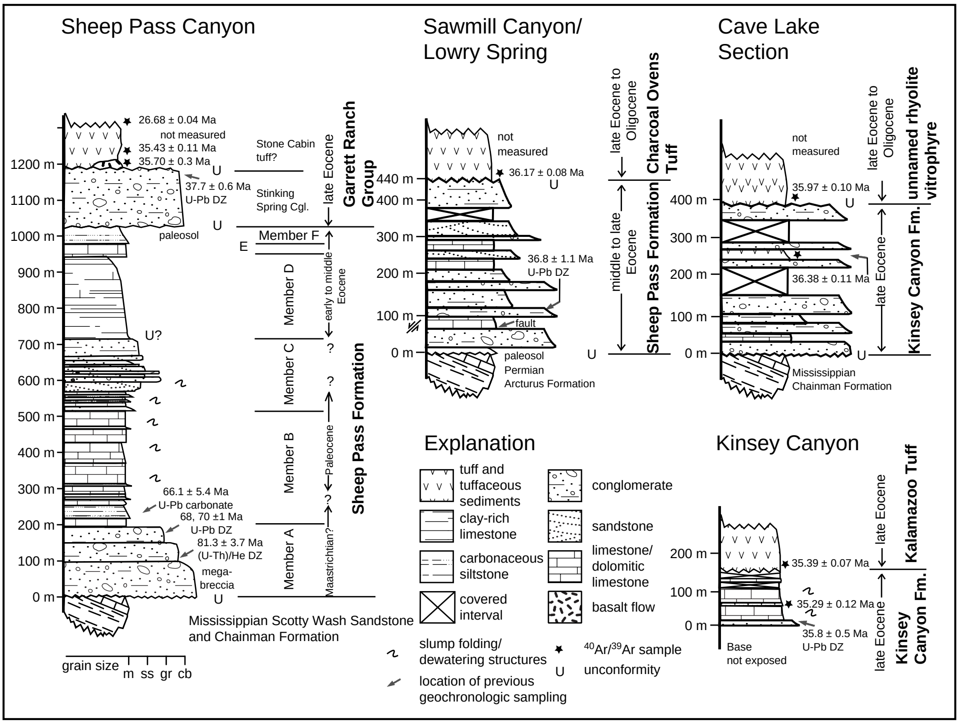

Figure 2. Stratigraphic column for the Sheep Pass Formation type section (modified from Fouch 1979), the Sawmill Canyon section of the central Egan Range, and the Kinsey Canyon and Cave Lake sections of the Kinsey Canyon Formation from the Schell Creek Range. Biostratigraphic correlations of members 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 Druschke 2009; Druschke *et al.* 2009) indicate maximum depositional ages. A U–Pb carbonate age from the basal portion of member B indicates a depositional age (Druschke *et al.* 2009).

composed of sandstone, siltstone, and conglomerate interbedded with silty to oncoidal limestone. Member C is interpreted as distal alluvial fan and marginal lacustrine deposits (Fouch 1979). Members D–F are composed of limestone and silty limestone deposited within marginal and potentially ephemeral lacustrine environments, member F locally containing palaeosol horizons (Winfrey 1958, 1960; Fouch 1979). The Sheep Pass Canyon type section is the only location where all six members are recognized, with members C–F absent in the Pancake Range and members A, C, and F absent in the Grant Range (Winfrey 1958, 1960).

Winfrey (1958, 1960) originally interpreted the Sheep Pass Formation to be deposited in a half-graben bounded by a normal fault to the east due to westward thinning of exposures and subcrop, although no normal fault demonstrably linked to deposition of the Sheep Pass Formation was identified. The 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. 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.* (2009) 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 that projects beneath the Sheep Pass Formation in Sheep Pass Canyon. The Ninemile fault exhibits approximately 4 km of stratigraphic throw based on the juxtaposition of upper Palaeozoic strata against lower Palaeozoic strata (Kellogg 1963, 1964). The Ninemile fault is interpreted as the basin-bounding fault for the Sheep Pass Formation type section based on evidence for motion during deposition of the Sheep Pass Formation (Druschke *et al.* 2009).

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 and 68 ± 1 Ma) within the uppermost beds of member A (Druschke *et al.* 2009). 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 Palaeocene to middle Eocene in age (Fouch 1979), and megabreccia deposits at Shingle Pass (Kellogg 1959, 1964) in the southern Egan Range overlie strata of late Palaeocene to middle Eocene(?) age (Good 1987).

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 2009), indicating a late Eocene maximum depositional age. The Stinking Spring Conglomerate in turn is unconformably overlain by approximately 400 m of rhyolitic ash-flow tuff, reworked tuff, and localized basalt flows of the Garrett Ranch Group in Sheep Pass Canyon (Winfrey 1958; Kellogg 1964; Hose *et al.* 1976; Figure 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 an ^{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; Figure 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; Figure 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 2009).

At Cooper Summit in the Schell Creek Range (Figure 1), a sequence of intercalated conglomerate, ash-flow 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. 38–35 Ma (McKee *et al.* 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 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 is 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 Palaeogene 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 Figure 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 100–300 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 analysed at the Nevada Isotope Geochemistry Laboratory

Table 1. Sample descriptions for volcanic units from the Egan and Schell Creek Ranges processed for $^{40}Ar/^{39}Ar$ age analyses at the NIGL.

