International Geology Review

ISSN: 0020-6814 (Print) 1938-2839 (Online) Journal homepage: https://www.tandfonline.com/loi/tigr20

# Rapid middle Miocene collapse of the Mesozoic orogenic plateau in north-central Nevada

Joseph P. Colgan & Christopher D. Henry

*International Geology Review*
Vol. 51, Nos. 9–11, September–November 2009, 920–961



# Rapid middle Miocene collapse of the Mesozoic orogenic plateau in north-central Nevada

Joseph P. Colgan[a]* and Christopher D. Henry[b]

[a]*US Geological Survey, Menlo Park, CA 94025, USA;* [b]*Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA*

(*Accepted 20 May 2009*)

The modern Sierra Nevada and Great Basin were likely the site of a high-elevation orogenic plateau well into Cenozoic time, supported by crust thickened during Mesozoic shortening. Although crustal thickening at this scale can lead to extension, the relationship between Mesozoic shortening and subsequent formation of the Basin and Range is difficult to unravel because it is unclear which of the many documented or interpreted extensional episodes was the most significant for net widening and crustal thinning. To address this problem, we integrate geologic and geochronologic data that bear on the timing and magnitude of Cenozoic extension along an ~200 km east–west transect south of Winnemucca, Battle Mountain, and Elko, Nevada. Pre-Cenozoic rocks in this region record east–west Palaeozoic and Mesozoic compression that continued into the Cretaceous. Little to no tectonism and no deposition followed until intense magmatism began in the Eocene. Eocene and Oligocene ash-flow tuffs flowed as much as 200 km down palaeovalleys cut as deeply as 1.5 km into underlying Palaeozoic and Mesozoic rocks in a low-relief landscape. Eocene sedimentation was otherwise limited to shallow lacustrine basins in the Elko area; extensive, thick clastic deposits are absent. Minor surface extension related to magmatism locally accompanied intense Eocene magmatism, but external drainage and little or no surface deformation apparently persisted regionally until about 16–17 Ma. Major upper crustal extension began across the region ca. 16–17 Ma, as determined by cross-cutting relationships, low-temperature thermochronology, and widespread deposition of clastic basin fill. Middle Miocene extension was partitioned into high-strain (50–100%) domains separated by largely unextended crustal blocks, and ended by 10–12 Ma. Bimodal volcanic rocks that erupted during middle Miocene extension are present across most of the study area, but are volumetrically minor outside the northern Nevada rift. The modern physiographic basins and ranges formed during a distinctly different episode of extension that began after about 10 Ma and has continued to the present. Late Miocene and younger faulting is characterized by widely spaced, high-angle normal faults that cut both older extended and unextended domains. Major widening of the Basin and Range at this latitude thus took place during a relatively brief interval in the middle Miocene, and the lack of major shortening west of the Sierra Nevada at this time suggests that the change in the plate margin from microplate subduction to lengthy transtensional strike-slip played an important role in allowing extension to occur when it did, as rapidly as it did. The onset of extension ca. 16–17 Ma was coeval with both Columbia River flood-basalt volcanism and the hypothesized final delamination of the shallow Farallon slab that lay beneath the western USA in the early Tertiary. However, it is unclear if these events were necessary prerequisites for extension, simply coincidental, or themselves consequences of rapid extension and/or reorganization of the plate boundary.

**Keywords:** crustal shortening; Mesozoic orogenic plateau; Basin and Range; Miocene; extension

*Corresponding author. Email: jcolgan@usgs.gov

ISSN 0020-6814 print/ISSN 1938-2839 online
DOI: 10.1080/00206810903056731
http://www.informaworld.com

## Introduction

The Mesozoic to early Tertiary continental margin of North America was characterized by a well-developed forearc basin, volcanic arc, and fold-thrust belts in Nevada and Utah that accommodated significant crustal shortening from the Jurassic to the Late Cretaceous (e.g. Cowen and Bruhn 1992; Miller *et al.* 1992; Figure 1). By the end of the Late Cretaceous, Mesozoic compression had significantly thickened the crust (up to $>60$ km) in the region between the Cretaceous arc and the Sevier fold-thrust belt in western Utah (Figure 1; e.g. Coney and Harms 1984; Molnar and Lyon-Caen 1988; Snoke and Miller 1988; Allmendinger 1992; DeCelles 2004). Crustal thickening in this region was accompanied by partial melting and metamorphism at depth (e.g. Miller and Gans 1989; Miller *et al.* 1990; McGrew and Snee 1994; Camilleri and Chamberlain 1997; Camilleri *et al.* 1997; Snoke *et al.* 1997; McGrew *et al.* 2000; Lee *et al.* 2003), and by uplift of the land surface, which may have reached surface elevations of up to 3–4 km above sea level by the early Cenozoic (e.g. Chase *et al.* 1998; Wolfe *et al.* 1998). The resulting plateau – now frequently called the 'Nevadaplano' by analogy to the South American Altiplano – persisted until it was brought down during Cenozoic Basin and Range extension.

Although thick crust and high surface elevations can store gravitational potential energy to drive subsequent extensional collapse (e.g. Dewey 1988; Sonder and Jones 1999), the relationship between any Mesozoic orogenic plateau in the western USA and Basin and

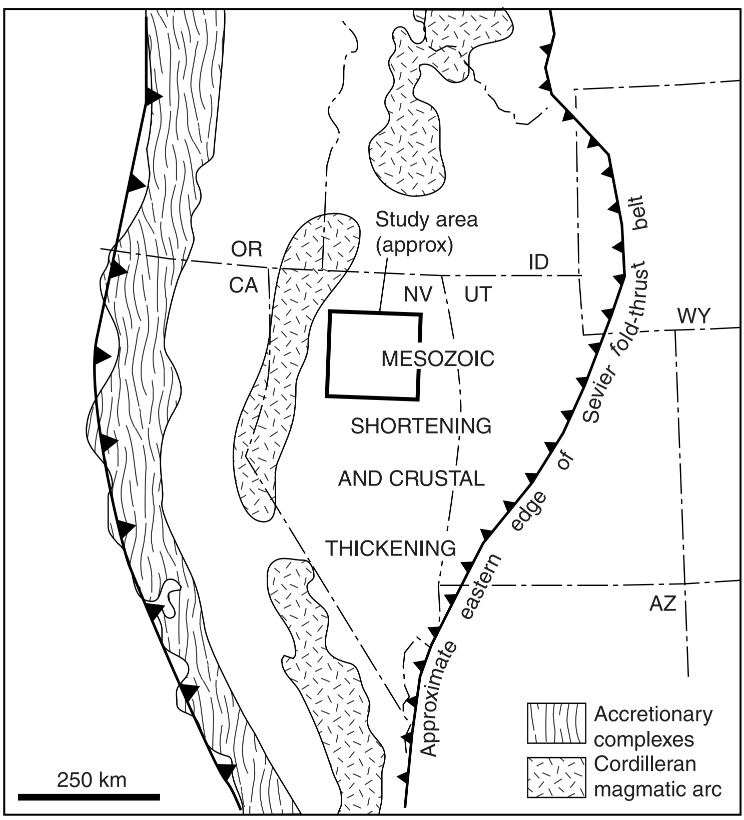


Figure 1. Late Mesozoic palaeogeographic map of the western USA (modified from DeCelles and Coogan 2006).

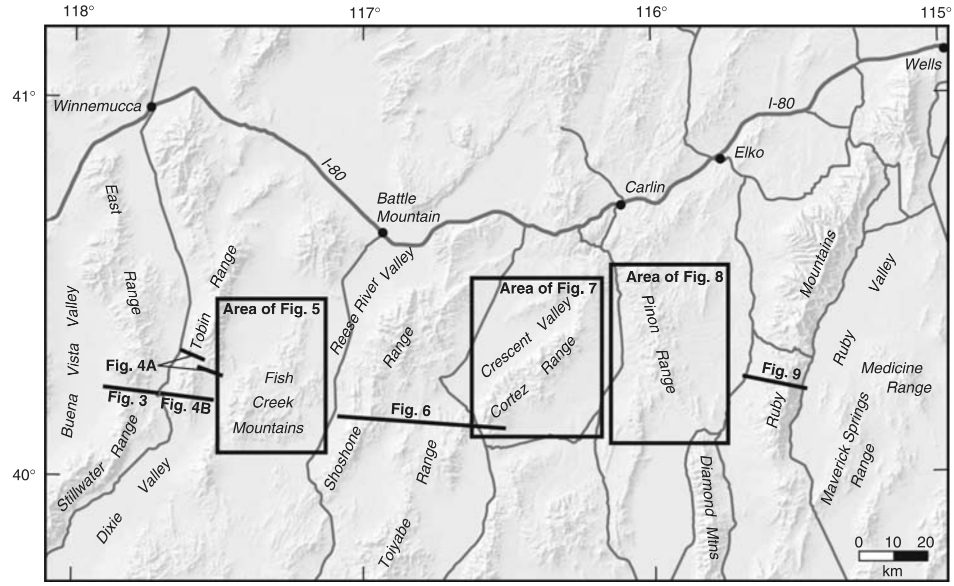


Figure 2. Shaded-relief map of north-central Nevada, showing major geographic features and location of maps and cross-sections discussed in the text.

Range extension is somewhat unclear. The problem is not that the timing of extension is unknown, but rather that it took place in one form or another over such a long span of time – the Late Cretaceous or earliest Tertiary, the Eocene and Oligocene, and from the Miocene to the present (see references in subsequent sections) – that it is unclear how regionally extensive most of these episodes were and which ones were most significant in terms of crustal thinning and map-view widening of the Basin and Range Province. In this paper, we synthesize recently published geologic and geochronologic data that bear on the timing and kinematics of Basin and Range extension along an ~200 km transect south of Winnemucca, Battle Mountain, and Elko, Nevada (Figure 2). This region crosses a large swath of the former 'Nevadaplano' (Figure 1) thought to have existed by the end of the Mesozoic. We find that this region likely persisted as a low-relief, externally drained plateau (possibly at a high elevation) until it was broken up during a relatively brief period of rapid extension in the middle Miocene (between about 17–16 and 10 Ma).

## Late Mesozoic to late Miocene tectonic evolution of north-central Nevada

### *Regional geology*

In the following section, we summarize and interpret existing data that bear on the tectonic history of each range (or part of each range), along a west-to-east transect across the study area (Figure 2). Because we are concerned with the formation and subsequent extensional collapse of a probable orogenic plateau, we focus on (1) when the most recent crustal shortening took place, (2) the timing and kinematics of extension, and (3) the stratigraphic record of the interval between compression and extension.

#### *Southern East Range: northern Stillwater Range*

The oldest exposed rocks in the southernmost East Range and northernmost Stillwater Range (here referred to as simply the 'Southern East Range' for brevity; Figure 2) are upper Palaeozoic (Mississippian to Permian) chert, quartzite, and argillite of the Golconda allochthon (the Havallah Sequence), tectonically emplaced during the late Palaeozoic Sonoma Orogeny (Figure 3(a)). These units are highly deformed and overlain unconformably by Lower Triassic volcaniclastic rocks of the Koipato Group, which are in turn overlain by Triassic limestone and dolomite of the Star Peak Group and fine-grained clastic rocks of the Auld Lang Syne Group (Nichols and Silberling 1977; Elison and Speed 1988). There is some uncertainty in the timing of emplacement of the Golconda allochthon (e.g. Ketner 2008), but major deformation in the Luning–Fencemaker Belt took place in the Early to Middle Jurassic (Wyld 2002).

Triassic rocks in the southern East Range were intruded by the Oligocene (33–31 Ma; Fosdick and Colgan 2008) Granite Mountain plutonic complex (Wallace 1977; Whitebread and Sorensen 1980). The oldest Tertiary extrusive rocks in this area are a sequence of ash-flow tuffs deposited locally on Triassic rocks in the Sou Hills (Nosker 1981; Fosdick 2007). These tuffs are undated but we presume that they correlate with mid-Tertiary (24–35 Ma) rocks erupted from calderas to the east (see later sections). Pre-Cenozoic basement, mid-Tertiary tuffs, and the Oligocene plutonic complex are all overlain by tuffaceous sedimentary rocks and interbedded basalt and rhyolite lava flows that range in age from 17 to 13 Ma (Figure 3(a); K–Ar dates from Nosker 1981).

The modern East Range is bounded to the west by a down-to-the-west normal fault and Tertiary rocks on both sides of the range dip east (Figure 3(a)). The oldest middle Miocene tuffaceous sediments and basalt flows dip 35–50° east, and in the Sou Hills they rest on the mid-Tertiary tuffs with no angular discordance (Fosdick 2007). The youngest basalt flows

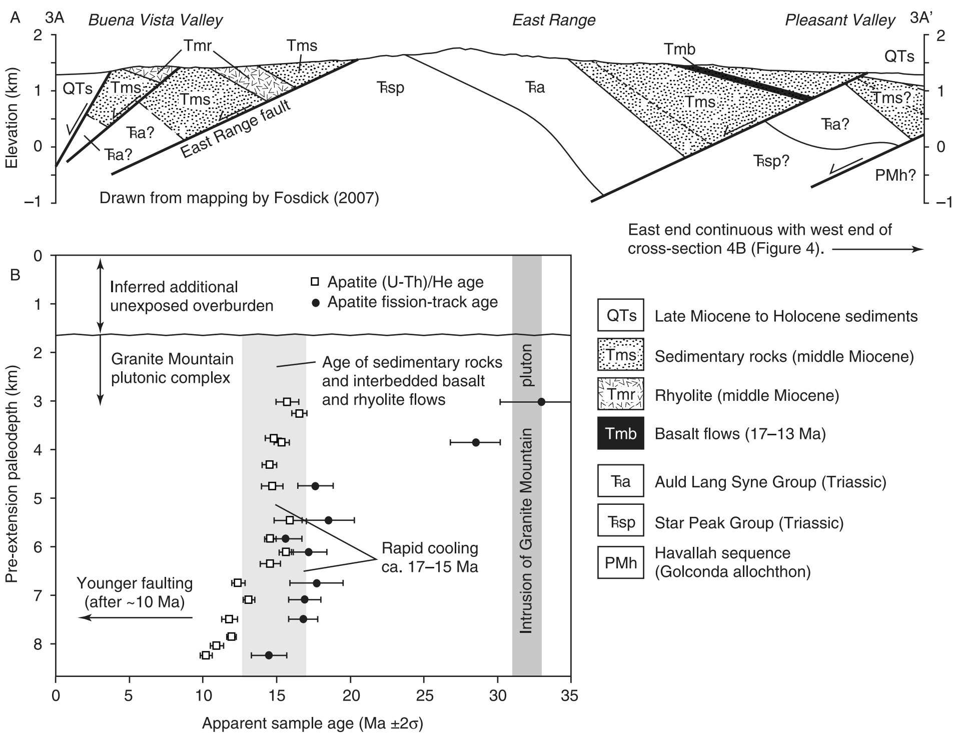


Figure 3. (a) Geologic cross-section of the East Range, drawn from mapping by Burke (1973) and Fosdick (2007), (b) Apatite fission-track and (U–Th)/He data from the East Range, modified from Fosdick and Colgan (2008).

dip more gently than the older basalt flows and older sediments, indicating that the basalts were erupted during tilting. Apatite fission-track and (U–Th)/He data from the Granite Mountain plutonic complex (Figure 3(b)) indicate that the uppermost part of the pluton cooled to near-surface temperatures (<60–70°C or <2–3 km) during emplacement. Deeper (western) parts of the pluton cooled rapidly at 17–15 Ma during inferred slip on the major west-dipping fault (Figure 3(b); Fosdick and Colgan 2008).

Middle Miocene lava flows and sedimentary rocks were tilted, incised, and partly buried by younger (likely Pliocene and younger) basin fill, indicating that they represent a distinctly older period of basin development than the modern Buena Vista and Pleasant Valleys. The youngest apatite (U–Th)/He age on the west side of the range is about 10 Ma (Figure 3(b)), requiring some post-10 Ma exhumation (equivalent to ~60°C or ~2–3 km) and cooling of the west side of the range. Quaternary fault scarps on the west side of the range dip steeply at the surface, but it is not clear if these faults sole into the more gently dipping middle Miocene fault or cut it at depth (Fosdick and Colgan 2008). Restored cross-sections indicate ~6 km of extension (~75% strain) across the East Range and Sou Hills (this study, cross-section Figure 3(a)), or ~14 km of slip and 11–12 km of extension on the East Range Fault itself (Fosdick and Colgan 2008, their Figure 4). Assuming dip-slip motion on the East Range Fault, the strike of tilted Tertiary rocks indicates that extension was oriented about 280–290°.

