Synconvergent surface-breaking normal faults of Late Cretaceous age within the Sevier hinterland, east-central Nevada

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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 and metamorphic rocks within the Raft River–Albion–Grouse Creek and Ruby–East Humboldt core complexes indicate that mid-crustal extension initiated in the Late Cretaceous (85–75 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 middle 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 décollement (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 nontuffaceous 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

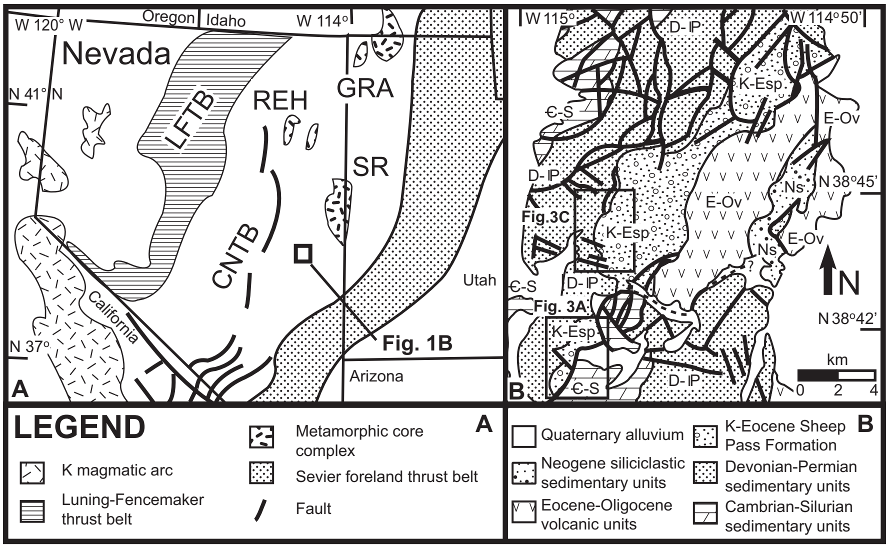

Figure 1. A: Generalized geologic map of the Sevier orogen in the vicinity of east-central Nevada. LFTB—Luning-Fencemaker thrust belt; CNTB—central Nevada thrust belt; REH—Ruby–East Humboldt core complex; GRA—Grouse Creek–Raft River–Albion core complex; SR—Snake Range core complex (modified from DeCelles, 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 Figures 3A (Ninemile Canyon) and 3C (Sheep Pass Canyon). K—Cretaceous.

faulting and associated volcanism, is generally accepted as late Eocene (ca. 38–35 Ma) (Gans et al., 1989, 2001; Axen et al., 1993).

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; see Table DR1 in the GSA Data Repository[1]). 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).

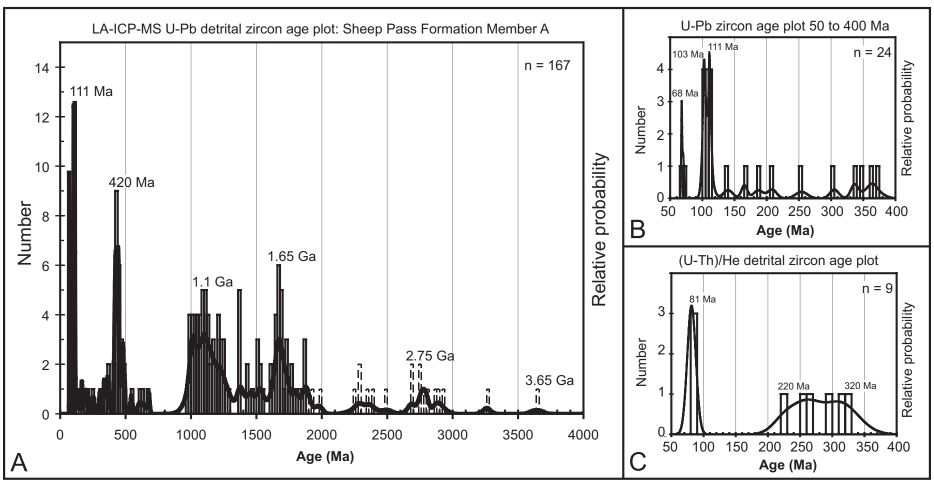

Figure 2. Probability density plots for U-Pb and (U-Th)/He detrital zircon age analyses. A: U-Pb detrital zircon age plot for Member A of the Sheep Pass Formation. B: U-Pb age plot displaying the Mesozoic age distribution of Member A. C: (U-Th)/He detrital zircon age plot for Member A. Mean age of Cretaceous peak is 81.3 ± 3.7 Ma.