Sample no.	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	n.a.
05SH1 Shingle Pass	af tuff	san	GRG	35.52 ± 0.08	n.a.
06MR2 Milk Ranch Cyn	wd tuff	san	GRG	26.68 ± 0.04	n.a.
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	n.a.
04CL13 Cave Lake	wd tuff	san	?	35.97 ± 0.10	n.a.
04KC6 Kinsey Cyn	wl tuff	san	KCF	35.29 ± 0.12	n.a.
06KZ1 Kinsey Cyn	wd tuff	san	KZT	35.39 ± 0.07	35.5 ± 0.5 Ma (K–Ar; Hagstrum and Gans 1989)

Notes: 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 and KZT, Kalamazoo Tuff.

(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 (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).

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 west (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 ash-flow 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 (Figure 3). Sample 04SP18 was collected from basal exposures of the overlying ash-flow tuff, and indicates an $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 35.43 ± 0.11 Ma (Figure 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 an $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 26.68 ± 0.04 Ma (Oligocene; Figure 3).

Approximately 20 km to the south of Sheep Pass Canyon at Shingle Pass (Figure 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 Palaeocene 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

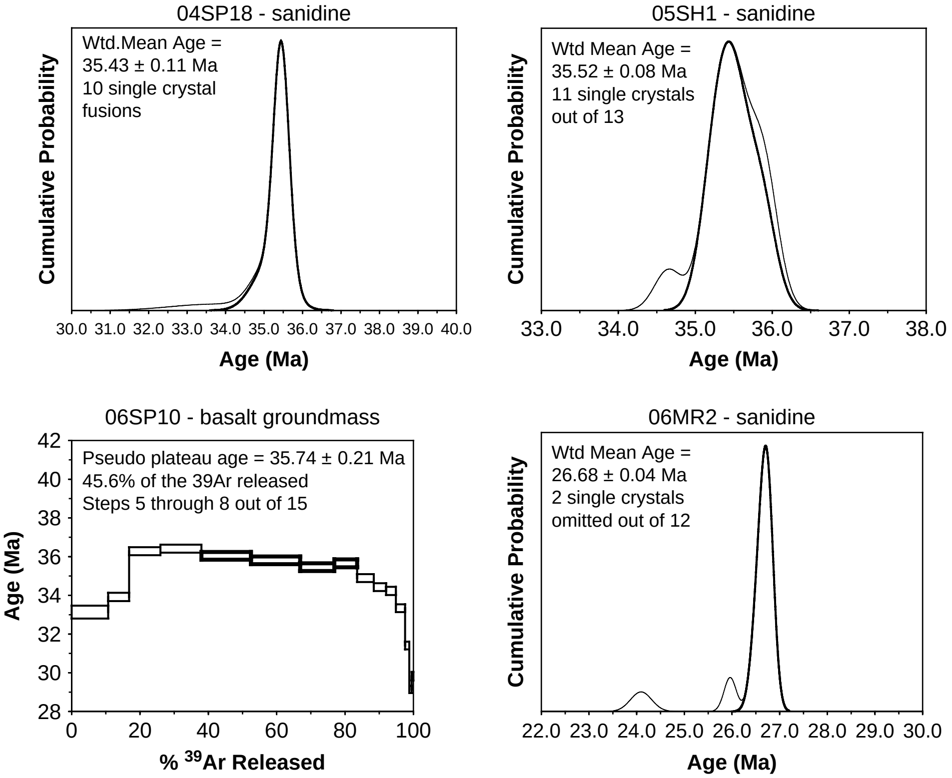

Figure 3. $^{40}Ar/^{39}Ar$ age results for samples collected from the Garrett Ranch Group within the southern Egan Range. Results from samples 04SP18, 05SH1, and 06MR2 consist of weighted mean ages of sanidine single crystal fusions. Results for sample 06SP10 consist of a pseudo plateau obtained from step heating of basaltic groundmass. No age isochrons were produced.

interbedded tuff and conglomerate, and yielded an $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 35.52 ± 0.08 Ma (Figure 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; Figure 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 2009). 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 an $^{40}Ar/^{39}Ar$ sanidine weighted mean age of 36.17 ± 0.08 Ma (Figure 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