### *Southern Tobin Range*

The oldest rocks in the southern Tobin Range (Figures 2 and 4) consist of over 5 km (structural thickness) of complexly folded and faulted Mississippian to Permian chert,

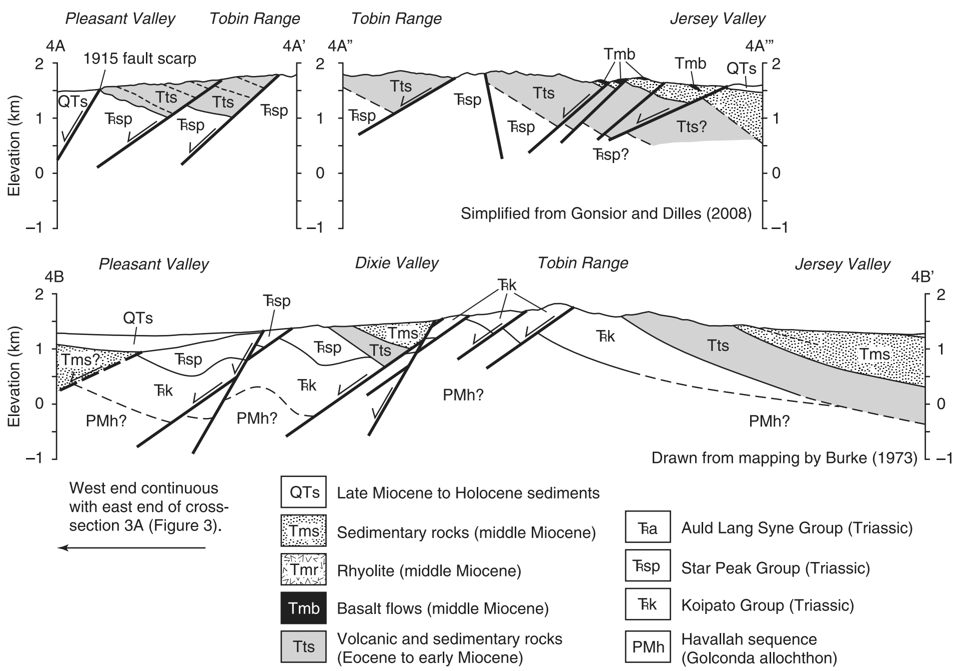


Figure 4. (a) Geologic cross-sections of the Tobin Range at Golconda Canyon (reproduced from Gonsior and Dilles (2008), with simplified units), (b) Geologic cross-section of the southern Tobin Range, drawn from mapping by Burke (1973).

argillite, and silty limestone of the Golconda allochthon (Stewart *et al.* 1986). The Golconda allochthon is overlain unconformably by Triassic rocks of the Koipato, Star Peak, and Auld Lang Syne Groups (Figure 4; Burke 1973; Burke and Silberling 1973; Stewart *et al.* 1986). Although major deformation within the Golconda allochthon is thus Palaeozoic, Ketner (2008) suggested that emplacement of the allochthon itself (i.e. slip on the Golconda Thrust) is actually Jurassic. Whether this is true or not, Triassic rocks in the vicinity of our cross-sections (Figure 4) are folded, indicating at least some post-Triassic shortening (Burke 1973).

In the southern part of the Tobin Range, Eocene to early Miocene rocks fill a ~1400 m-deep, roughly west-trending palaeovalley cut into Triassic rocks of the Star Peak Group (Burke 1973; Gonsior and Dilles 2008). The oldest dated unit (within 50 m of the bottom of the section) is the 33.8 Ma Caetano Tuff (33.75 ± 0.06 Ma; $^{40}Ar/^{39}Ar$ date from John *et al.* 2008). The youngest dated unit (~300 m from the top of the section) is the 24.7 Ma (24.72 ± 0.06 Ma; $^{40}Ar/^{39}Ar$ date from John *et al.* 2008) Fish Creek Mountains Tuff (Gonsior and Dilles 2008). The intervening and overlying fill of >1 km consists of coarse volcaniclastic rocks, lava flows, and megabreccia deposits (Gonsior and Dilles 2008). Both the Caetano Tuff and Fish Creek Mountains Tuff were sourced from calderas to the east (discussed in subsequent sections), indicating westerly drainage down this palaeovalley in the Oligocene and earliest Miocene. Mid-Tertiary palaeovalley fill and adjacent Triassic rocks are both overlain by middle Miocene sedimentary rocks and interbedded basalt flows; Gonsior and Dilles (2008) report a 14.1 Ma age from a basalt flow at the base of this section (their cross-section B–B′, reproduced here as Figure 4(a)).

Tertiary rocks in the southern Tobin Range are east-tilted and cut by closely spaced (1–2 km) moderately west-dipping normal (30–40°) faults (Figure 4(a,b)). Gonsior and Dilles (2008) infer a minor early Oligocene period of faulting, with subsequent extension beginning as early as 24 Ma and peaking at 17–18 Ma before continuing up to the present. Miocene sedimentary rocks upsection from the 14.1 Ma basalt flow dip as much or more (40°) than the Eocene and Oligocene volcanic rocks (25–40°; Gonsior 2006), indicating that most tilting – and therefore net map-view widening of the Tobin Range – took place after 14 Ma, although it may have begun shortly before. Middle Miocene sedimentary rocks on the west side of Jersey Valley (Figure 4(b)) are now tilted, uplifted, and eroded (Burke 1973; Gonsior 2006), indicating that they represent a distinctly older period of sedimentation than the modern basin in Jersey Valley. The modern Tobin Range is a horst block bounded on both sides by high-angle faults that probably formed at the same time as the modern basins (i.e. after deposition of the middle Miocene sedimentary sequence). Beyond that it is not known when the modern range-bounding faults began to form, but both have Quaternary scarps and the western one is marked by a spectacular scarp from the 1915 M7.1 Pleasant Valley earthquake (Wallace 1984).

Gonsior and Dilles (2008) calculated 46% strain (~1.4 km) on their cross-section A–A′ [our Figure 4(A–A′)] and 25% strain (~1.5 km) on their cross-section B–B′ [our Figure 4(A″–A‴)]. We estimate ~13 km of combined extension across the central East Range (Figure 3(a)) and southern Tobin Range (Figure 4(b)), or about ~60% strain between the western edge of the East Range and the western edge of the Fish Creek Mountains (Figure 2). Assuming dip-slip motion on major west-dipping normal faults, the strike of tilted Tertiary units on the maps of Burke (1973) and Gonsior (2006) indicates that extension was oriented 280–295°. Most of this extension took place after 14.1 Ma in two distinct episodes – an earlier period of tilted 'domino-style' normal faults that accommodated most of the tilting, and a younger period of high-angle horst-and-graben style faulting that formed the modern Tobin Range.

*Fish Creek Mountains*

The bulk of the roughly circular 20 km-wide Fish Creek Mountains (Figure 2) consists of the Fish Creek Mountains caldera, source of the 24.72 ± 0.06 Ma Fish Creek Mountains Tuff (McKee 1970; John *et al.* 2008). Pennsylvanian and Permian rocks of the Golconda allochthon are exposed on the west side of the range along the western caldera margin (Figure 5), but it is unclear if they were at the surface during the Eocene and Oligocene. In the northern part of the range, Eocene to Oligocene volcanic rocks rest on Triassic rocks of the Star Peak and Auld Lang Syne Groups (Figure 5; Stewart *et al.* 1977). The Fish Creek Mountains caldera and underlying rocks are essentially undeformed and gently east-tilted in the footwall of a west-dipping normal fault that bounds the range to the west (Figure 5). The age of this fault is not known, but it formed the modern Fish Creek Mountains and is therefore probably late Miocene or younger. A chain of small Pliocene–Quaternary basaltic cones parallels the northern part of this fault (Figure 5; Cousens and Henry 2008). If these eruptions were focused by the fault, then it must be at least as old as Pliocene.

*Southern Shoshone and northern Toiyabe ranges*

The southern Shoshone and northern Toiyabe ranges (Figure 2) expose primarily deep-water siliceous rocks of the Palaeozoic Roberts Mountains allochthon, which were emplaced during the Antler Orogeny. Local erosional and structural windows through the allochthon expose Cambrian to Devonian rocks of the Palaeozoic continental shelf (Gilluly and Gates 1965; Gilluly and Masursky 1965). In several places the Roberts Mountains allochthon is unconformably overlain by Pennsylvanian to Permian rocks that were deposited after the Antler Orogeny (the 'Antler overlap sequence'; Gilluly and Gates 1965; Gilluly and Masursky 1965; Moore *et al.* 2005). The timing and nature of Mesozoic shortening in this area are very poorly known, but Gilluly and Gates (1965) discuss evidence for a 'Lewis Orogeny'

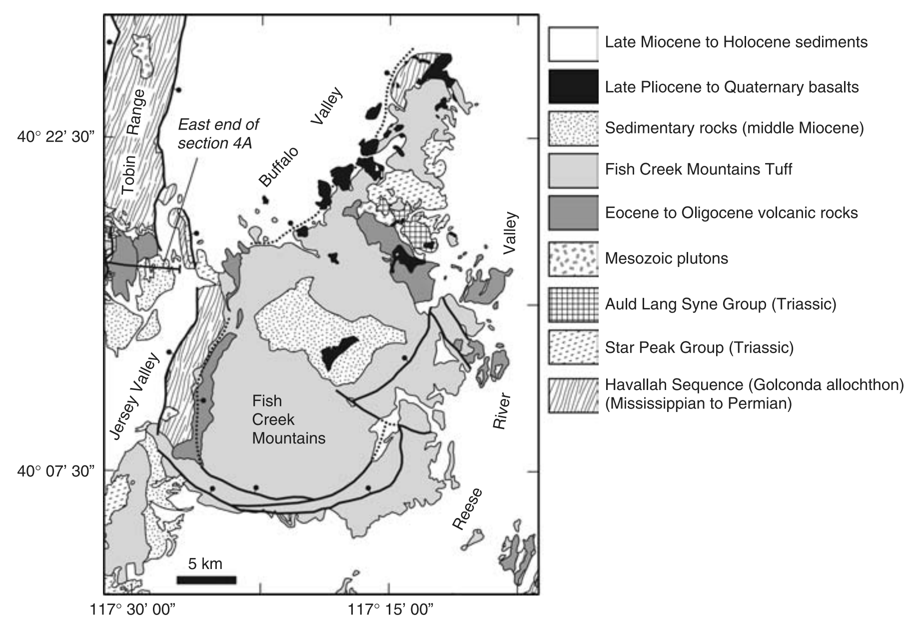


Figure 5. Geologic map of the Fish Creek Mountains, simplified from McKee (1970) and Stewart *et al.* (1977).

that involves folded Permian and Triassic rocks and must therefore be post-Triassic, consistent with geologic relationships in nearby areas discussed above and below.

The oldest Tertiary rocks are rare mafic lava flows and conglomerates deposited in palaeovalleys cut into the Roberts Mountains allochthon (John *et al.* 2008). The Caetano caldera formed during eruption of the Caetano Tuff at 33.8 Ma and filled with up to 4 km of intracaldera tuff and breccia (John *et al.* 2008). Outflow Caetano Tuff from this eruption was deposited on the Roberts Mountains allochthon and locally on overlying Pennsylvanian and Permian rocks (Gilluly and Gates 1965; Gilluly and Masursky 1965; John *et al.* 2008). Following the eruption, sedimentary rocks and distally derived ash-flow tuffs accumulated within the caldera until about 25 Ma, but these sedimentary deposits are absent outside the topographic depression left by caldera collapse (John *et al.* 2008).

Eocene to Oligocene rocks that filled the Caetano caldera are now exposed in a series of strongly east-tilted (30–60°) fault blocks cut by west-dipping normal faults that accommodated $\sim$22 km of extension oriented $\sim$290°, or roughly 110% strain over an area that now is at least 42 km wide (Figure 6; Colgan *et al.* 2008). The western boundary of this extended domain (with the unextended Fish Creek Mountains) is now buried beneath Reese River Valley (Figures 2 and 5), and the eastern boundary is defined by the Cortez Fault, which separates it from the much-less-extended Cortez Range (Figures 6 and 7). Sedimentary rocks deposited in narrow half-graben basins during this period of extension range in age from 16–15 to $<$12 Ma (Figure 6; Colgan *et al.* 2008). The tilts of the oldest deposits are approximately the same as underlying 34–25 Ma rocks, indicating that extension began at or shortly before $\sim$16 Ma, and that it was ongoing until at least 12 Ma, possibly 10 Ma (Colgan *et al.* 2008). The middle Miocene faults and sedimentary basin deposits in the southern Shoshone and northern Toiyabe ranges are cut by younger, more widely spaced (20–30 km) high-angle faults that outline the modern basins and ranges but did not accommodate significant horizontal extension or fault-block tilting (Colgan *et al.* 2008). The time at which this younger faulting began is unclear, but it must postdate the tilting and exhumation of $\sim$12 Ma fill in the Miocene basins. These younger high-angle faults have documented Quaternary slip in the Shoshone Range (Figure 2) north of the Caetano caldera (Wesnousky *et al.* 2005).

### *Crescent Valley and Cortez Range*

The oldest rocks exposed in the Cortez Range (Figures 2 and 7) are Cambrian to Devonian carbonates and siliciclastic rocks of the Palaeozoic continental shelf; these units were overthrust by deep-water rocks of the Roberts Mountains allochthon (Figure 7; Gilluly and Masursky 1965). Pennsylvanian to Permian carbonates and sandstones of the overlap sequence unconformably overlie the deformed Roberts Mountains allochthon in the southern part of the range (Figure 7; Muffler 1964). Palaeozoic rocks are overlain and intruded by Jurassic volcanic rocks and cogenetic shallow intrusive rocks (Muffler 1964). In the northeastern part of the range, Jurassic volcanic rocks are overlain by up to 660 m of Cretaceous clastic sedimentary rocks of the Lower Cretaceous Newark Canyon Formation (Figure 7; Smith and Ketner 1976) from which Druschke *et al.* (2008) reported a U–Pb zircon age of 116 Ma from an interbedded tuff. The most recent shortening in the Cortez Range involves the Jurassic volcanic rocks and is inferred to be either Late Jurassic (prior to deposition of the Newark Canyon Formation, e.g. Muffler 1964; Ketner and Alpha 1992) or Early Cretaceous (during deposition of the Newark Canyon Formation, e.g. Vandervoort and Schmitt 1990).

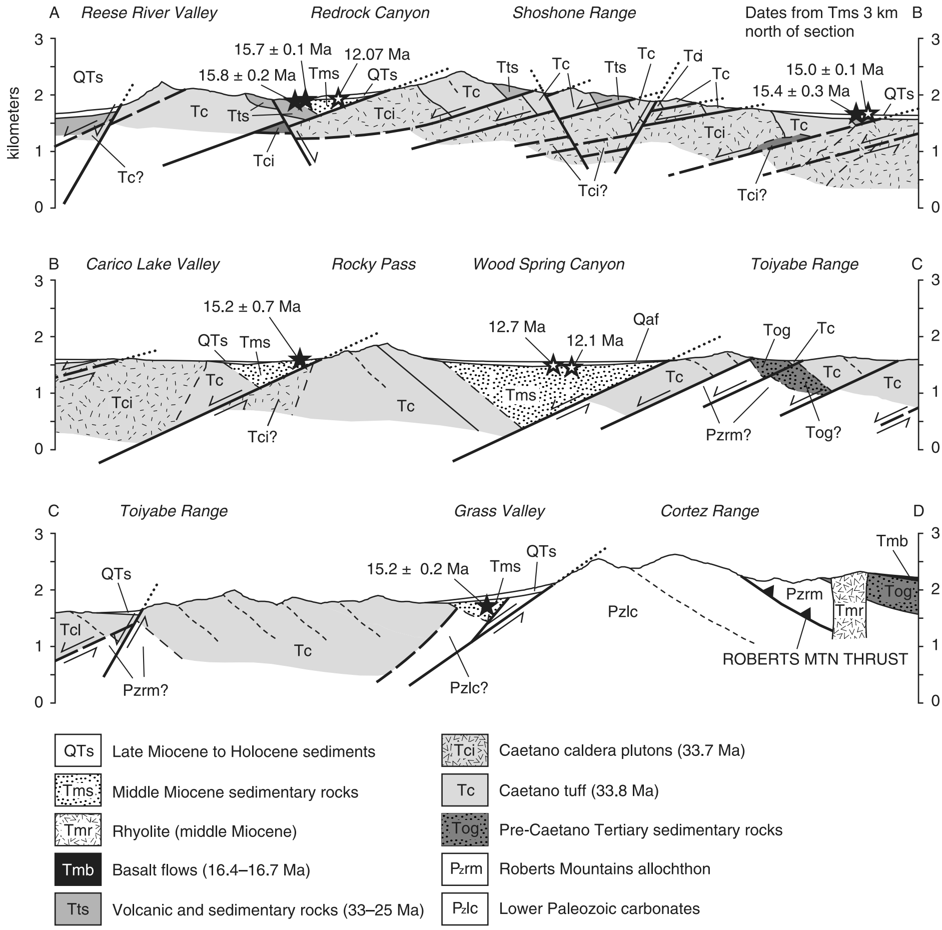


Figure 6. Geologic cross-section of the Caetano caldera, Shoshone, and northern Toiyabe ranges, modified from Colgan *et al.* (2008). Section continues seamlessly from B to B and C to C. Stars are dates on Miocene sedimentary rocks (open = tephra correlation, filled = $^{40}$Ar/$^{39}$Ar sanidine age) from Colgan *et al.* (2008).

The southern part of the Cortez Range is capped by ~100 m of Miocene (ca. 16.5 Ma) basalt flows, which locally are underlain by ~400 m of poorly exposed Tertiary sediments (unconsolidated gravel for the most part; John *et al.* 2000). The Tertiary gravels were deposited primarily on the Roberts Mountains allochthon, but in the southern part of the range they fill an ~1 km-deep palaeovalley cut through the Roberts Mountains thrust into lower-plate Devonian carbonates (east end of Figure 6(c,d) and southwest corner of Figure 7; Gilluly and Masursky 1965; John *et al.* 2008). Numerous north-northwest-trending Miocene mafic dikes intruded older rocks in the south-central part of the range and probably fed overlying basalt flows – these dikes and flows are part of the northern Nevada rift (Figure 7), which trends ~340° across the region and formed during a narrow interval between about 16.5 and 15 Ma (Zoback and Thompson 1978; Zoback *et al.* 1994; John *et al.* 2000). Basalt flows within the rift dip ~6° SE, indicating very little tilting and presumably extensional faulting since about 15 Ma.