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; Table DR2). 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 were performed on zircons obtained from the same samples, they were not conducted on the same zircons (Reiners et al., 2005). Cooling ages of 81 Ma 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) corroborates earlier Maastrichtian to Paleocene fossil age assignments (Fouch, 1979; Good, 1987). Given that Member A has produced two zircon ages of 68 ± 1 and 70 ± 1 Ma, and that its contact with Member B is gradational, the Sheep Pass basin may have initiated in the Maastrichtian with a sig-

[1]GSA Data Repository item 2009110, Tables DR1–DR3 (analytical results used for U-Pb detrital zircon, (U-Th)/He detrital zircon, and U-Pb carbonate age determinations), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

nificant 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 northeast and dipping 15°–25° northwest 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 northwest 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.

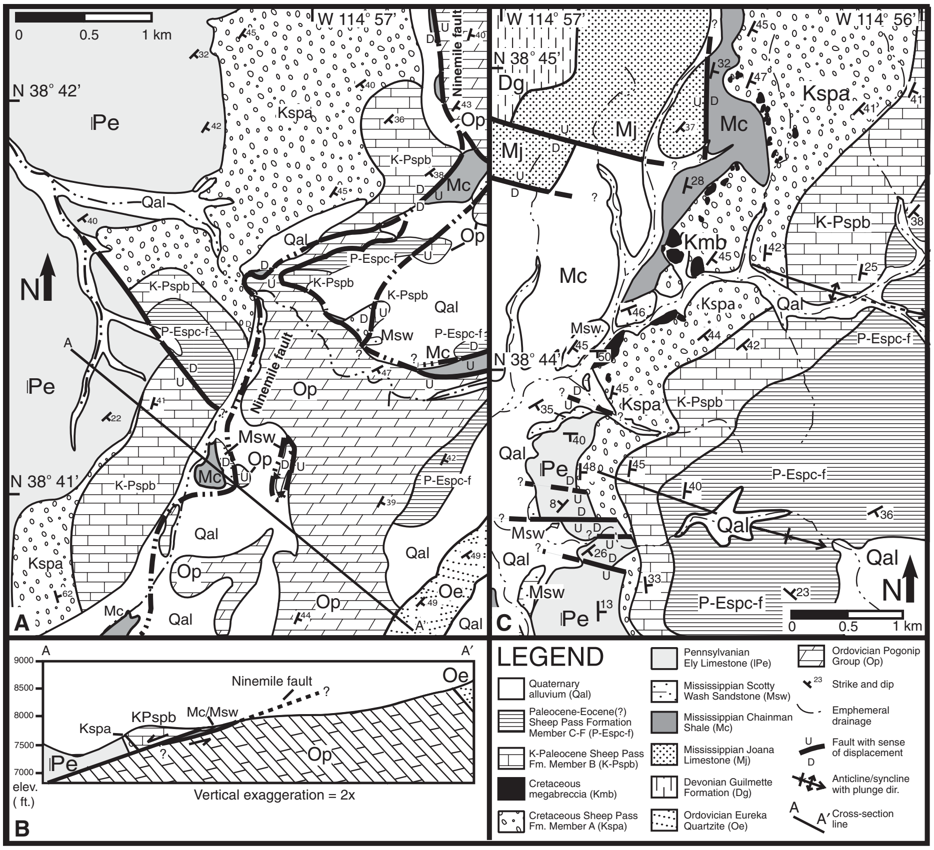

Figure 3. A: Geologic map of Ninemile Canyon. B: Cross section from A to A′ in Figure 3A. Sheared blebs of the Mississippian Chainman Shale and Scotty Wash Sandstone form discontinuous outcrops along the Ninemile fault. C: Geologic map of Sheep Pass Canyon. K—Cretaceous; Fm—Formation.

Intrabasinal 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 east-west 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.

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