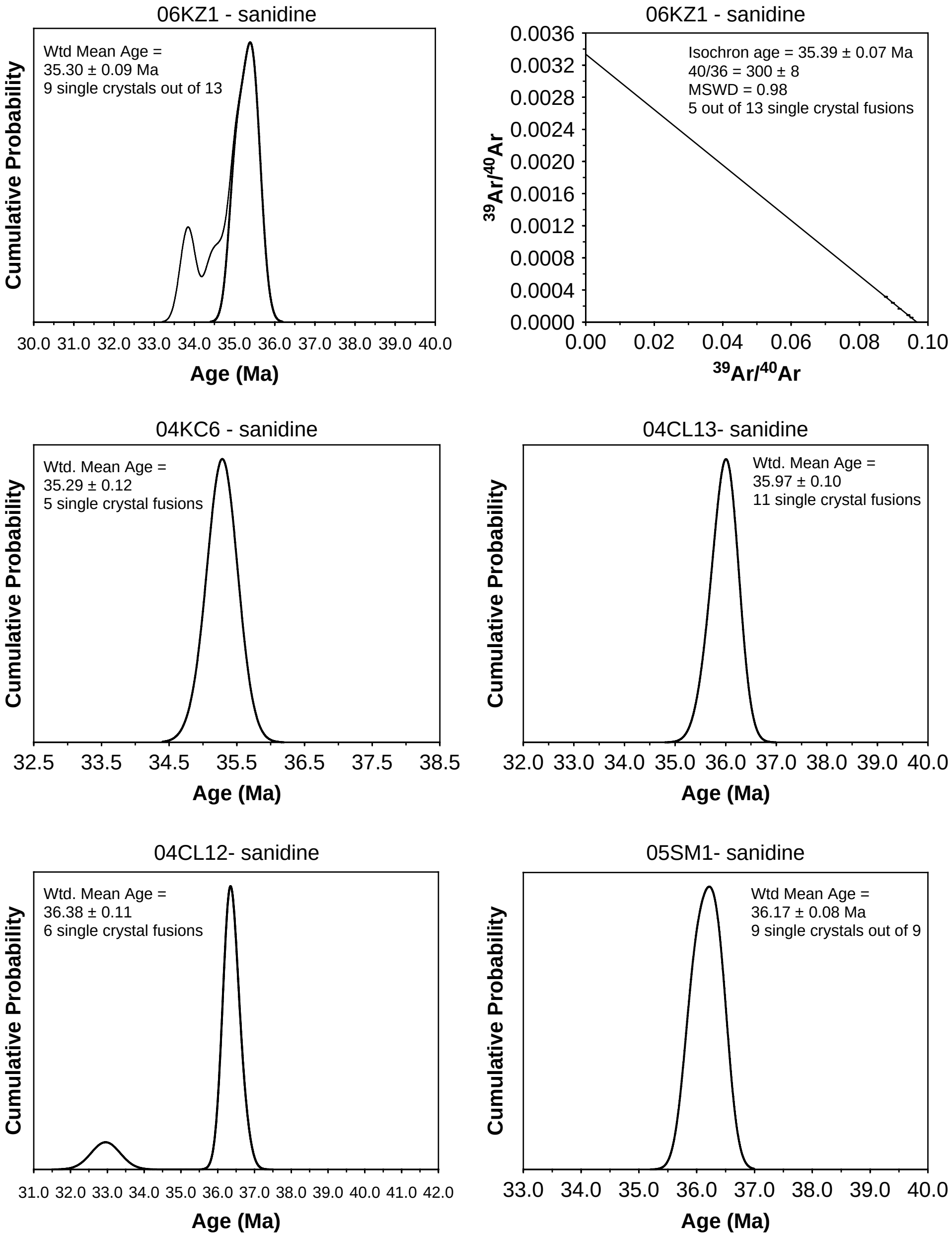

Figure 4. ^{40}Ar/^{39}Ar age results for samples collected from late Eocene volcanic strata of the central Egan Range (sample 05SM1), and the Schell Creek Range. Results for sample 06KZ1 consist of a weighted mean age of sanidine single crystal fusions, and a resulting age isochron. Results for samples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

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 *et al.* 1976). The Cooper Summit Tuff has produced a K–Ar biotite age of 38.0 ± 3.8 Ma (Drewes 1967).

Results: 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 a 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 kilometres 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 2009).

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 an ^{40}Ar/^{39}Ar sanidine weighted mean age of 35.29 ± 0.12 Ma (Figure 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 (Figure 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 (Figure 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 an ^{40}Ar/^{39}Ar sanidine weighted mean age of 36.38 ± 0.11 Ma (Figure 4). The overlying rhyolite vitrophyre (sample 04CL13) yields an ^{40}Ar/^{39}Ar sanidine weighted mean age of 35.97 ± 0.10 Ma (Figure 4).

Palaeocurrent analysis methods and results

Previous workers have inferred palaeotransport directions for the Sheep Pass Formation based on conglomerate clast provenance, and the thickness and distribution of lithostratigraphic members, although no palaeocurrent 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. Palaeocurrent measurements, principally from pebble imbrications within alluvial fanglomerates, were collected from numerous intervals of members A and C of the Sheep Pass Formation type section, and from the overlying Stinking Spring Conglomerate. Additional palaeocurrent 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 palaeocurrent measurements were measured. 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 (Figure 5). A mean azimuth palaeotransport direction of 278° was obtained from the Sheep Pass Formation type section, and a similar mean palaeotransport 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 palaeotransport directions of 262° and 264°, respectively. Previous palaeomagnetic analyses of the Kalamazoo Tuff suggest that 28° ± 12° of clockwise rotation has 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 palaeoflow 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.* 2009). 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 (Figure 6), a series of exposures of Mississippian Chainman Shale and Scotty Wash Sandstone, Pennsylvanian Ely Limestone and Cretaceous to Palaeocene member B of the Sheep Pass Formation are juxtaposed against late Palaeocene 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-striking, 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