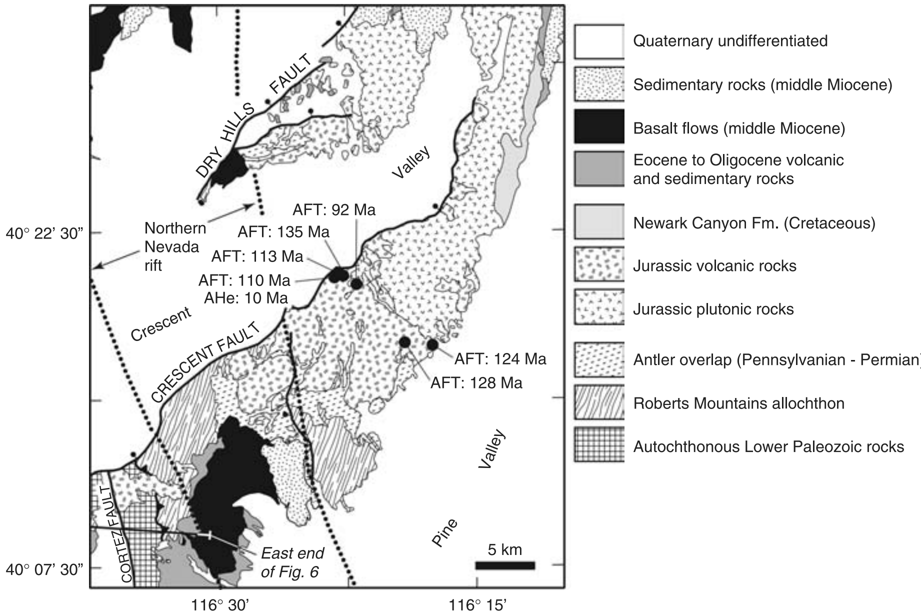


Figure 7. Geologic map of the Cortez Range, modified from Muffler (1964) and Roberts *et al.* (1967). AFT, Apatite fission-track; AHe, apatite (U–Th)/He. Ages from Colgan and Metcalf (2006b).

Pre-Tertiary rocks in the Cortez Range may have been deformed in the Mesozoic (e.g. Muffler 1964; Ketner and Alpha 1992), but subsequently the area remained largely undeformed until the late Miocene. Apatite fission-track ages from Jurassic granite in the central Cortez Range range from 92 to 135 Ma (Figure 7; Colgan and Metcalf 2006b), indicating that these rocks have been at temperatures ≤60°C (within 2–3 km of the surface) since at least the Cretaceous. The modern range is bound on the west side by the high-angle, down-to-the-northwest Crescent Fault, which cuts Quaternary deposits and middle Miocene (15.2 Ma, Colgan *et al.* 2008) sedimentary rocks in the hanging wall of the Cortez Fault (Figures 6 and 7). Colgan and Metcalf (2006b) report an ~9 Ma apatite (U–Th)/He age from the west side of the range adjacent to the Crescent Fault (Figure 7), requiring at least 2 km of vertical slip since that time to bring this sample to the surface from a depth equivalent to 60°. The Crescent Fault is therefore younger than 15.2 Ma and has significant slip since 10 Ma. Total slip on the Crescent Fault is unknown, but gravity data indicate ~1 km of fill in Crescent Valley (Watt *et al.* 2008), consistent with about 2–3 km of vertical offset but only ~1 km of horizontal extension (Colgan and Metcalf 2006b). Friedrich *et al.* (2004) report evidence for Quaternary (~2.8 ka) slip on this fault, and Wesnousky *et al.* (2005) report two slip events at 5.8 and 14–18 ka on the nearby Dry Hills Fault (Figure 7).

### *Piñon Range*

The oldest exposed rocks in the Piñon Range (Figures 2 and 8) are Ordovician to Devonian sedimentary rocks (mostly carbonates) overlain by a thick (up to 2 km) section of Mississippian clastic rocks that were shed into the Antler foreland basin during emplacement of the Roberts Mountains allochthon (Figure 8; Smith and Ketner 1975; Johnson and Visconti 1992). Pennsylvanian to Permian limestones (up to >1 km thick) unconformably overlie both the Roberts Mountains allochthon and the Mississippian

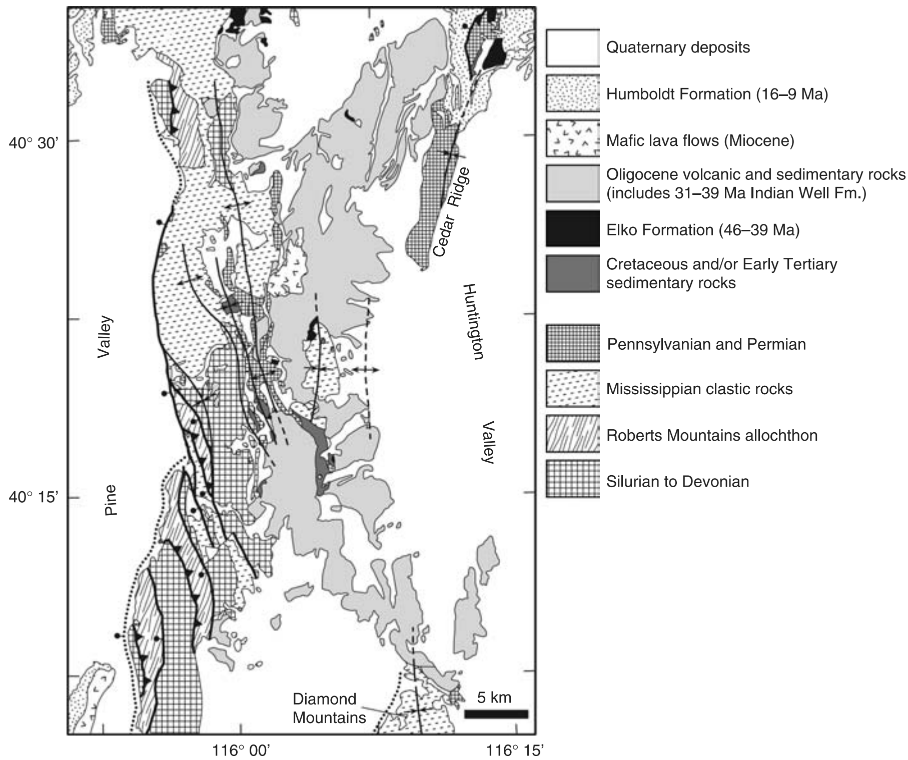


Figure 8. Geologic map of the Piñon Range, simplified from Smith and Ketner (1978) and Coats (1987).

clastic rocks (Smith and Ketner 1978). Palaeozoic rocks in the Piñon Range are now exposed in open, north-trending folds with subvertical axial planes (Figure 8; Smith and Ketner 1978). Smith and Ketner (1978) mapped several scattered outcrops of Cretaceous Newark Canyon Formation overlying Palaeozoic rocks in the Piñon Range and report Early Cretaceous fossils from one outcrop that is now in the core north-trending syncline (Figure 8). Although the Piñon Range has a complex history of Palaeozoic deformation (e.g. Smith and Ketner 1975; Trexler *et al.* 2000), the most recent crustal shortening is Mesozoic and inferred to have taken place predominantly during the Late Jurassic and/or Early Cretaceous (Ketner and Smith 1974; Smith and Ketner 1976; Vandervoort and Schmitt 1990; Ketner and Alpha 1992).

Isolated outcrops of undated conglomerate and sandstone throughout the Piñon Range were assigned ages ranging from Cretaceous (Newark Canyon Formation, see above) to early Eocene by Smith and Ketner (1978), but the oldest definitively Tertiary rocks are isolated outcrops of Eocene lacustrine limestone and shale of the 46–39 Ma Elko Formation (Smith and Ketner 1976, 1978; Haynes 2003). Palaeozoic to Eocene rocks on the east side of the range are overlain by tuffaceous sedimentary rocks and ash-flow tuffs of the 38–33 Ma Indian Well Formation (Figure 8; Smith and Ketner 1978). The middle Miocene (16–9 Ma, Wallace *et al.* 2008) Humboldt Formation on the west side of Huntingon Valley (Figure 8) is variably deposited on Palaeozoic, Eocene, and Oligocene rocks (Smith and Ketner 1978). In the central Piñon Range, the Indian Well Formation is also overlain by undated mafic lava flows that Smith and Ketner (1976) assign a Miocene age.

The modern Piñon Range is bounded to the west by a high-angle normal fault (Figure 8) that was active during deposition of the Pliocene to Pleistocene Hay Ranch Formation that is exposed in Pine Valley (Gordon and Heller 1993), although it may also have been active during deposition of the Humboldt Formation (Wallace *et al.* 2008). The 38–33 Ma Indian Well Formation dips only 5° east within the Piñon Range, and the main body of it on the southeast side of the range (Figure 8) is essentially flat-lying on the cross-sections of Smith and Ketner (1978), indicating very little post-Oligocene tilting (and extension) aside from slip on the Pine Valley Fault. North of Cedar Ridge (Figure 8), no angular unconformity is present between 10–20° east-dipping Indian Well Formation and overlying 16–9 Ma Humboldt Formation (Smith and Ketner 1978; Wallace *et al.* 2008), indicating that tilting – and presumably extension – in western Huntington Valley postdates 16 Ma.

The record of pre-Indian Well (>38 Ma) extension is less clear. Undated conglomerates assigned to the Eocene by Smith and Ketner (1978) dip up to 65–75° east, which would require that the entire Piñon Range (or a large part of it) be block-tilted 65–75° and bounded by west-dipping (now) low-angle normal faults. However, for the following reasons, we suggest that the entire range is not tilted on its side, and that pre-Indian Well Formation extension is much more modest. First, the undated 'Eocene' conglomerates are only exposed on the east side of the range and neither they nor any other Tertiary rocks have been repeated by normal faults within the range itself (Figure 8); Second, no gently west-dipping normal faults have been mapped cutting Palaeozoic rocks within the Piñon Range itself – Palaeozoic rocks there are cut only by small-offset, high-angle normal faults; Third, if the Piñon Range was strongly east-tilted (i.e. up to 65–75°), we would expect exposed Palaeozoic units to young eastwards (as they do in the southern Ruby Mountains, see next section), but instead they were exposed in upright (subvertical axial plane) folds with Permian (locally Cretaceous) rocks in the cores of synclines and Mississippian to Devonian rocks in the cores of anticlines (Figure 8; Smith and Ketner 1978). We attempted to constrain the timing of most recent exhumation in the Piñon Range using low-temperature thermochronology but were unable to obtain apatite from three samples of Devonian quartzite (Oxyoke member of the Nevada Formation) and two samples of Mississippian sandstone (Diamond Peak Formation). Although there is no evidence for major Eocene normal faulting in the Piñon Range, there is (locally) an angular unconformity of up to 15° between the 46 and 39 Ma Elko Formation and 38 Ma volcanic rocks in the Indian Well Formation in the vicinity of Elko (Figure 2, northeastern part of Figure 8). This unconformity has been inferred to record minor northwest-directed Eocene extension (Smith and Ketner 1976; Henry and Faulds 1999; Haynes 2003).

### *Southern Ruby Mountains*

The southern Ruby Mountains (south of the Harrison Pass pluton) expose a thick (~5 km) section of Precambrian to Mississippian sedimentary rocks (Sharp 1942; Willden and Kistler 1979). This section is east-tilted and continues east under Ruby Valley and underlies Pennsylvanian to Triassic rocks in the Medicine Range (Collinson 1966; Coats 1987). The entire section is about 10 km thick and deformed by open folds with axial planes that now dip east but were originally (in the Mesozoic) closer to vertical, depending on how much Tertiary tilt is assumed (see below). In the area of Figure 9, folding is only constrained to be post-Mississippian, but Triassic rocks in the Medicine and Maverick Springs ranges to the east (Figure 2) are involved in north-trending folds and the most recent shortening is therefore post-Triassic.

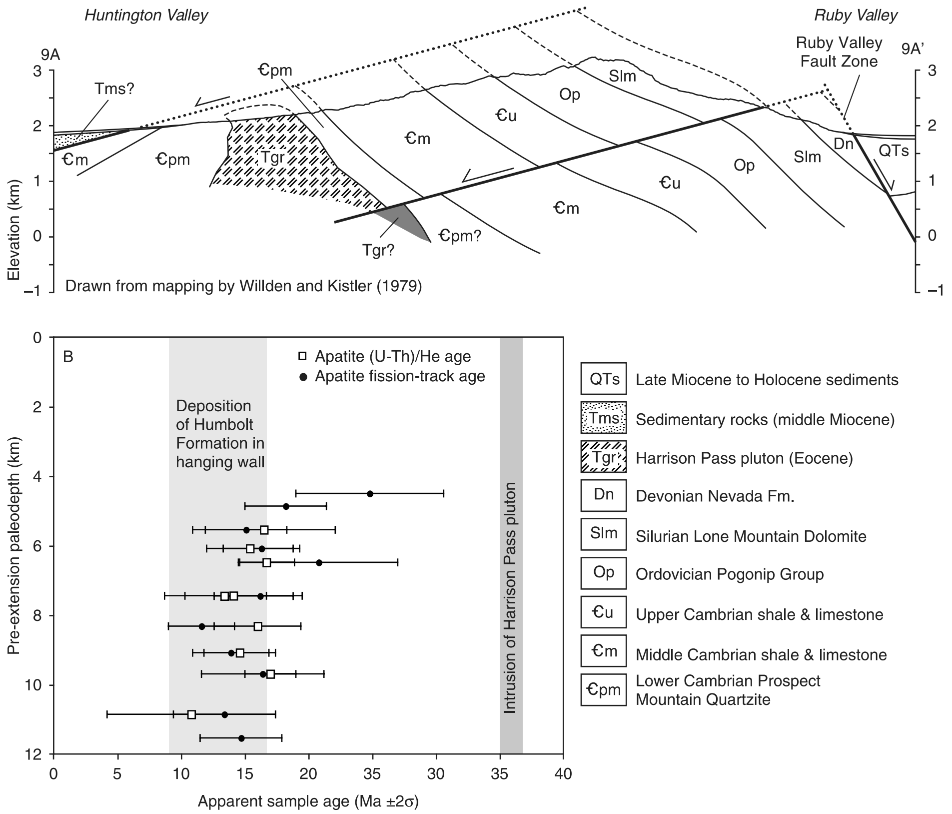


Figure 9. (a) Geologic cross-section of the southern Ruby Mountains, drawn from mapping by Willden and Kistler (1979). (b) Apatite fission-track and (U–Th)/He ages from the Harrison Pass pluton (8 km north of cross-section; from Colgan and Metcalf 2006a).

No Tertiary sedimentary or volcanic rocks are mapped within the southern Ruby Mountains themselves, although they are exposed on the east side of the Piñon Range (see previous section) and have been reported from drill holes in Huntington Valley (Hess *et al.* 2004; Figures 2 and 9). Eocene (ca. 36 Ma) rhyolite flows and domes rest on Mississippian rocks near Bald Mountain 30 km south, as shown in Figure 9 (Nutt and Hart 2004), and undated (presumably Eocene) lava flows rest on Permian rocks in the Medicine and adjacent Maverick Springs ranges (Figure 2; Coats 1987). The central part of the Ruby Mountains was intruded by the 36 Ma Harrison Pass pluton (Wright and Snoke 1993; Barnes *et al.* 2001), which now separates largely unmetamorphosed Palaeozoic rocks to the south from igneous and metamorphic rocks in the northern part of the range (e.g. Willden and Kistler 1979; Burton 1997).

Palaeozoic rocks in the southern Ruby Mountains are east-tilted in the footwall of a gently (<20°) west-dipping normal fault that merges to the north with a mylonitic shear zone on the west side of the range (e.g. Willden and Kistler 1979; Hudec 1992; Burton 1997). Because the Palaeozoic rocks were folded prior to Tertiary tilting, the amount of tilting cannot be measured directly but is probably about 30–40° (Burton 1997; Barnes *et al.* 2001; Colgan and Metcalf 2006a). Biotite K–Ar ages young westwards across the Harrison Pass pluton from 36 to 20 Ma (Kistler *et al.* 1981) and are inferred to record exhumation and slip on the west-dipping fault over that interval (Dallmeyer *et al.* 1986;

Dokka *et al.* 1986). Apatite fission-track and (U–Th)/He ages from the Harrison Pass pluton range from 18 to 10 Ma and average about 15 Ma (Figure 9(b); Colgan and Metcalf 2006a). Modelled time-temperature paths from these samples indicate rapid cooling at about 16–14 Ma, and are inferred to record rapid fault slip and extension coincident with deposition of thick sections of clastic sediment in Huntington Valley (the 16–9 Ma Humboldt Formation, Smith and Ketner 1978; Wallace *et al.* 2008).

In contrast to earlier studies that infer significant Oligocene unroofing of the southern Ruby Mountains (e.g. Kistler *et al.* 1981; Dokka *et al.* 1986; Burton 1997; Satarugsa and Johnson 2000), we think it most likely that the major west-dipping fault is entirely a middle Miocene structure that began to form ca. 16–17 Ma, and that the older (36–20 Ma) K–Ar biotite ages record something other than fault slip, possibly partial argon loss at elevated temperatures during the time between pluton emplacement (36 Ma) and middle Miocene cooling. No sedimentary rocks or volcanic rocks have so far been found in the area around the southern Ruby Mountains that date between 31 and 16 Ma, either in outcrop or in drill holes, and no significant angular unconformity is present where the ca. 16 Ma base of the Humboldt Formation rests on the ca. 33 Ma top of the Indian Well Formation on the east side of the Piñon Range (Smith and Ketner 1978). We consider it highly unlikely that a major episode of slip on an initially high-angle fault in the brittle crust would produce no sedimentary basin at all, or that such a basin could subsequently have been entirely removed by erosion during a narrow window between 20 and 17 Ma, without disturbing underlying Eocene and early Oligocene rocks (the same point was raised by Wallace *et al.* 2008). By contrast, middle Miocene extension was accompanied by deposition of thick sequences of well-preserved coarse clastic sediment (the Humboldt Formation) in the hanging wall of the west-dipping fault.

## *Tectonic history of north-central Nevada: from Mesozoic shortening to Miocene extension*

### *Mesozoic shortening and crustal thickening*

Mesozoic crustal shortening occurred across the entire study area, although the amount is not presently known and the timing is only locally well constrained. Nevertheless, available data from the study area are consistent with the bulk of the shortening being somewhat older (Early to Middle Jurassic) to the west, in the southern East Range and Tobin range, and younger to the east (Late Jurassic or Early Cretaceous), in the Cortez and Piñon Ranges. Shortening may have progressed continuously eastwards across the study area from the Early Jurassic in the west to the Late Jurassic or Early Cretaceous in the east and ultimately to the Late Cretaceous in the Sevier Belt (Figure 1) to the east of our study area (e.g. DeCelles and Currie 1996; Taylor *et al.* 2000; DeCelles and Coogan 2006). However, Jurassic deformation in northern Nevada may have been a spatially and temporally distinct event from the Cretaceous deformation in the Sevier Belt (e.g. Miller *et al.* 1988; Smith *et al.* 1993; Wyld 2002). In any case, evidence is lacking for significant surface deformation in the study area during the Late Cretaceous, when significant upper-crustal shortening was ongoing in the Sevier Belt (Figure 1; e.g. DeCelles and Coogan 2006). Deeply exhumed rocks in the northern Ruby Mountains do record peak metamorphism in the Late Cretaceous, however, consistent with the most recent crustal thickening in the eastern part of the study area taking place at this time (e.g. Snoke and Miller 1988; Hodges *et al.* 1992; Camelleri and Chamberlain 1997; McGrew *et al.* 2000). Any surface uplift that accompanied Late Cretaceous crustal thickening thus appears to have taken place without significant surface deformation, consistent with crustal thickening being accommodated by the underthrust 'roots' of thrust sheets that broke the surface to the east of the study area. Limited deformation and exhumation ($\leq$2 km) during the Late Cretaceous is consistent with Early Cretaceous (>100 Ma) apatite fission-track ages from Jurassic plutons in the study area, which indicate that these plutons and their wallrocks were already at near-surface (<60°C) temperatures by 100 Ma (Schmauder *et al.* 2005; Colgan and Metcalf 2006b; Colgan *et al.* 2006). From the standpoint of later extension, the most important aspect of the Mesozoic geology is that crustal shortening took place either continuously or episodically from the Early Jurassic onwards, with the most recent crustal thickening being Late Cretaceous. The crust in the region thus reached something close to its maximum thickness by the end of the Mesozoic. To the extent that this crust supported high elevations, an 'orogenic plateau' would have existed in north-central Nevada by the beginning of the Cenozoic.

Estimates of crustal thickness in the pre-extensional Basin and Range (including our study area) by the end of Mesozoic shortening vary from about 40 km to as great as 70 km (up to 60 km, Coney and Harms 1984; up to 50 km, Gans 1987; 50–70 km, Molnar and Lyon-Caen 1988; 40–50 km, Snoke and Miller 1988; 45 km, Smith *et al.* 1991, >50 km, DeCelles and Coogan 2006) with thicker crust beneath the 'hinterland' of the Sevier fold-thrust belt (Figure 1; the eastern part of our study area). The modern crust beneath our study area is about 30–35 km thick (Potter *et al.* 1987), possibly with slightly thicker (up to 34–35 km) crust to the east (Satarugsa and Johnson 1998; Stoerzel and Smithson 1998). If the 40–50% total strain we describe in the section 'Rapid middle Miocene extension ...' is uniformly distributed and not much crust has been lost or flowed out-of-plane, the pre-extension crust would have been at most 45–50 km thick everywhere – at *most*, because at least some of the modern crustal column consists of material added during later mid-Tertiary magmatism (e.g. Gans 1987). Thicker (55–60 km) Mesozoic beneath the Sevier hinterland in the eastern part of the study area is possible but would have to be compensated by <40–45 km thick crust elsewhere; any difference could have been smoothed out by lower crustal flow during later extension (e.g. Klemperer *et al.* 1986; Gans 1987). In Figure 10(a), we show the Late Cretaceous crust about 42–48 km thick, with the thicker part to the east. Unless a substantial amount of Mesozoic crust is no longer present, or large parts of the Basin and Range are much more highly extended than north-central Nevada, there is not enough crust left to account for much more than 45 km-thick pre-extensional crust across the entire province – for example, the 50–70 km thick crust shown by DeCelles and Coogan (2006, their Figure 12).

### *Mid-Tertiary volcanism and minor extension*

Using published 1:250,000 scale geologic county maps compiled by Crafford (2007), we constructed a palaeogeologic map of pre-Tertiary basement rocks exposed in the Eocene and Oligocene (Figure 11). Figure 10(a) shows traces of contacts and drill holes where sedimentary and volcanic rocks from 43–34 and 34–17 Ma (age divisions from Stewart 1980) rest directly on pre-Tertiary basement. Within the study area, these age divisions actually represent rocks ranging from about 46 to 25 Ma (based on dates discussed in previous sections). We then restored the map to an approximate pre-extensional state based on the extension domains shown, discussed in the following section (Figure 12), although this required extrapolating them north and south outside of where they are currently documented (for which we have no evidence). West of the Piñon Range, we assumed the strain to be evenly distributed in the extended domains; the Ruby Mountains were restored assuming all extension took place on the west-dipping

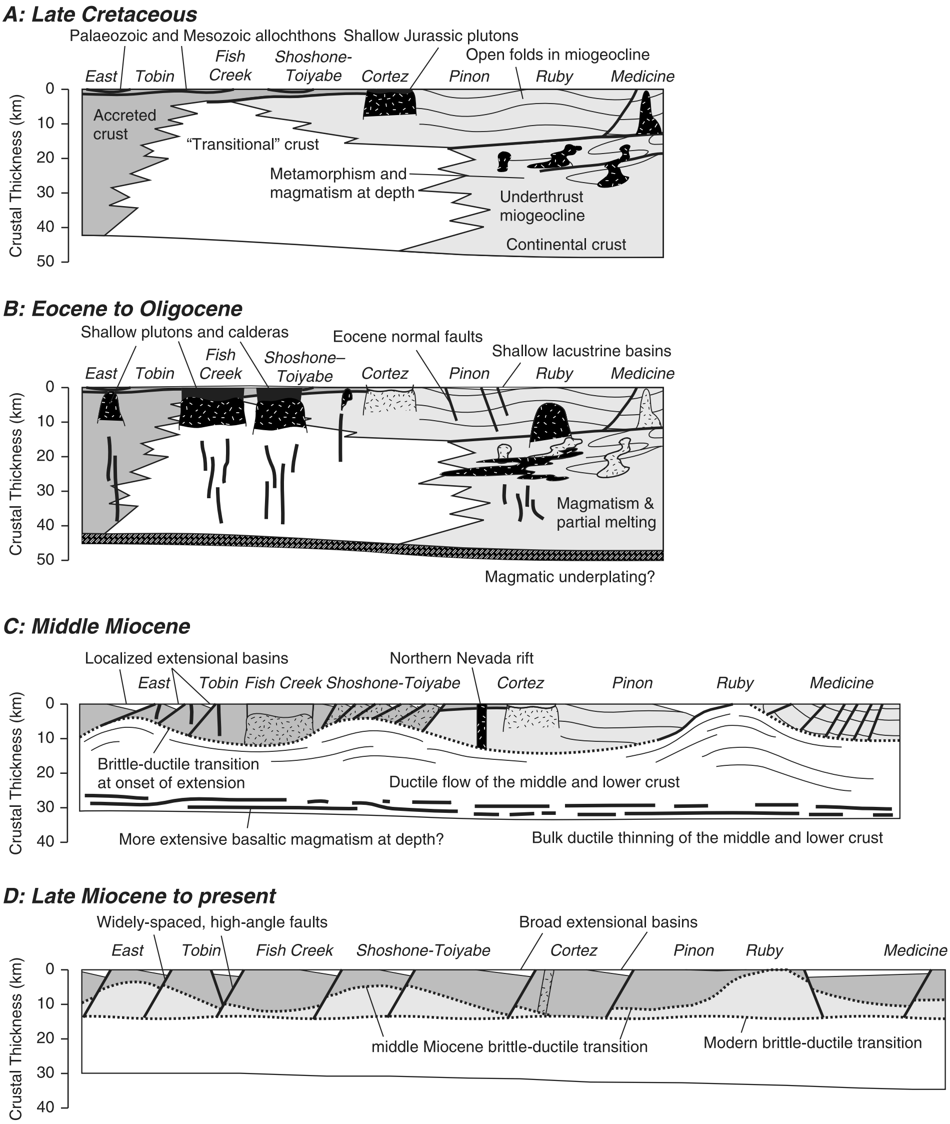


Figure 10. Schematic cross-sections (no vertical exaggeration) showing tectonic evolution of north-central Nevada from Late Cretaceous to present.

detachment. Finally, we extrapolated pre-Tertiary basement between exposed contacts using mapped pre-Tertiary basement as a guide (i.e. if Permian rocks are presently exposed in a given area, older rocks could not have been exposed there in the Eocene).

A map such as Figure 11 is obviously incorrect or incomplete in many of its details, but it clearly illustrates Mesozoic and older structures beneath Eocene and Oligocene rocks, consistent with little, if any, tectonic activity in the study area between the end of Mesozoic shortening and the onset of Tertiary volcanism (cf. Armstrong 1968, 1972). During this time, north-central Nevada was characterized by a low-relief land surface incised by palaeovalleys cut up to 1.5 km deep into Mesozoic and Palaeozoic basement. Given the previous history of Mesozoic shortening and crustal thickening, it is likely that

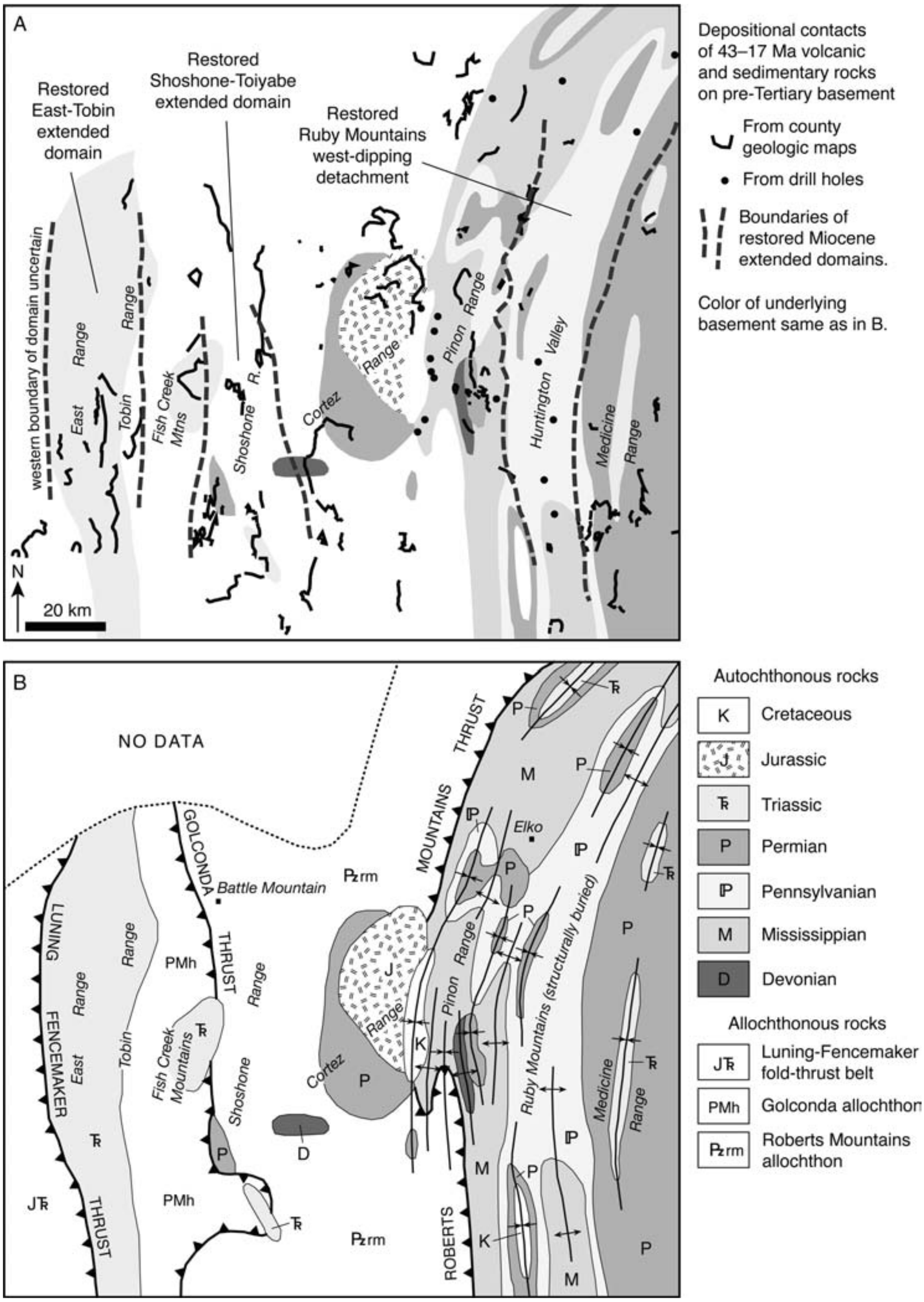


Figure 11. Mid-Tertiary palaeogeologic map of north-central Nevada, corresponding to approximate restored area of Figures 2, 10, and 11. (a) Black lines are depositional contacts between Eocene to early Miocene (43–17 Ma) sedimentary and volcanic rocks and pre-Tertiary basement, as shown on county geologic maps compiled by Crafford (2007). Black dots are drill-hole intercepts of depositional contacts between pre-Tertiary basement and 43–30 Ma rocks (Indian Well and Elko Formations; Hess *et al.* 2004). (b) Distribution of pre-Tertiary map units from (a), with map and unit symbols added. Scale is approximate.

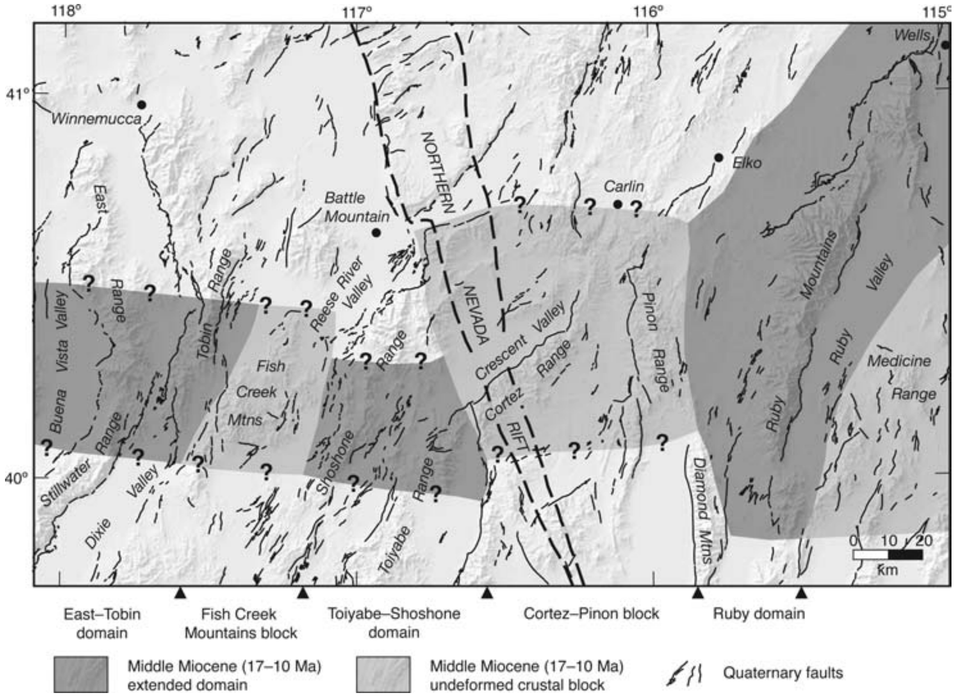


Figure 12. Map showing domains of middle Miocene extension and overprinting Quaternary faults (some of which are as old as late Miocene). Quaternary faults from US Geological Survey and Nevada Bureau of Mines and Geology (2006).

the land surface was elevated ($\geq 2$ km above sea level), and that the palaeovalleys had been cut (at least initially), during Mesozoic surface uplift. Major volcanism began in northeastern Nevada in the Eocene and was part of the regional southward sweep of volcanic activity across the western Cordillera in the mid-Tertiary (e.g. Best *et al.* 1989; Armstrong and Ward 1991; Best and Christiansen 1991; Christiansen and Yeats 1992). Rocks later exhumed from mid-crustal depths in the northern Ruby Mountains record continuous partial melting from 40 to 30 Ma (in addition to older magmatism; Wright and Snoke 1993; Howard, K., and Wooden, J. Personal communication 2009); presumably this process was ongoing at depth in other parts of the study area (Figure 10(b)). At shallower levels, Eocene to Oligocene magmatism produced numerous dikes and formed large magma chambers, some of which erupted ash-flow tuffs from calderas (Best *et al.* 1989; Brooks *et al.* 1995; Ressel and Henry 2006; Henry 2008; John *et al.* 2008). We show 2–3 km of material added to the crust at this time in Figure 10(b), but this is merely to indicate that some material was likely added – we have no quantitative estimate of the actual amount.