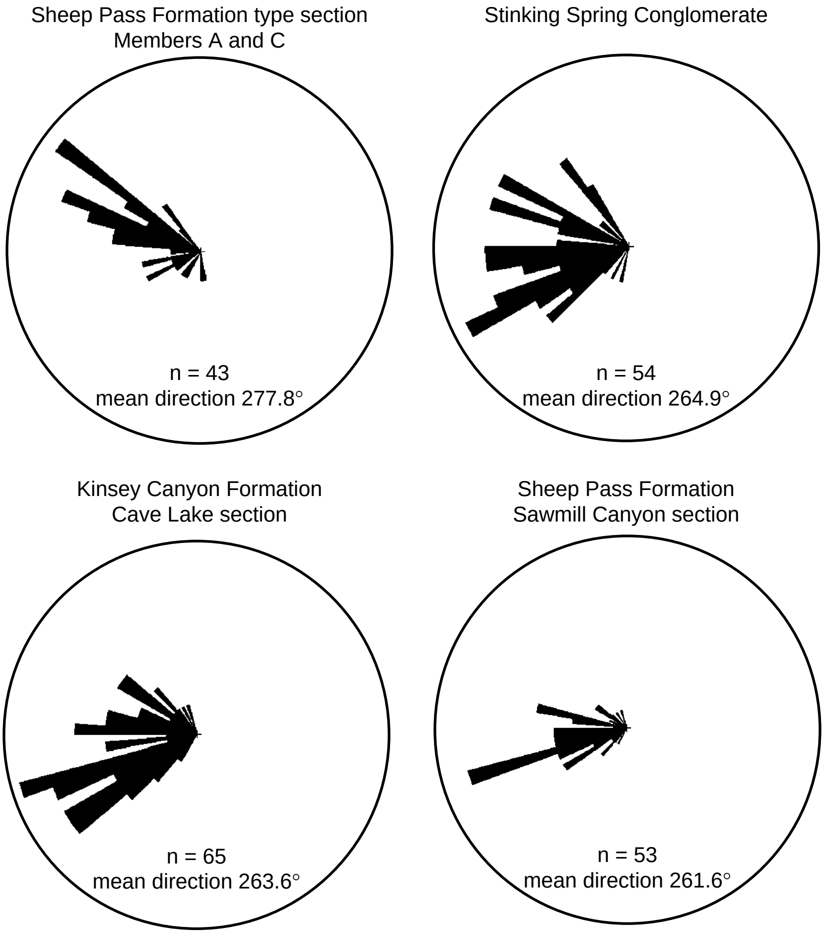

Figure 5. Equal-area rose diagram plots of palaeocurrents from the Sheep Pass Formation type section (members A and C combined), the overlying Stinking Spring Conglomerate, the Sawmill Canyon section of the Sheep Pass Formation in the central Egan Range, and the Cave Lake section of the Kinsey Canyon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

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 Palaeozoic 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 Palaeozoic strata within the footwall of the Ninemile fault, but are not contiguous with the Blue Spring fault system.