From the Piñon Range west to the East Range, dated mid-Tertiary rocks range from Eocene to late Oligocene (38–24 Ma), with a few outcrops of undated sedimentary rocks and mafic lava flows that are slightly older. These rocks are confined to palaeovalleys such as those cut into pre-Tertiary basement in the Tobin and Cortez Ranges, or to the depressions left from caldera collapse. With the possible exception of a minor ($<5°$) unconformity in part of the Tobin Range (Gonsior and Dilles 2008), no angular unconformity is present within sections of this age, indicating that Eocene to late Oligocene extension was minimal. East of the Piñon Range, there is evidence for some

Eocene extension in the vicinity of Elko (Figure 2) where dated mid-Tertiary rocks range from Eocene to Oligocene (predominantly 46–37 Ma, with a single ash-flow tuff at 31 Ma). The 46–39 Ma Elko Formation consists of a basal conglomerate overlain by lacustrine limestone and shale exposed in small, widely scattered outcrops (e.g. Figure 8; Solomon *et al.* 1979; Cline *et al.* 2005; Henry 2008). Most workers have interpreted that these scattered outcrops were once part of a large, contiguous Elko Basin (e.g. Solomon *et al.* 1979; Satarugsa and Johnson 2000; Haynes *et al.* 2002), possibly formed by extension during an early phase of slip on the west-dipping shear zone that bounds the northern Ruby Mountains. Alternatively, Henry (2008) suggested that damming of palaeovalleys by volcanic eruptions created small, non-contiguous Elko Formation lacustrine basins. Whether the Elko Formation itself is synextensional or not, an angular unconformity of up to 15° is locally present between it and overlying $\leq 38$ Ma rocks in the Elko area, indicating a period of tilting (and presumably normal faulting) ca. 39 Ma, coincident with the most voluminous pulse of magmatism in the area (Smith and Ketner 1976; Solomon *et al.* 1979; Henry and Faulds 1999; Henry *et al.* 2001; Haynes 2003; Cline *et al.* 2005; Ressel and Henry 2006; Henry 2008). The few demonstrably Eocene normal faults in this region appear to indicate NW–SE extension at this time (Hickey *et al.* 2005; Muntean and Henry 2007), as do northeast-striking dikes in some volcanic fields (Henry 2008). The amount of strain accommodated by these faults is unknown but probably small – if it were as extensive as the middle Miocene extension that followed, Eocene coarse clastic rocks would be much more voluminous and widely distributed.

Following late Eocene and early Oligocene volcanism, no Tertiary rocks (that have been mapped or dated) were deposited within or east of the Piñon Range between 31 and 16 Ma, and no major angular unconformity is present where the ca. 16 Ma Humboldt Formation rests on the 33–31 Ma top of the Indian Well Formation (Figure 8; Smith and Ketner 1978). West of the Piñon Range, no Tertiary rocks are known to exist between 24 and 17 Ma, and no angular unconformity is present where middle Miocene (ca. 16 Ma) sedimentary rocks rest directly on older (24–35 Ma) volcanic rocks in the East Range, Tobin Range, Shoshone Range, and northern Toiyabe Range. The hiatus in deposition between 24 and 16 Ma (west) and 34–16 Ma (east) is consistent with a combination of external drainage, low relief, and little surface faulting in the Oligocene and early Miocene (e.g. Wallace *et al.* 2008). Relatively little pre-17 Ma upper-crustal extension is consistent with exposures of depositional basement to Eocene and Oligocene rocks shown on our palaeogeologic map (Figure 10), which represent much shallower levels of the pre-Tertiary stratigraphy than are presently exposed. For example, Eocene and Oligocene rocks in the area of the present-day Ruby Mountains were deposited on Mississippian and younger rocks (locally Devonian in the core of the Piñon Range; Figure 11(b)), but today the metamorphic underpinnings of the Palaeozoic section are exposed at the surface.

Our interpretation of relatively minor (compared to what followed) pre-17 Ma extension in north-central Nevada is different from previous interpretations that assign most of the extension to the Eocene and Oligocene, mainly because we give more weight to the sedimentary and low-temperature thermochronologic record of upper-crustal extension. This disparity is most acute with respect to the Ruby Mountains–East Humboldt metamorphic core complex, which is inferred to have undergone significant extension in the Late Cretaceous and/or Palaeocene (e.g. Hodges *et al.* 1992; Camilleri and Chamberlain 1997; McGrew *et al.* 2000), Eocene (e.g. Mueller and Snoke 1993; McGrew and Snee 1994; Camilleri and Chamberlain 1997), and Oligocene (e.g. Kistler *et al.* 1981; Dallmeyer *et al.* 1986; Dokka *et al.* 1986), in addition to the Miocene. We see two possibilities for reconciling these interpretations. Either significant pre-Miocene upper crustal extension took place in such a way that the evidence for it has been buried by younger (middle Miocene) basin fill or removed by erosion, or rocks were exhumed from deeper crustal levels during the mid-Tertiary without concurrent major extension at the surface. Here, we take the lack of sedimentary, volcanic, and structural evidence for major pre-Miocene extension of the upper crust to indicate that there was no major pre-Miocene extension of the upper crust. This does not preclude major deformation, metamorphism, and exhumation of rocks in the middle and lower crust during the Eocene and early Oligocene – a variety of hypotheses have been proposed for how to exhume deep crustal rocks without concurrent surface extension, including 'intracrustal subduction' (Wernicke and Getty 1997), ductile flow of the middle crust away to somewhere else (McQuarrie and Chase 2000), expulsion of a mid-crustal basement wedge (Applegate and Hodges 1995), or diapir-like gneiss domes (Whitney *et al.* 2004). Our interpretation does preclude major Oligocene to early Miocene slip on the west-dipping fault that bounds the Ruby Mountains, however, which (as discussed previously) we consider unlikely given the absence of hanging-wall basin fill of that age (in contrast to the great abundance of post-16 Ma basin fill). Even if mid-Tertiary upper-crustal extension was greater than presently indicated by surface geology, it was confined to a relatively small part of northeastern Nevada and, at a regional scale, was minor compared to what followed.

### *Rapid middle Miocene extension and minor bimodal volcanism*

In contrast to the Eocene to early Miocene sedimentary and structural record, there is widespread and abundant evidence for major extension beginning throughout the study area at about 16–17 Ma. Middle Miocene extension was strongly partitioned into highly extended domains (50–100% strain or more) separated by essentially undeformed crustal blocks (Figure 12). Extended domains are characterized by west-dipping faults and east-tilted crustal blocks separated by half-graben basins. In the East–Tobin domain and Shoshone–Toiyabe domain, extension was accommodated by sets of closely spaced (1–3 km), initially high-angle, 'domino-style' normal faults (cf. Proffett 1977; Chamberlain 1983). In the southern Ruby Mountains, extension was accommodated by a single major west-dipping fault that merges to the north with the mylonitic shear zone that exhumed high-grade metamorphic rocks in the northern part of the range (e.g. Howard 2003).

Middle Miocene extension took place within a relatively narrow time span between about 17 and 10 Ma, but the precise onset is difficult to determine. Individual apatite fission-track ages from the study area typically have $2\sigma$ uncertainties of 10–20%, and individual (U–Th)/He ages are typically reproducible to within $\sim 10\%$ (Colgan and Metcalf 2006a, 2006b; Fosdick and Colgan 2008). Modelled time-temperature paths from these data generally outline bands 2–3 Ma wide at any given temperature (e.g. Fosdick and Colgan 2008), and it is therefore difficult to pinpoint the onset of cooling (and thus faulting) more precisely than to within $\pm 1$ Ma. Sanidine $^{40}Ar/^{39}Ar$ dates from tuffs interbedded with synextensional sedimentary rocks are very precise – generally better than 0.2 Ma at $2\sigma$ – but there is always some section below the lowest dated unit and the dates provide only a minimum age for the onset of deposition. Wallace *et al.* (2008) report dates from middle Miocene basins as old as $\sim 16.3$ Ma (from the Carlin basin, Figure 13), and Colgan *et al.* (2008) report dates as old as 15.8 and 15.9 Ma from basins in the central Shoshone Range (Figures 6 and 13). Middle Miocene faults initiated at high angles in the brittle crust and would therefore have created significant topography, creating accommodation space for sediment, providing a source for it, and disrupting pre-existing external drainage networks. Therefore, we consider the best record of the onset

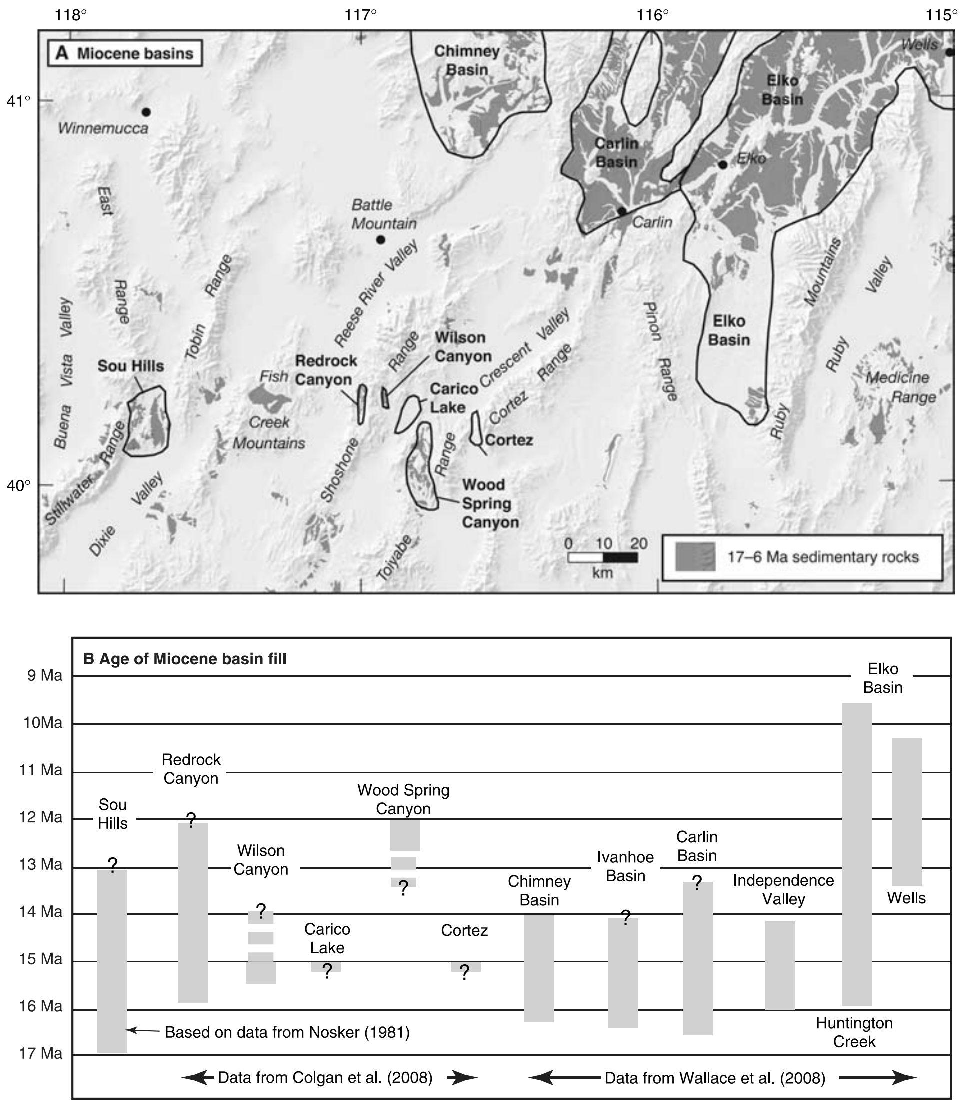


Figure 13. (a) Map showing location of Miocene basins and distribution of middle to late Miocene (17–6 Ma) sediments in the study area (from Crafford 2007). (b) Timing of sedimentation in middle Miocene basins from Wallace *et al.* (2008) and Colgan *et al.* (2008), with exception of Sou Hills from K–Ar dates on interbedded basalt flows by Nosker (1981).

of extension to be the onset of deposition in the Miocene basins (Figure 13), which suggests that extension began across the region between 16 and 17 Ma. This is consistent with less-precise constraints from cross-cutting relationships and time-temperature paths from exhumed fault blocks.

Determining the precise end of middle Miocene extension is more difficult. Apatite (U–Th)/He ages from the East Range, Cortez Range, and southern Ruby Mountains are as young as 9–12 Ma at deeper levels of exposure, but it is unclear if these ages represent cooling through closure temperature or partial resetting at elevated temperatures prior to a distinctly younger period of faulting. Most dates from the sedimentary basins are in the

15–16 Ma range, but they are commonly as young as 12 Ma and as young as 9 Ma in the Elko Basin (Figure 13; Colgan *et al.* 2008; Wallace *et al.* 2008). The basins would continue to fill even after faulting had stopped, however, so it is unclear whether faulting was ongoing during the entire time of basin filling. Our best interpretation of the thermochronologic and sedimentary records is that extension continued until 12 or 10 Ma at the latest, but it could have stopped earlier everywhere, or at different times in each of the domains discussed here.

We estimate approximately 50–60 km of middle Miocene extension across a 200 km transect from the East Range to Ruby Valley (about 40% strain), partitioned into three zones of major extension separated by two zones of little to no extension (Figure 12). The East–Tobin domain underwent ~13 km of extension (roughly 60% strain) between the western edge of the East Range and the western edge of the Fish Creek Mountains (Burke 1973; Gonsior 2006; Fosdick and Colgan 2008). The Fish Creek Mountains block appears to be undeformed, but its margins are covered by Jersey Valley (on the west) and Reese River Valley (on the east). Colgan *et al.* (2008) estimated ~22 km of extension (~110% strain) across the Shoshone–Toiyabe domain, from the inferred (buried) western edge of the Caetano Caldera to the Cortez Fault (Figure 7). The amount of middle Miocene extension in the Cortez–Piñon block appears to be small, including dike intrusion in the northern Nevada rift that accommodated a few kilometres of extension (John *et al.* 2000). If high-angle normal faults in the Piñon Range are middle Miocene, total extension may be a few kilometres more, but no more then 10% strain across the entire 60–70 km-wide block. Extension in the southern Ruby Mountains took place almost entirely on the west-dipping fault that separates the range from Huntington Valley. At the latitude shown in Figure 9, Colgan and Metcalf (2006a) estimated 15–20 km of extension on this fault during tilting and exhumation of the range. Extension appears to be consistently oriented about 280–290° across all domains. Strain rates during this period were of the order of 10 km/Ma (50–60 km of extension between 17–16 and 10–12 Ma is 15–7 km/Ma).

Middle Miocene extension in the study area was accompanied by small-volume but widespread bimodal volcanism. In the southern East Range, basalt flows and rhyolite flows and domes range from 17 to 13 Ma (Nosker 1981) and are interbedded with Miocene sedimentary rocks deposited during extension (Fosdick and Colgan 2008). In the Tobin Range, Gonsior and Dilles (2008) report a 14 Ma age from a basalt flow interbedded with tilted Miocene sedimentary rocks. No middle Miocene volcanic rocks have so far been found in the Fish Creek Mountains, central Shoshone Range, or northern Toiyabe Range. The middle Miocene northern Nevada rift cuts southeast across the central part of the study area (Figure 12; Zoback *et al.* 1994; John *et al.* 2000). The rift changes from an ~18 km-wide graben containing mafic dikes, mafic to felsic lavas, and interbedded volcaniclastic rocks in the northern Shoshone Range, to an ~12 km-wide, shallow graben containing mafic lavas and volcanicastic deposits in the Cortez Range, to a relatively little faulted, ~6 km-wide zone of abundant mafic dikes in the Roberts Mountains south of our study area (Zoback *et al.* 1994; John *et al.* 2000; Murphy *et al.* 2007). Dated rocks within the rift range from 16.5 to 14.7 Ma (John *et al.* 2000). In the northern Piñon Range, the 15.3 Ma Palisade Canyon rhyolite (Henry and Faulds 1999; Wallace *et al.* 2008) is interbedded with middle Miocene sedimentary rocks of the Humboldt Formation, and Smith and Ketner (1978) mapped undated 'upper Miocene' mafic lava flows in the central Piñon Range. Hudec (1990) reported 15.5 Ma ages from two mafic dikes intruding the Harrison Pass pluton in the Ruby Mountains. Within the limits of the available data, middle Miocene volcanism in the study area appears to have begun at the same time (between 16 and 17 Ma) as the extensional faulting dated by low-temperature thermochronology and synextensional basin fill.

*Late Miocene and younger extension*

In contrast to the well-defined domains of middle Miocene extension, late Miocene and younger faulting took place on widely spaced (20–30 km), high-angle faults that cut both previously extended and unextended domains (Figure 12). The largest of these faults accumulated kilometres of slip and created the modern basin-and-range topography of the study area, which is superimposed on the middle Miocene basin and ranges (Figure 12). In places, the older middle Miocene basins have been uplifted as part of the modern ranges; presumably, other middle Miocene basins have been downdropped and buried by modern basins. The late Miocene and younger faults cross-cut the older middle Miocene faults where they are exposed (e.g. at the Cortez Mine, Figure 6), and in at least one place in the subsurface – the February 2008 M6.0 Wells earthquake (just to the northeast of our study area) occurred on a fault that dips 55° southeast and extends to 15 km depth, cross-cutting numerous gently west-dipping middle Miocene faults (Smith *et al.* 2009; Henry and Colgan 2009).

The onset of this younger faulting is not currently well constrained but can be assigned an upper limit based on cross-cutting relationships with the older middle Miocene basins. Because basin filling would have continued even after middle Miocene faulting had ceased, the youngest fill in these basins should provide an approximate age for the onset of the faulting that dismembered them and established a new pattern of ranges and basins. Dated middle Miocene basin fill is regionally as young as 12 Ma (usually with additional undated deposits upsection) and locally 9 Ma in the Elko Basin (Figure 13; Colgan *et al.* 2008; Wallace *et al.* 2008), so we suggest that younger faulting began around 10 Ma (sometime between 9–12 Ma). This is consistent with the youngest U–Th/He ages from the East Range (10 Ma, Fosdick and Colgan 2008) and Cortez Range (9 Ma, Colgan and Metcalf 2006b), which record subsurface temperatures of ~60°C and imply 2–3 km of exhumation since that time (at a geothermal gradient of 20–30°C/km). The implied ~0.2–0.3 km/Ma rate of (vertical) fault displacement (2–3 km of vertical displacement in 10 Ma) is comparable to 0.1–0.2 km/Ma vertical displacement rates estimated over the last 20 ka for northern Basin and Range normal faults (Wesnousky *et al.* 2005; their Table 3 given as total slip since 20 ka).

The magnitude of map-view strain associated with this younger faulting is negligible compared to middle Miocene deformation but difficult to estimate because key relationships are buried beneath the modern basins. Even the largest modern range-bounding faults – e.g. the Crescent Fault (Figure 7) or the Ruby Valley Fault (Figure 9) – probably accommodate no more than 1 km of horizontal extension, and we tentatively infer only about 5–6 km of post-10 Ma extension across the study area. It appears to be oriented slightly northwest like the middle Miocene extension, with the exception of pronounced northwest-directed extension in the Cortez Range area (Figure 12; e.g. on the Crescent Fault, Figure 7). The low magnitude of late Miocene to Holocene strain in north-central Nevada is consistent with geodetic data indicating that much of central Nevada – as far west as the East Range (Figure 2) – is presently behaving as a rigid (unextending) microplate within the resolution of the GPS data (e.g. Bennett *et al.* 2003; Hammond and Thatcher 2004).

## Middle miocene extension in the northern Basin and Range

If the geologic history we have outlined here is correct, north-central Nevada was characterized by a low-relief, externally drained, high-elevation land surface for at least 50 million years, from the Late Cretaceous (or earlier) until the middle Miocene (ca. 16–17 Ma). It then collapsed to near its present elevation and crustal thickness during a period of rapid extension that lasted only a few million years. In the following sections, we focus on the regional extent and possible causes of what appears to be the most significant phase of Basin and Range extension in this area.

## ***Regional context for middle Miocene extension in north-central Nevada***

### *Miocene extension in the northern Basin and Range Province*

In terms of documented total strain across the whole province, the best-studied part of the Basin and Range is the southern Nevada–Arizona–California border region [the 'central Basin and Range' of Wernicke (1992)]. Here, Wernicke and Snow (1998), reconstruct about 120 km of east–west extension between the Sierra Nevada and the Colorado Plateau between 16 and 10 Ma, and studies of many individual fault systems document rapid slip beginning about 17–15 Ma (e.g. Fitzgerald *et al.* 1991; Gans and Bohrson 1998; Reiners *et al.* 2000; Faulds *et al.* 2001; Carter *et al.* 2006; Fitzgerald *et al.* 2009). Subsequent (post-10 Ma) deformation in this area involved a significant component of right-lateral transtension, but the timing and kinematics (mainly west-directed extension) of the 16–10 Ma event are nearly identical to the history of Miocene extension we outline here for north-central Nevada, over 300 km to the north. No comparable estimates exist for the total amount of 16–10 Ma extension across the entire Basin and Range in the intervening region or at the latitude of our study area, but the similarity in the timing and kinematics (mainly west-directed) of extension between our study area and southern Nevada suggests that deformation of similar timing and style also took place in the intervening region. Available data are consistent with this; rapid middle Miocene extension has been documented in western Nevada (Stockli *et al.* 2002; Surpless *et al.* 2002; Lee *et al.* 2009) and eastern Nevada and western Utah (Miller *et al.* 1999; Stockli *et al.* 2001). Stockli (2005) summarized low-temperature thermochronologic data documenting rapid cooling of fault blocks (and inferred extension) that began about 18–15 Ma across much of the Basin and Range at about latitude 40° N. Overall, then, there seems to be good evidence that rapid middle Miocene extension in north-central Nevada was part of a more extensive episode of extension that affected much of the northern Basin and Range Province in what is now Nevada, resulting in significant westward motion of the Sierra Nevada relative to the Colorado Plateau.

### *Mid-Tertiary surface elevations and drainage patterns in the Basin and Range*

Recent studies of mid-Tertiary surface elevations in the Basin and Range and Sierra Nevada indicate high surface elevations in the Eocene and Oligocene, consistent with relatively little extension prior to the Miocene. Here, we summarize results of these studies as interpreted by their authors; detailed overviews of different palaeoaltimetry methods can be found in Kohn (2007). Stable-isotope palaeoaltimetry from the Sierra Nevada is interpreted to indicate that the Eocene and Oligocene western slope of the northern Sierra is similar to the modern slope – i.e. that the modern range is largely the result of Basin and Range subsidence to the east, rather than uplift of the Sierra itself relative to sea level (e.g. Mulch *et al.* 2006; Crowley *et al.* 2008; Cassel *et al.* 2009). Stable-isotope palaeoaltimetry from the Basin and Range (including the area discussed in this paper) is also inferred to record high surface elevations (>2–3 km) in the Eocene and Oligocene (Horton *et al.* 2004). Horton and Chamberlain (2006) interpret stable isotopic data from a large area of the modern Basin and Range to record a drop in surface elevations from the middle Miocene to the present, consistent with extension and crustal thinning taking during this interval. Wolfe *et al.* (1997) interpret fossil leaf morphologies from western Nevada to indicate a 1.5 km drop in surface elevations between about 16 and 14 Ma – again, consistent with major extension and crustal thinning being of this age.

These data are consistent with the wide distribution of Oligocene and Eocene ash-flow tuffs (e.g. Best *et al.* 1989; Faulds *et al.* 2005; Henry 2008; Best *et al.* 2009; Cassel *et al.* 2009; this study, Figure 14), which were able to disperse across hundreds of kilometres, primarily by travelling down pre-existing drainage networks. In our study area, both the 34 Ma Caetano Tuff and the 25 Ma Fish Creek Mountains Tuff travelled as far west as the Tobin Range (Figure 2). Regionally, other tuffs show much wider distributions. The 40 Ma tuff of Big Cottonwood Canyon flowed more than 100 km down palaeovalleys adjacent to the Ruby Mountains–East Humboldt metamorphic core complex (Henry 2008), consistent with extension at that time having relatively little impact on the surface. The 28.8 Ma tuff of Campbell Creek (Figure 14), which probably erupted from a poorly studied caldera in the Desatoya or Clan Alpine Mountains, travelled more than 200 km west over (what is now) the Sierra Nevada (Henry *et al.* 2009; Brooks *et al.* 2008), and more than 100 km north into (and beyond) the Caetano caldera depression (John *et al.* 2008).

As noted by Cassel *et al.* (2009), if the elevation of the Eocene–Oligocene crest of the Sierra Nevada was similar to the elevation of the modern crest, Eocene–Oligocene surface elevations in what is now the Basin and Range must have been at least that high (they could have been higher), or the ash-flow tuffs would not have been able to flow west all the way to the Great Valley. High-Oligocene surface elevations and external drainage are

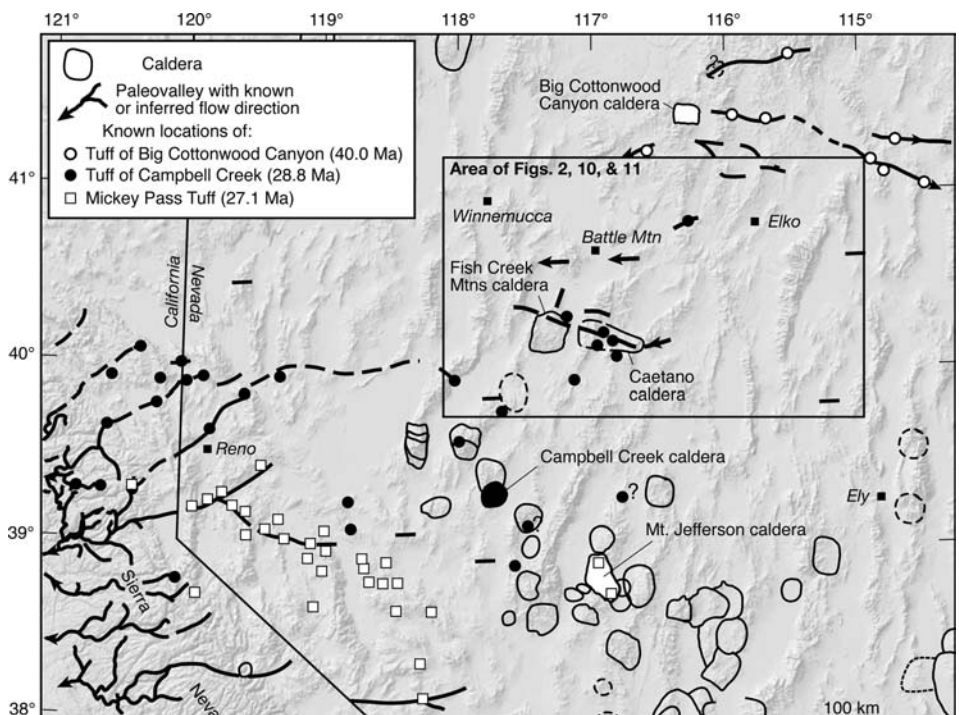


Figure 14. Map showing mid-Tertiary palaeovalleys and calderas in Nevada and eastern California, along with the source and extent of three widely distributed ash-flow tuffs.

consistent with major extension, crustal thinning, and a regional drop in surface elevations being middle Miocene, and inconsistent with major east–west pre-Oligocene extension, which would lead to both lower surface elevations and create north-south trending topographic barriers to dispersal of ash-flow tuffs.

### *Causes and consequences of middle Miocene extension*

Middle Miocene extension in north-central Nevada appears to be part of a more regional event that affected much of the northern Basin and Range Province, and studies of Eocene and Oligocene surface elevations and drainage patterns suggest that much of this area was an elevated, externally drained plateau prior to this time (at least during the Eocene and Oligocene and possibly since the late Mesozoic). Many studies have pointed to the gravitational potential energy of high topography as a driving force for extension or orogenic collapse, both worldwide (e.g. England 1982; Dewey 1988; Rey *et al.* 2001) and specifically in the western USA (e.g. Jones *et al.* 1998; Sonder and Jones 1999). If most east–west extension and widening of the northern Basin and Range took place in the Miocene, it would have sustained thick crust and high elevations for much of the Cenozoic before finally collapsing. Why did this not happen until 16–17 Ma? In this section, we consider three major Miocene tectonic events argued to have played a key role in Basin and Range extension.

#### *Mid-Tertiary volcanism and the Farallon slab*

Many researchers have inferred that early Tertiary subduction beneath the western USA was characterized by a subhorizontal Farallon slab, which extinguished the Cretaceous magmatic arc and transferred Laramide deformation to the continental interior (e.g. Coney and Reynolds 1977; Dickinson and Snyder 1978; Engebretson *et al.* 1984; Bird 1988), and cooled and hydrated the overlying lithosphere (e.g. Dumitru *et al.* 1991; Humphreys *et al.* 2003). Subsequent removal of the slab brought hot asthenosphere into contact with the base of the lithosphere, causing the voluminous mid-Tertiary 'ignimbrite flareup' (e.g. Coney 1980; Armstrong and Ward 1991). From about 55 Ma in Idaho, caldera-forming volcanic eruptions swept southwards across the future Basin and Range, reaching northern Nevada (and our study area) in the Eocene, central Nevada in the early Oligocene, and ultimately progressing to southern Nevada around 21–17 Ma (Figure 15). This southward sweep is inferred to have been matched by a similar northwest sweep out of Mexico (only the northmost part of which is shown on Figure 15), which also reached southern Nevada at about 21–17 Ma (e.g. Armstrong and Ward 1991; Christiansen and Yeats 1992). If the migrating magmatic fronts track the edges of the delaminating slab, then it was progressively removed from its northern and southern edges towards the centre (e.g. Humphreys 1995), with the last piece falling away from southern Nevada after 21 Ma. Although some early extension is thought to have taken place in concert with the migrating magmatic fronts, Armstrong and Ward (1991) proposed that middle Miocene extension could not occur until all – not just part – of the slab had fallen away, which finally happened in southern Nevada between 21 and 17 Ma. With the 'burning of the lithosphere bridge', the Sierra Nevada was free to move away from the Colorado Plateau with the Basin and Range extending behind it (Armstrong and Ward 1991). *In this scenario, the future Basin and Range was held together by a strong, cold, progressively shrinking piece of the Farallon slab until 16–17 Ma, when the last remnant of the slab fell away and the Basin and Range was free to collapse during rapid extension.*

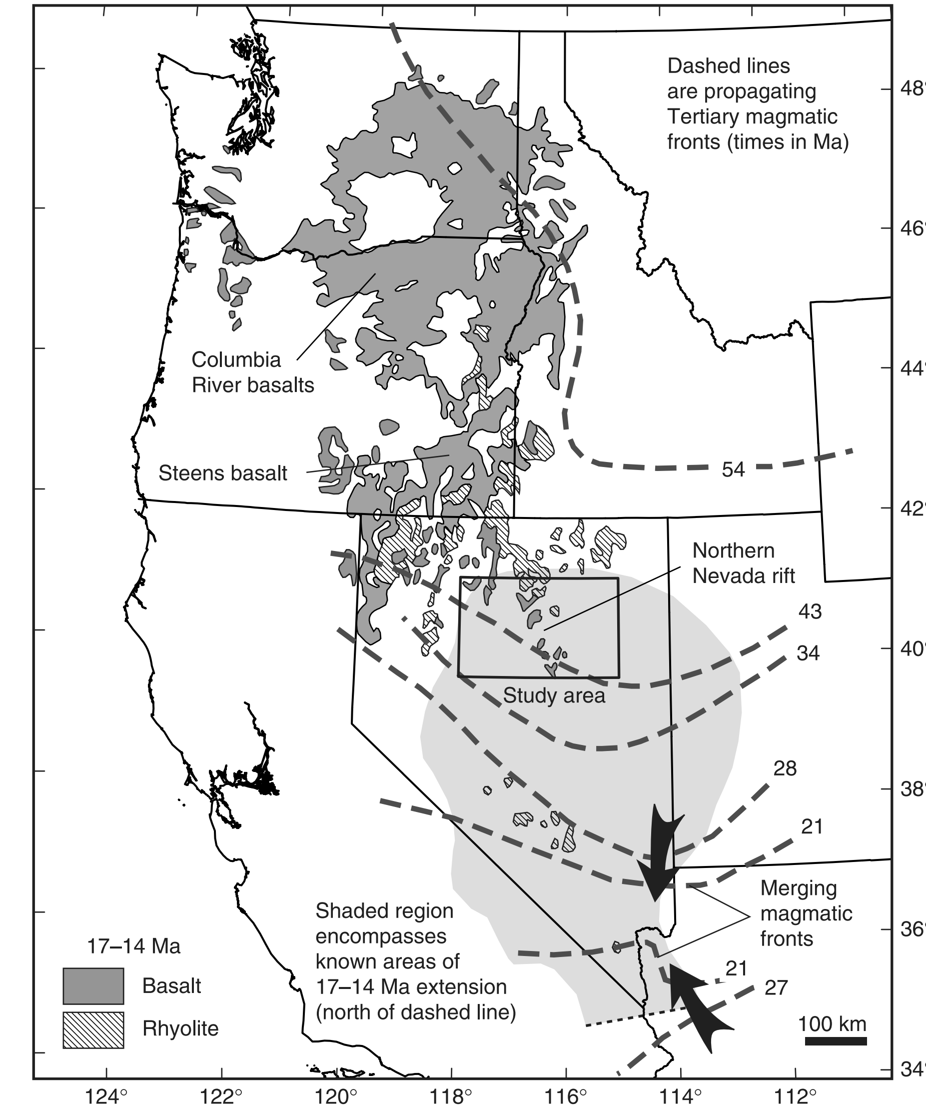


Figure 15. Map illustrating some aspects of Eocene to Miocene volcanism in the western USA (excluding the Cascade arc). Migrating 'magmatic fronts' from Humphreys (1995), based on Christiansen and Yeats (1992); 17–14 Ma bimodal volcanic rocks from Christiansen and Yeats (1992). Shaded area encompasses areas where extension was ongoing at 17–14 Ma (references in text).

*Middle Miocene bimodal volcanism and the Yellowstone hotspot*

Middle Miocene bimodal volcanism in north-central Nevada was coeval with a much larger episode of basaltic volcanism that covered much of northwestern Nevada, Oregon, and Washington with the Steens and Columbia River basalts (Figure 15). The earliest eruptions of this episode are the ca. 16.7 Ma Steens Basalt in southern Oregon and northwestern Nevada (e.g. Camp *et al.* 2003; Brueseke *et al.* 2007; Jarboe *et al.* 2008), and the most voluminous eruptions took place from 16 to 15 Ma (e.g. Hooper *et al.* 2007).