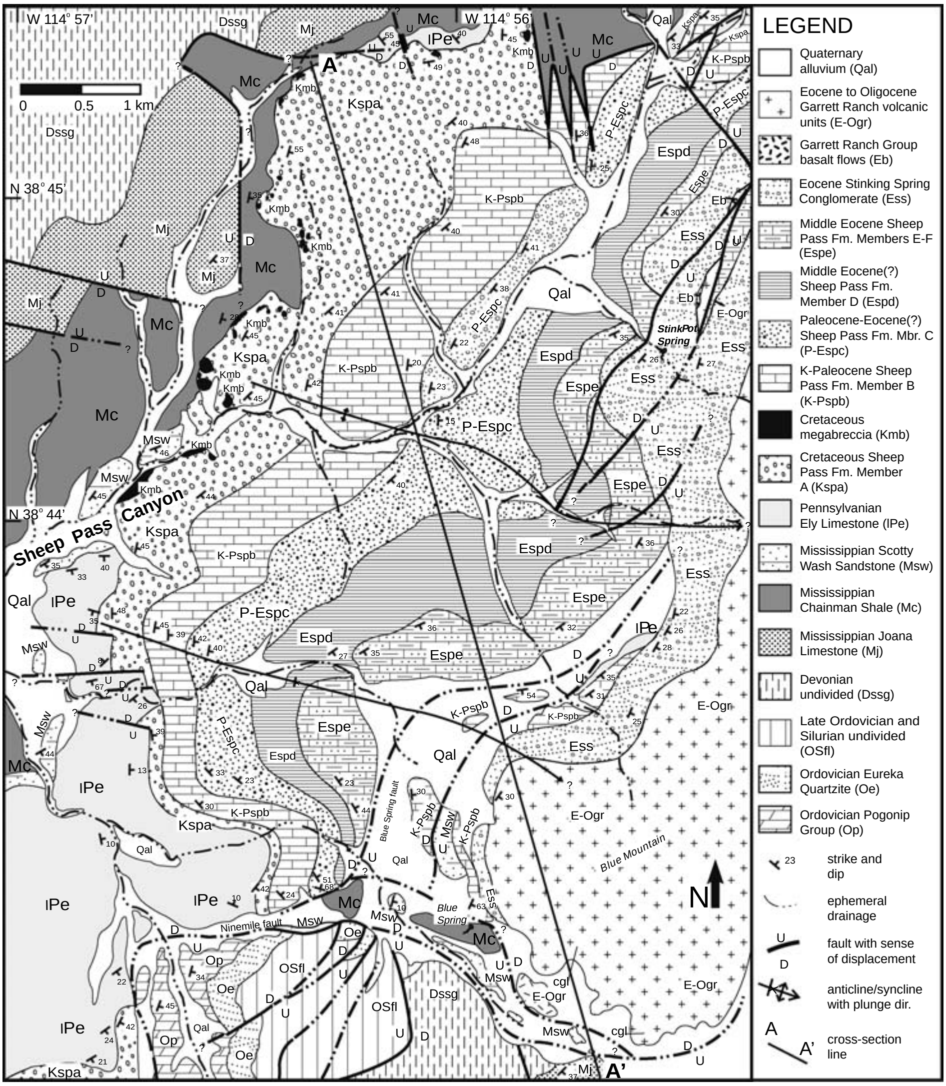

Figure 6. Geologic map of Sheep Pass Canyon in the southern Egan Range. The Ninemile fault strikes E–W along the southern boundary of the map area, before resuming a NE strike to the east of Sheep Pass Canyon. A series of inferred fault splays strike NE from the Ninemile fault in the vicinity of Blue 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).

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 (Figure 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 strike of the Ninemile fault, (2) the sense of down-to-the-northwest transport is the same as that of

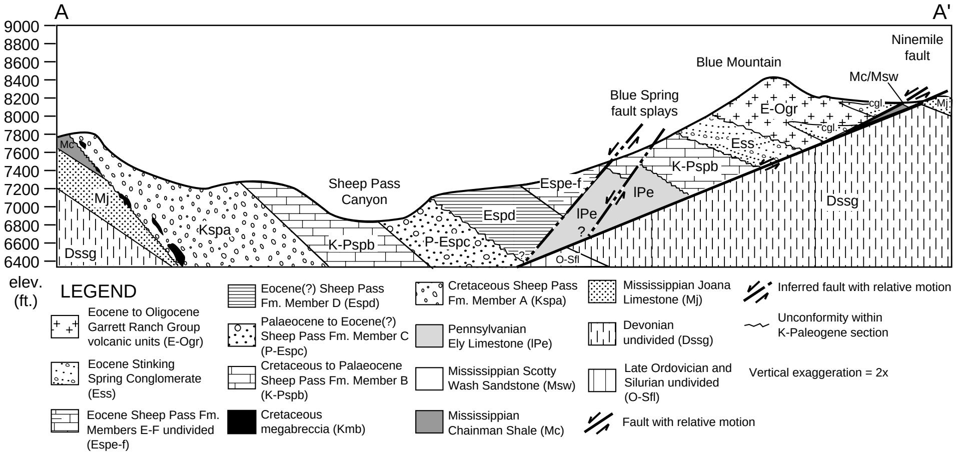

Figure 7. Schematic cross-section from A to A′ (Figure 7) across the type section of the Sheep Pass Formation, the basal portion of the Garrett Ranch Group, the Blue Spring fault system and the Ninemile fault within the southern Egan Range. Thickness of buried Palaeozoic strata adapted from Kellogg (1963).

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 2009). 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 grey-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.* 50.5–45.4 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 2009). 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 bevelled 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.* 2009).

In map view (Figure 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 ash-flow 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.

Palaeogene structure and stratigraphy at Shingle Pass

The Sheep Pass Formation and Garrett Ranch Group at Shingle Pass (Figure 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 (Figure 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 Palaeocene 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.

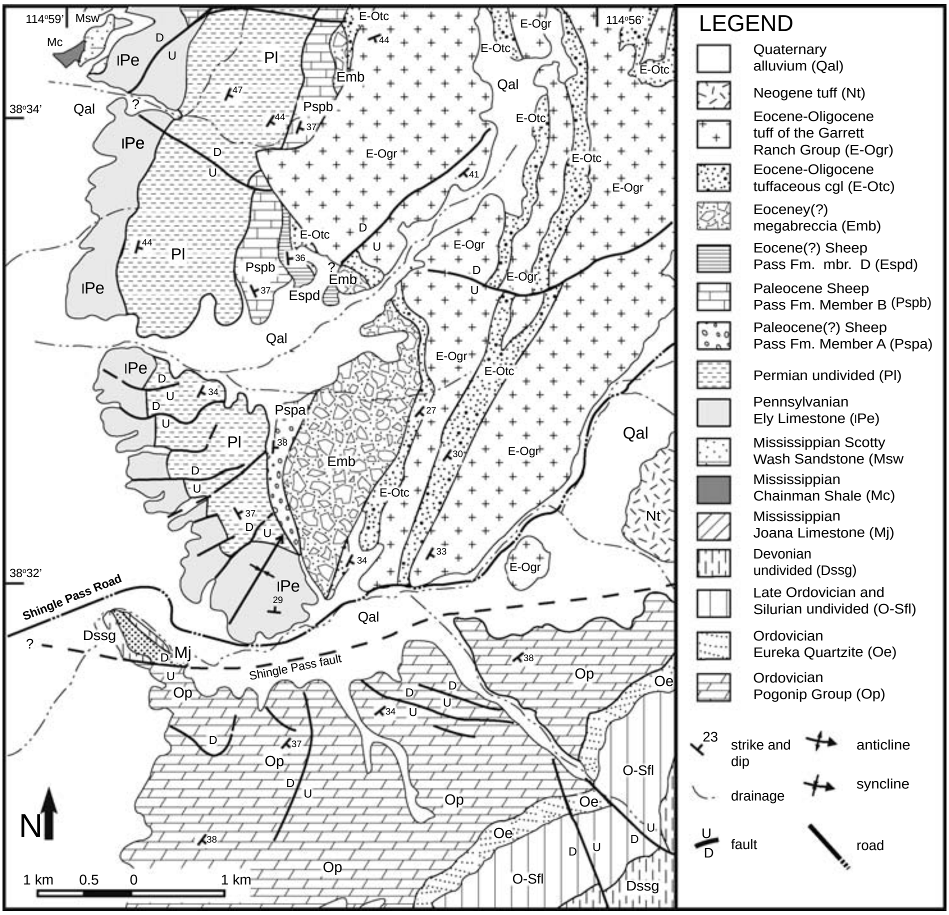

Figure 8. Geologic map of Shingle Pass within the southern Egan Range, modified from Kellogg (1959). Megabreccia within the hanging wall of the Shingle Pass fault overlies members A, B and D of the Sheep Pass Formation. Mapped members of the Sheep Pass Formation at Shingle Pass should be considered lithofacies,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

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 bevelling. The overlying rhyolite vitrophyre has produced an ^{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 bevelling, and eruption of the overlying rhyolite vitrophyre occurred over the span of a maximum of 620K years, and potentially as little as 200K years.

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 bevelled 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 bevelling 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 290K years 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; Figure 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 (Figure 9(a)). These soft-sedimentary structures are encased within planar, undeformed strata, and contain rip-up clasts (Figure 9(b)), pebble lags (Figure 9(c)), and load casts (Figure 9(d)) 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 (Figure 9(e)) that are laterally traceable for several hundred metres 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 addition to slump-folds (Figure 9(f)), sandy beds of member C commonly display flame structures, fluidization pipes, and ball-and-pillar structures (Figure 9(g)). 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 palaeoflow indicators within alluvial facies of members A and C. Large-scale slump deposits demonstrate that low-energy lacustrine deposition within the Maastrichtian to Palaeocene (Fouch 1979; Good 1987; Druschke 2009) 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 Palaeocene 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