Caldera-forming rhyolite eruptions accompanied basaltic volcanism in northwestern Nevada (Noble *et al.* 1970; Rytuba and McKee 1984; Castor and Henry 2000; Figure 15). Middle Miocene bimodal volcanism also took place in southern Nevada, where it was coeval with large-magnitude extension (e.g. Gans and Bohrson 1998; Faulds *et al.* 2001). In the area discussed in this paper, middle Miocene volcanism was synextensional. In northwestern Nevada and adjacent Oregon, extension postdates middle Miocene volcanism (Colgan *et al.* 2006; Scarberry 2007). Columbia River Basalt volcanism in Oregon is generally considered to have occurred in a back-arc, extensional environment (e.g. Hooper *et al.* 2007; Camp and Hanan 2008) characterized by only small-magnitude extension (e.g. Cummings *et al.* 2000), and eastern Washington remains largely unextended (e.g. Wells 1990; Cummings *et al.* 2000). Thus, although the local relationship between volcanism and extension is highly variable, the middle Miocene was fundamentally a time of extension and bimodal volcanism that affected much of the Cordillera – from southern Nevada to southern Washington – at a very specific time (ca. 16–17 Ma).

The dominant proposed origin for the Columbia River basalts and related rocks is the rise, impingement on the lithosphere, and partial melting of a deep mantle plume (e.g. Morgan 1972; Camp and Ross 2004; Hooper *et al.* 2007; Wolff *et al.* 2008) which is now centred beneath Yellowstone (e.g. Pierce and Morgan 1992). The very close coincidence in timing between volcanism and extension both within our study area and at the scale of the whole Cordillera strongly suggests some relationship – either one caused the other, or they both share an underlying cause. Arrival of the deep plume is ‘external’ in the sense that its ascent from the mantle is not controlled by surface tectonics. Therefore, if basaltic volcanism was caused by arrival of a deep plume, the onset of extension at that time was also most likely caused by the same plume. *In this scenario, middle Miocene Basin and Range extension was triggered by impingement of the voluminous plume head of the Yellowstone hotspot, which thermally weakened and uplifted the overlying lithosphere, causing it to collapse during rapid extension.*

### *Miocene Pacific–North American plate interactions*

From the inception of the Pacific–North American transform margin ca. 30 Ma (e.g. Atwater 1970) until the late Miocene (about 8 Ma), the Pacific plate was moving away from the North American plate margin, requiring a component of extension in addition to strike-slip along the transform boundary (e.g. Stock and Hodges 1989; Atwater and Stock 1998). However, the transform segment of the plate margin apparently did not fully develop until much later than 30 Ma (e.g. Nicholson *et al.* 1994; Wilson *et al.* 2005; McCrory *et al.* 2009). Nicholson *et al.* (1994) noted that, although the Mendocino triple junction was propagating northwards from 30 Ma onwards, several microplates continued to subduct beneath North America during that time (Figure 16(a)), and their demise between 20 and 16 Ma (Figure 16(a,b)) caused the Pacific–North American transform segment of the margin to lengthen from ~600 to ~1200 km. Sudden growth of the transform margin exposed a significant part of continental North America to the divergent component of Pacific plate motion, at which point extension was required somewhere in the continent to compensate (Atwater 1970; Stock and Molnar 1988; Best and Christiansen 1991; Dickinson 1997, 2002). Hausback (1984) and Stock and Hodges (1989) proposed a nearly identical mechanism for ca. 12 Ma ‘proto-Gulf extension’ along the southern part of the transform margin along the western edge of Baja California, in which a sudden 1000 km southward jump in the Riviera triple junction (Figure 16(c)) required subsequent

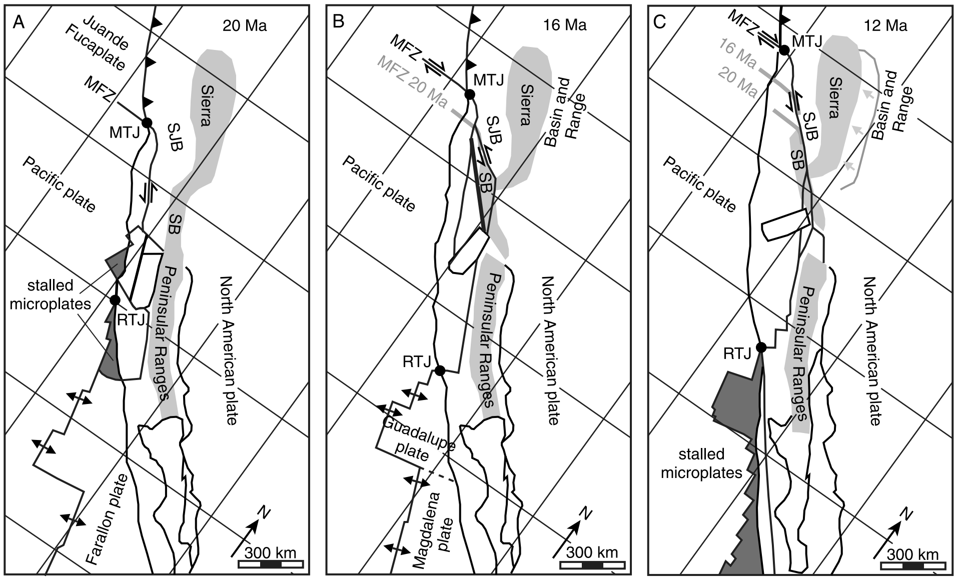


Figure 16. Tectonic model of Pacific–North American plate interactions from 20–12 Ma (Modified slightly from Nicholson *et al.* 1994). MFZ, Mendocino fracture zone; MTJ, Mendocino triple junction; RTJ, Riviera triple junction; SB, Salinian block; SJB, San Joaquin Basin. Westward translation of Sierra Nevada between (a) and (c) traced directly from Nicholson *et al.* (1994).

extension in what is now the Gulf of California. Wernicke and Snow (1998) argued that plate-boundary forces strongly influenced rapid 16–10 Ma extension in the 'central' Basin and Range in southern Nevada. *In this scenario, middle Miocene Basin and Range extension was a consequence of plate-margin tectonics (possibly rapid lengthening of the transform boundary), which required extension in the continent to compensate for the Pacific plate moving west away from North America.*

### *A tectonic model for Miocene extension in the northern Basin and Range*

If the three scenarios outlined above are all correct, middle Miocene Basin and Range extension was caused by simultaneous (1) arrival of the Yellowstone mantle plume in northern Nevada and (2) final delamination of the remnant Farallon slab in southern Nevada during (3) a profound reorganization of the Pacific–North American plate boundary. In our judgement, this requires too many unrelated events to happen coincidentally at the same time. Some are more likely causes, and some more likely effects, but which ones?

Middle Miocene Basin and Range extension resulted in westward motion of the intact Sierra Nevada– Great Valley Block (here referred to simply as the 'Sierra Nevada Block') relative to the Colorado Plateau (Figure 17). The total amount of westward motion has only been fully estimated for southern Nevada, where it was about 120 km from 16–10 Ma (Wernicke and Snow 1998). We infer 50–60 km extension between 16 and 10 Ma – also accommodated by westward motion of the Sierra Nevada – in north-central Nevada, but this area covers less than half the width of the Basin and Range, and the total amount is likely much more. More detailed estimates await further mapping, but a conservative estimate is that the Sierra Nevada Block moved at least 100 km west between 16–17 and 10 Ma. Unless a comparable amount of east–west shortening took in place in the California

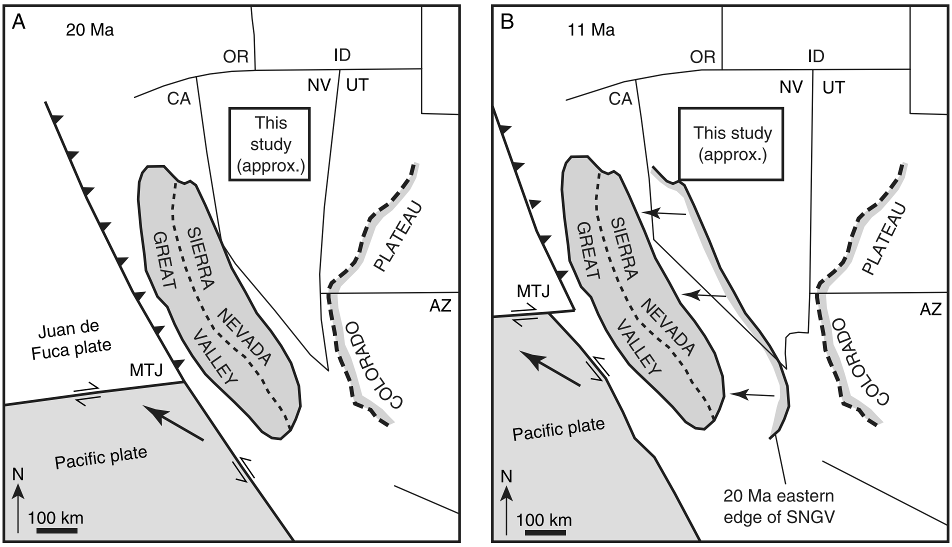


Figure 17. Map showing relative positions of Colorado Plateau, Sierra Nevada–Great Valley Block, and Mendocino triple junction at (a) 20 Ma, and (b) 11 Ma (simplified from Atwater and Stock 1998; plate boundaries, block outlines, and retro-deformed state borders exactly as they show them). MTJ, Mendocino triple junction; SNGV, Sierra Nevada–Great Valley block.

Coast Ranges, westward motion of the Sierra Nevada Block must have been accommodated by westward motion of the Pacific and Juan de Fuca plates (Figure 17). The middle Miocene geology of the California Coast Ranges is complicated by Miocene and younger strike-slip faulting, but Page *et al.* (1998) estimated 24–48 km of shortening across the central and southern Coast Ranges between latitudes 38–35° N, all since 10.5 Ma, mostly since about 4 Ma; Namson and Davis (1990) estimated 27 km of shortening since 4 Ma (at ~35° N). Coast Range shortening is therefore too young (and in any case too little) to accommodate more than a small fraction of westward motion of the Sierra Nevada Block during Basin and Range extension – the rest must have been taken up by westward motion of the Pacific plate relative to North America. Did the Basin and Range 'push' the plate margin out of the way, or did it 'follow' the plate margin as it moved west?

We consider the second scenario more likely for several reasons. Figure 17 shows the configuration of the Sierra Nevada Block and Mendocino triple junction at 20 and 11 Ma – before and after major Basin and Range extension (from Atwater and Stock 1998). The Mendocino triple junction was west of the Sierra Nevada Block while it moved west to accommodate Basin and Range extension; thus, both subduction and transform segments of the plate boundary must also have moved west to accommodate this motion. Although it might be possible for the expanding Basin and Range to push the continental margin west and override the subduction zone, it is unlikely to have moved the transform margin west, as that would require transporting the entire Pacific plate out of the way. In any case, no such pushing would have been necessary, inasmuch as relative motion of the Pacific plate west of the transform margin at this time was divergent (heavy arrow in Figure 17; Atwater and Stock 1998). Finally, not only was shortening in coastal California minimal during the middle Miocene, but rapid subsidence of sedimentary basins in some places is more consistent with extension during this time (e.g. Graham and Williams 1985; Graham *et al.* 1989; Wilson *et al.* 2005). These observations are more consistent with the plate margin moving west as fast or faster than the advancing Sierra Nevada Block, rather than being pushed west by the expanding Basin and Range in the interior of the continent.

We suggest the following scenario for middle Miocene extension in the northern Basin and Range, building on the previous work and interpretations discussed above. First, integration of the transform segment of the Pacific–North American plate boundary in the middle Miocene (Figure 16) led to divergent motion between the plates over a large area, and extension was required in the continent to compensate. The cold, strong Sierra Nevada Block resisted deformation, but to the east, the old Mesozoic orogenic plateau was composed of thickened, gravitationally unstable continental crust underlain by warm mantle following removal of the remnant Farallon slab. It was thus primed to extend and did so rapidly over a wide area. Because the Sierra Nevada Block remained intact as it moved west to keep pace with the Pacific plate, extension took place in the entire region to the east of it, not just east of the transform boundary south of the Mendocino triple junction. Westward motion of the Sierra Nevada north of the Mendocino triple junction was probably accommodated by clockwise rotation of the southern Cascade Range, which is generally interpreted to have rotated contemporaneously with Basin and Range extension (Magill *et al.* 1981; Wells 1990). Basin and Range extension was thus a process of orogenic collapse in the sense that it resulted in significant crustal thinning and loss of surface elevation, but this process did not occur until the plate margin evolved to a geometry that provided space for its collapse. Removal of the shallow Farallon slab may have influenced the distribution of strain, first by cooling and strengthening the Sierra Nevada–Great Valley Block, then by warming and weakening the thrust-thickened continental crust to the east. Removal of the slab was not the cause of extension, however, which would have happened anyway – although possibly in a different form – once the plate margin required it.

This leaves middle Miocene volcanism – did a deep mantle plume arrive at the precise time of a major tectonic reorganization, purely by coincidence? Or was the burst of middle Miocene basaltic volcanism caused by something other than a plume? A variety of non-plume models for middle Miocene volcanism have been proposed, including, but not limited to lithospheric delamination (Hales *et al.* 2005), upper mantle convection (Christiansen *et al.* 2002), and plume-like convection in response to shear imposed by the Pacific plate (Dickinson 1997). We favour a scenario such as the one proposed by Dickinson (1997), in which middle Miocene volcanism was a consequence of (rather than the cause of) the tectonic reorganization that was ongoing in the Basin and Range and on the plate margin.

## Suggestions for further research

We have outlined a history for Basin and Range extension in north-central Nevada and proposed a more regional tectonic model for this deformation, implying that key elements of our proposed tectonic history are also true for a larger area of the Basin and Range Province, notably central Nevada. Here, we restate these elements in the form of testable hypotheses we believe are worthy of future research.

(1) *Extension – map-view widening of the Basin and Range Province accommodated by westward translation of the Sierra Nevada – prior to 17 Ma was of much smaller magnitude than post-17 Ma extension and did not lead to significant crustal thinning*. Pre-17 Ma extension as it is presently documented in the Basin and Range (although it may be locally significant) adds up to temporally and spatially isolated pockets that cannot account for significant widening of the entire

Basin and Range – i.e. an early orogenic collapse that preceded Miocene extension. Significant Eocene and Oligocene extension is also at odds with emerging data sets indicating high surface elevations and long-distance transport of ash-flow tuffs at this time. Is pre-17 Ma extension more extensive than presently known, and does it represent significant widening of the Basin and Range? If so, how does this square with high elevations and external drainage in the Oligocene? If not, what does it represent? Eocene to early Miocene exhumation and ductile deformation of rocks at deep crustal levels have been documented in metamorphic core complexes and appears to be coeval with magmatism. Was it accompanied by correspondingly major extension at the surface? If so, why has so little evidence for this – particularly sedimentary basins – been found to date? If not, what processes were at work in the mid-Tertiary crust?

(2) *Middle Miocene extension was characterized by high-strain domains separated by little-extended areas and represents significant crustal thinning and thus collapse of any pre-existing plateau*. The history we have outlined for north-central Nevada is strikingly similar to that of southern Nevada, with minimal pre-16 Ma extension, rapid westward motion of the Sierra Nevada from 16–10 Ma, and a different extensional regime in the late Miocene. Although some Miocene high-strain domains in the intervening area have been studied in detail, strain patterns in much of the northern Basin and Range have yet to be fully characterized. Major east–west extension in these areas should be middle Miocene. When trying to understand the magnitude of strain across the entire province (for any time, not just the Miocene), the extent and distribution of little-extended domains is as important as the highly extended ones. How widespread are these?

(3) *Middle Miocene extension did not form the modern ranges in the Basin and Range, which are superimposed on the older domains of high and low extension*. This seems to be true in north-central Nevada, but is it true elsewhere in the Basin and Range? Is there a time gap between older large-magnitude extension and younger late Miocene faulting? Why is late Miocene and younger extension characterized by such a different structural style than the previous deformation, one characterized by evenly spaced high-angle faults that break up both the old extended and unextended domains?

(4) *Middle Miocene extension was either caused or allowed by a reorganization of the Pacific-North American plate boundary*. The general nature (transition from microplate subduction to transtensional strike-slip) and timing (between 20 and 12 Ma) of this transition is known, but can its timing be determined more precisely, and does it really coincide with the 16–17 Ma onset of rapid extension? What was the tectonic environment west of the Sierra Nevada at 17 Ma? Was it extensional, compressional, or different in different places? Either way, how much deformation (extension or compression) took place in western California at that time? If extension was caused or allowed by the geometry of the plate margin, is coincidental arrival of a deep mantle plume at this time required to cause coeval bimodal volcanism? Is there a plausible geodynamic scenario in which middle Miocene volcanism could have been caused by either extensional processes or by the same plate-margin reorganization that allowed extension to take place? Conversely, is there a plausible geodynamic scenario in which Basin and Range extension could drive the Miocene plate-margin reorganization to take place, rather than the reverse?

## Acknowledgements

The ideas in this paper took shape during discussions and fieldwork with David John, Keith Howard, Alan Wallace, Jim Faulds, Elizabeth Miller, Trevor Dumitru, and Julie Fosdick. Funding for this work was provided by a US Geological Survey Mendenhall postdoctoral research fellowship to J. Colgan. We thank Keith Howard, Alan Wallace, Sandra Wyld, and Elizabeth Miller for reviews and comments that sharpened our arguments and greatly improved the final manuscript.