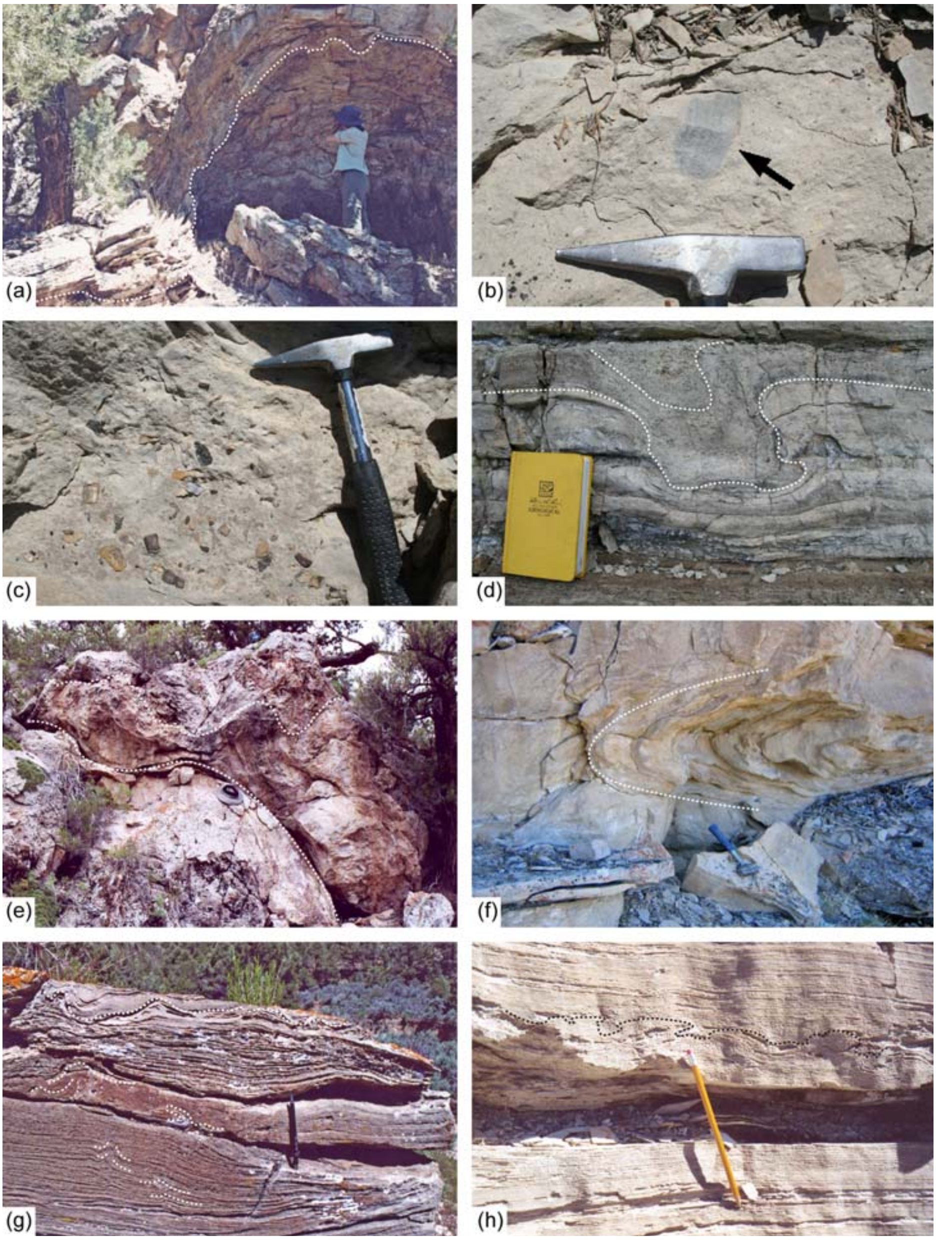

Figure 9. (a) Large-scale soft-sedimentary slump fold in member B of the Sheep Pass Formation type section. (b) Lacustrine limestone rip-up clast associate with a debris slump in member B. (c) Limestone (intra and extra-basinal), chert, and quartzite pebbles incorporated into a dominantly carbonate-mud 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.

laminated carbonate mudstone are laterally traceable across the available exposures (Figure 9(h)). 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 Figures 7 and 10). Ruptured and overturned bedding in sandstone of the Sheep Pass Formation type section (Figure 9(g)) resemble examples of sand volcanoes caused by seismically induced dewatering (Montenat *et al.* 2007, their Figures 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 Palaeogene Sevier hinterland has not previously been documented.

Discussion

Palaeogene 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 Palaeozoic 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 north eastern Nevada, Camilleri (1996) identified the Pequop fault as a low-angle normal fault that juxtaposes unmetamorphosed upper Palaeozoic 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 Palaeogene 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.* 2009). In many cases, the lack of available age control for latest Cretaceous to Palaeogene 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 Palaeocene time. Within the Sheep Pass Formation type section, widespread evidence for large-scale soft-sedimentary slumping, liquefaction, and dewatering in Maastrichtian to upper Palaeocene 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 Palaeocene (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 Palaeocene 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 2009) 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 (Figure 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 (Figure 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 and 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. 50.5–44.5 Ma; Emry 1990; Emry and Korth 1990) are preserved within a sequence of coarse fanglomerate and lacustrine limestone conformably overlain by strata containing

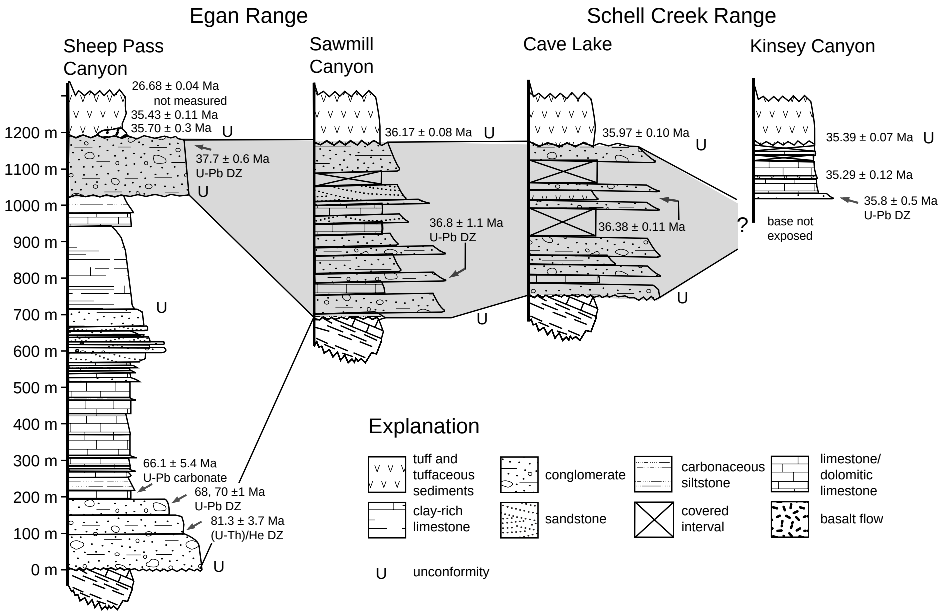

Figure 10. Correlation diagram for uppermost Cretaceous to Eocene strata of the Egan and Schell Creek Ranges. In contrast, to earlier correlations by Fouch (1979), the uppermost Cretaceous to middle Eocene (Bridgerian; 50.5–45.4 Ma) Sheep Pass Formation type section predates the deposition of middle to upper 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 grey. 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 volcanic section of the lower Garrett Ranch Group in Sheep Pass Canyon. Detrital zircon U–Pb, (U–Th)/He and U–Pb carbonate ages from Druschke (2009).

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 million years age range of previous biostratigraphic correlations (Fouch 1979; Good 1987; Emry 1990; Emry and Korth 1990).

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 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 (2009), a >140 m thick sequence of boulder

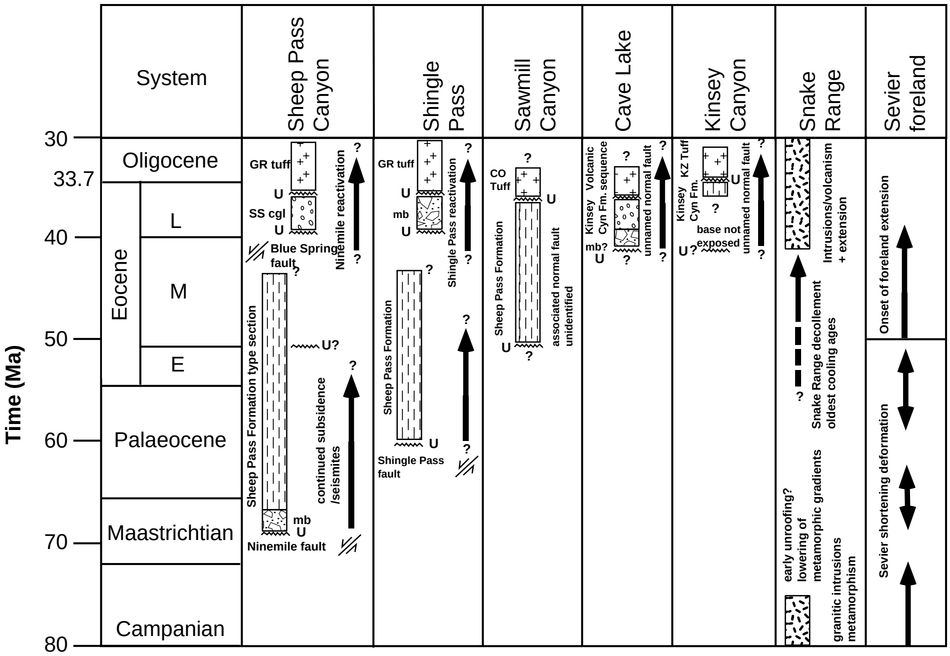

Figure 11. Diagram comparing age relations of normal faults, associated extensional basin deposits, angular unconformities and megabreccia within the Egan and Schell Creek Ranges. Black arrows depict the potential age span for motion along corresponding normal faults. Inferred normal faulting in the 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) – Palaeocene 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 DeCelles (1994), and timing for initiation of extension in the Sevier foreland from Constenius (1996). GR, Garrett Ranch Group; CO, Charcoal Ovens; KZ, Kalamazoo; mb, megabreccia and U, unconformity.

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 2009), while the overlying Stone Cabin Formation has produced an ^{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 38–35 Ma.

Evidence that extension predated volcanism within the latest Cretaceous to Palaeogene 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 Palaeogene 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 Palaeogene extension.

Implications for palaeogeography 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 Palaeogene units of east-central Nevada overlie Palaeozoic strata with typically $<10°$ of angular discordance (Armstrong 1968, 1972). The assessment that Upper Cretaceous and Palaeogene strata display little discordance with underlying upper Palaeozoic 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 Palaeozoic 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, 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 (Figure 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 Palaeozoic 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, angular 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 Palaeogene 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 Palaeozoic strata protruded up to several hundred metres 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, 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 palaeotopography 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 Palaeozoic 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 2009). Megabreccia blocks derived from Devonian limestone overlie Palaeocene 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 Palaeozoic carbonate has been documented within Palaeocene 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.

Palaeocurrent 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 2009) 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 Palaeogene. 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 north eastern Nevada represent a series of east-flowing palaeocanyons, and that relief within the Ruby-East Humboldt core complex was low in Eocene time (Henry 2008). However, studies supporting the palaeocanyon hypothesis lack palaeocurrent analyses (Henry 2008). In east-central Nevada, no palaeocanyons have been identified in association with middle to late Eocene deposits, and 215 palaeocurrent 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 Palaeocene 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 Palaeocene, and middle to late Eocene reactivation. New ^{40}Ar/^{39}Ar dates derived from volcanic strata of the Garrett Ranch Group indicates that the 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 palaeocurrent trends are considered, and significant post-Eocene east-west extension is restored. Evidence for long-lived, westward palaeocurrent trends and progressive unroofing of Palaeogene deposits suggest 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 Palaeogene 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 Eocene reactivation of the Ninemile and Shingle Pass faults.

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