## References

Allmendinger, R.W., 1992, Fold-thrust tectonics of the western United States exclusive of the accreted terranes, *in* Burchfield, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous US, Decade of North American Geology, Geological Society of America, Boulder, Colorado, Vol. G-3, p. 169–203.

Applegate, J.D.R., and Hodges, K.V., 1995, Mesozoic and Cenozoic extension recorded by metamorphic rocks in the Funeral Mountains, California: Geological Society of America Bulletin, v. 107, p. 1063–1076.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

Armstrong, R.L., 1972, Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah: Geological Society of America Bulletin, v. 83, p. 1729–1754.

Armstrong, R.L., and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, p. 13,201–13,224.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

Atwater, T., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States – An update: International Geology Review, v. 40, p. 375–402.

Barnes, C.G., Burton, B.R., Burling, T.C., Wright, J.E., and Karlsson, H.R., 2001, Petrology and geochemistry of the late Eocene Harrison Pass pluton, Ruby Mountains core complex, Nevada: Journal of Petrology, v. 42, p. 901–929.

Bennett, R.A., Wernicke, B.P., Niemi, N.A., and Friedrich, A.M., 2003, Contemporary strain rates in the northern Basin and Range province from GPS data: Tectonics, v. 22, doi: 10.1029/2001TC001355.

Best, M.G., and Christiansen, E.H., 1991, Limited extension during peak Tertiary volcanism, Great Basin of Nevada and Utah: Journal of Geophysical Research, v. 96, p. 13,509–13,528.

Best, M.G., Christiansen, E.H., Deino, A.L., Grommé, C.S., McKee, E.H., and Noble, D.C., 1989, Excursion 3A: Eocene through Miocene volcanism in the Great Basin of the western United States: New Mexico Bureau of Mines and Mineral Resources Memoir, v. 47, p. 91–133.

Best, M.G., Barr, D.L., Christiansen, E.H., Gromme, S., Deino, A.L., and Tingey, D.G., 2009, The Great Basin Altiplano during the middle Cenozoic ignimbrite flareup: insights from volcanic rocks: International Geology Review, v. 51, p. 589–633.

Bird, P., 1988, Formation of the Rocky Mountains, western United States: A continuum computer model: Science, v. 239, p. 1501–1507.

Brooks, W.E., Thorman, W.E., and Snee, L.W., 1995, The $^{40}Ar/^{39}Ar$ ages and tectonic setting of the middle Eocene northeast Nevada volcanic field: Journal of Geophysical Research, v. 100, p. 10,403–10,416.

Brooks, E.R., Henry, C.D., and Faulds, J.E., 2008, Age and character of silicic ash-flow tuffs at Haskell Peak, Sierra County, California: Part of a major Eocene(?)–Oligocene paleovalley spanning the Sierra Nevada–Basin and Range boundary: California Geological Survey Map Sheet 55A, 1:12,000, 41 p. text.

Brueseke, M.E., Heizler, M.T., Hart, W.K., and Mertzman, S.A., 2007, Distribution and geochronology of Oregon Plateau (USA) flood basalt volcanism: The Steens Basalt revisited: Journal of Volcanology and Geothermal Research, v. 161, p. 187–214.

Burke, D.B., 1973, Reinterpretation of the Tobin thrust—pre-Tertiary geology of the southern Tobin Range, Pershing County, Nevada [Ph.D. thesis]: Stanford, California, Stanford University, 82 p.

Burke, D.B., and Silberling, N.J., 1973, The Auld Lang Syne Group of Late Triassic and Jurassic(?) age, north-central Nevada: US Geological Survey Bulletin 1394-E, 14 p.

Burton, B.R., 1997, Structural geology and emplacement history of the Harrison Pass pluton, central Ruby Mountains, Nevada [Ph.D. thesis]: Wyoming, University of Wyoming, 296 p.

Camilleri, P., and Chamberlain, K.R., 1997, Mesozoic tectonics and metamorphism in the Pequop Mountains and Wood Hills, northeast Nevada: Implications for the architecture and evolution of the Sevier orogen: Geological Society of America Bulletin, v. 109, p. 74–94.

Camilleri, P., Yonkee, W.A., Coogan, J.C., DeCelles, P.G., McGrew, A., and Wells, M., 1997, Hinterland to foreland transect through the Sevier orogen, NE Nevada to SW Wyoming: Structural style, metamorphism, and kinematic history of a large contractional orogenic wedge, *in* Link, P.K., and Kowallis, B.J., eds., Proterozoic to Recent Stratigraphy, Tectonics, and Volcanology, Utah, Nevada, Southern Idaho and Central Mexico: Brigham Young University Geology Studies, v. 42, part 1, p. 297–309.

Camp, V.E., and Hanan, B.B., 2008, A plume-triggered delamination origin for the Columbia River Basalt Group: Geosphere, v. 4, p. 480–495.

Camp, V.E., and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest: Journal of Geophysical Research, v. 109, doi: 10.1029/2003JB002838.

Camp, V.E., Ross, M.E., and Hanson, W.E., 2003, Genesis of flood basalts and Basin and Range volcanic rocks from Steens Mountain to the Malheur River Gorge, Oregon: Geological Society of American Bulletin, v. 115, p. 105–128.

Carter, T.J., Kohn, B.P., Foster, D.A., Gleadow, A.J.W., and Woodhead, J.D., 2006, Late-stage evolution of the Chemehuevi and Sacramento detachment faults from apatite (U–Th)/He thermochronology – evidence for mid-Miocene accelerated slip: Geological Society of America Bulletin, v. 118, p. 689–709, doi: 10.1130/B25736.1.

Cassel, E.J., Graham, S.A., and Chamberlain, C.P., 2009, Cenozoic tectonic and topographic evolution of the northern Sierra Nevada, California, through stable isotope paleoaltimetry in volcanic glass: Geology, v. 37, p. 547–550.

Cassel, E.J., Calvert, A.T., and Graham, S.A., 2009, Age, geochemical composition, and distribution of Oligocene ignimbrites in the northern Sierra Nevada, California: implications for landscape morphology, elevation, and drainage divide geography of the Nevadaplano: International Geology Review, v. 51, p. 723–742.

Castor, S.B., and Henry, C.D., 2000, Geology, geochemistry, and origin of volcanic rock-hosted uranium deposits in northwestern Nevada and southeastern Oregon: Ore Geology Reviews, v. 16, p. 1–40.

Chamberlain, R.M., 1983, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico: A summary: New Mexico Geological Society 34th Field Conference Guidebook, p. 111–118.

Chase, C.G., Gregory, K.M., Parrish, J.T., and DeCelles, P.G., 1998, Topographic history of the western Cordilleran of North America and controls on climate, *in* Crowley, T.J., and Burke, K., eds., Tectonic boundary conditions for climate reconstructions: Oxford Monographs on Geology and Geophysics, n. 39, p. 73–99.

Christiansen, R.L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Geology of North America, The Cordilleran Region: Geological Society of America Decade in North American Geology Series, v. G-3, p. 261–406.

Christiansen, R.L., Foulger, G.R., and Evans, J.R., 2002, Upper-mantle origin of the Yellowstone hotspot: Geological Society of America Bulletin, v. 114, p. 1245–1256.

Cline, J.S., Hofstra, A.H., Muntean, J.L., Tosdal, R.M., and Hickey, K.A., 2005, Carlin-type gold deposits in Nevada: Critical geologic characteristics and viable models, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfard, R.J., and Richards, J.P., eds., 100th Anniversary Volume of Economic Geology, Society of Economic Geologists, Littleton, CO, p. 451–484.

Coats, R.R., 1987, Geology of Elko County, Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 101, 112 p., scale 1:250,000.

Colgan, J.P., and Metcalf, J.R., 2006a, Rapid middle Miocene unroofing of the southern Ruby Mountains, Nevada: Geological Society of America Abstracts with Programs, Fall 2006.

Colgan, J.P., and Metcalf, J.R., 2006b, Apatite fission-track and (U–Th)/He dating of slip on the Crescent Fault, Nevada: AGU, December, Abstract no. T11D-0466.

Colgan, J.P., Dumitru, T.A., Reiners, P.W., Wooden, J.L., and Miller, E.L., 2006, Cenozoic tectonic evolution of the Basin and Range Province in northwestern Nevada: American Journal of Science, v. 306, p. 616–654.

Colgan, J.P., John, D.A., Henry, C.D., and Fleck, R.J., 2008, Large-magnitude Miocene extension of the Eocene Caetano caldera, Shoshone and Toiyabe Ranges, Nevada: Geosphere, v. 4, p. 107–131, doi:10.1130/GES00115.1.

Collinson, J.W., 1966, Permian and Triassic biostratigraphy of the Medicine Range, Elko County, Nevada [Ph.D. thesis]: Stanford, Stanford University, 156 p.

Coney, P.J., 1980, Cordilleran metamorphic core complexes: An overview: Geological Society of America Memoir No. 153, p. 7–31.

Coney, P.J., and Harms, T.A., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550–554.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406.

Cousens, B., and Henry, C.D., 2008, Alkaline basalts of the Quaternary Buffalo Valley volcanic field, NW Fish Creek Mountains, north-central Nevada, Great Basin: Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract V41D-2126.

Cowen, D.S., and Bruhn, R.L., 1992, Late Jurassic to early Late Cretaceous geology of the US Cordillera, *in* Burchfield, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous US, Decade of North American Geology, Geological Society of America, Boulder, Colorado, vol. G-3, p. 169–203.

Crafford, A.E.J., 2007, Geologic Map of Nevada: US Geological Survey Data Series 249, 1 CD-ROM, 46 p., 1 plate.

Crowley, B.E., Koch, P.L., and Davis, E.B., 2008, Stable isotope constraints on the elevation history of the Sierra Nevada Mountains, California: Geological Society of America Bulletin, v. 120, p. 588–598, doi: 10.1130/B26254.1.

Cummings, M.L., Evans, J.G., Ferns, M.L., and Lees, K.R., 2000, Stratigraphic and structural evolution of the middle Miocene synvolcanic Oregon–Idaho graben: Geological Society of America Bulletin, v. 112, p. 668–682.

Dallmeyer, R.D., Snoke, A.W., and McKee, E.H., 1986, The Mesozoic–Cenozoic tectonothermal evolution of the Ruby Mountains, East Humboldt Range, Nevada: A Cordilleran metamorphic core complex: Tectonics, v. 5, p. 931–954.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, p. 105–168.

DeCelles, P.G., and Coogan, J.C., 2006, Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah: Geological Society of America Bulletin, v. 118, p. 841–864.

DeCelles, P.G., and Currie, B.S., 1996, Long-term sediment accumulation in the Middle Jurassic-early Eocene Cordilleran retroarc foreland-basin system: Geology, v. 24, p. 591–594.

Dewey, J.F., 1988, Extensional collapse of orogens: Tectonics, v. 7, p. 1123–1139.

Dickinson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California: Geological Society of America Bulletin, v. 107, p. 936–954.

Dickinson, W.R., 2002, The Basin and Range Province as a composite extensional domain: International Geology Review, v. 44, p. 1–38.

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny: Geological Society of America Memoir, no. 151, p. 355–366.

Dokka, R.K., Mahaffie, M.J., and Snoke, A.W., 1986, Thermochronologic evidence of major tectonic denudation associated with detachment faulting, northern Ruby Mountains – East Humboldt Range, Nevada: Tectonics, v. 5, p. 995–1006.

Druschke, P., Hanson, A.D., and Wells, M., 2008, Detrital zircon provenance of Cretaceous to Eocene strata in the Sevier hinterland, central Nevada: Implications for tectonics and paleogeography: Geological Society of America Abstracts with Programs, v. 40, p. 78.

Dumitru, T.A., Gans, P.B., Foster, D.A., and Miller, E.L., 1991, Refrigeration of the western Cordilleran lithosphere during Laramide shallow–angle subduction: Geology, v. 19, p. 1145–1148.

Elison, M.W., and Speed, R.C., 1988, Triassic flysch of the Fencemaker allochthon, East Range, Nevada: Fan facies and provenance: Geological Society of America Bulletin, v. 100, p. 185–199.

Engebretson, D.C., Cox, A., and Thompson, G.A., 1984, Correlation of plate motions with continental tectonics: Laramide to Basin-Range: Tectonics, v. 3, p. 115–119.

England, P.C., 1982, Some numerical investigations of large scale continental deformation, *in* Hsu, K.J., ed., Mountain Building Processes, Academic Press, New York, p. 129–139.

Faulds, J.E., Feuerbach, D.L., Miller, C.F., and Smith, E.I., 2001, Cenozoic evolution of the northern Colorado River extensional corridor, Utah Geological Association Publication 30, Pacific Section American Association of Petroleum Geologists Publication GB78, p. 239–271.

Faulds, J.E., Henry, C.D., and Hinz, N.H., 2005, Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific – North American plate boundary: Geology, v. 33, p. 505–508.

Fitzgerald, P.G., Fryxell, J.E., and Wernicke, B.P., 1991, Miocene crustal extension and uplift in southeastern Nevada: Constraints from apatite fission track analysis: Geology, v. 19, p. 1013–1016.

Fitzgerald, P.G., Duebendorfer, E.M., Faulds, J.E., and O'Sullivan, P., 2009, TC2001, South Virgin–White Hills detachment fault system of SE Nevada and NWArizona: Applying apatite fission track thermochronology to constrain the tectonic evolution of a major continental detachment fault: Tectonics, v. 28, doi:10.1029/2007TC002194.

Fosdick, J.C., 2007, Miocene extension in the East Range: Documenting multiple episodes of normal faulting using low-temperature thermochronology [M.S. Thesis]: Stanford, Stanford University, 60 p.

Fosdick, J.C., and Colgan, J.P., 2008, Miocene extension in the East Range, Nevada: A two-stage history of normal faulting in the northern Basin and Range: Geological Society of America Bulletin, v. 120, p. 1198–1213.

Friedrich, A.M., Lee, J., Wernicke, B.P., and Sieh, K., 2004, Geologic context of geodetic data across a Basin and Range normal fault, Crescent Valley, Nevada: Tectonics, v. 23, TC205, doi: 10.1029/2003TC001528.

Gans, P.B., 1987, An open-system, two-layer crustal stretching model for the eastern Great Basin: Tectonics, v. 6, no. 1, p. 1–12.

Gans, P.B., and Bohrson, W.A., 1998, Suppression of Volcanism During Rapid Extension in the Basin and Range Province, United States: Science, v. 279, p. 66–68, doi: 10.1126/science.279.5347.66.

Gilluly, J., and Gates, O., 1965, Tectonic and igneous geology of the northern Shoshone Range, Nevada, Gravity in Crescent Valley, by D. Plouff, Economic geology, by K.B. Ketner: US Geological Survey Professional Paper 465.

Gilluly, J., and Masursky, H., 1965, Geology of the Cortez Quadrangle, Nevada: US Geological Survey Bulletin, v. 1175, 117 p.

Gonsior, Z.J., 2006, The timing and evolution of Cenozoic extensional normal faulting in the southern Tobin Range, Pershing County, Nevada [M.S. thesis]: Corvallis, Oregon State University, 52 p.

Gonsior, Z.J., and Dilles, J.H., 2008, timing and evolution of Cenozoic extensional normal faulting and magmatism in the southern Tobin Range, Nevada: Geosphere, v. 4, p. 687–712.

Gordon, I., and Heller, P.L., 1993, Evaluating major controls on basinal stratigraphy, Pine Valley, Nevada: Implications for syntectonic deposition: Geological Society of America Bulletin, v. 105, p. 47–55.

Graham, S.A., and Williams, L.A., 1985, Tectonic, Depositional, and Diagenetic History of Monterey Formation (Miocene), Central San Joaquin Basin, California: American Association of Petroleum Geologists Bulletin, v. 69, p. 385–411, doi: 10.1306/AD4624F7-16F7-11D7-8645000102C1865D.

Graham, S.A., Stanley, R.G., Bent, J.V., and Carter, J.B., 1989, Oligocene and Miocene paleogeography of central California and displacement along the San Andreas fault: Geological Society of America Bulletin, v. 101, p. 711–730, doi: 10.1130/0016-7606(1989)101 < 0711:OAMPOC > 2.3.CO;2.

Hales, T.C., Abt, D.L., Humphreys, E.D., and Roering, J.J., 2005, A lithospheric instability origin for Columbia River flood basalts and Wallowa Mountains uplift in northeaster Oregon: Nature, v. 438, p. 842–845.

Hammond, W.C., and Thatcher, W., 2004, Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the Global Positioning System: Journal of Geophysical Research, v. 109, p. B08403, doi: 10.1029/2003JB002746.

Hausback, B.P., 1984, Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico, *in* Frizzell Jr., A., ed., Geology of the Baja California Peninsula: Pacific Section SEPM, v. 39, p. 219–236.

Haynes, S.R., 2003, Development of the Eocene Elko Basin, northeastern Nevada: Implications for paleogeography and regional tectonism [M.S. thesis]: Vancouver, University of British Columbia, 138 p.

Haynes, S.R., Hickey, K.A., Mortensen, J.K., and Tosdal, R.M., 2002, Onset of extension in the Basin and Range: basin analysis of the Eocene Elko Formation, NE Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 83.

Henry, C.D., 2008, Ash-flow tuffs and paleovalleys in northeastern Nevada: Implications for Eocene paleogeography and extension in the Sevier hinterland, northern Great Basin: Geosphere, v. 4, p. 1–35, doi: 10.1130/GES00122.1.

Henry, C.D., and Colgan, J.P., 2009, The regional structural setting of the 2008 Wells earthquake and Town Creek Flat basin: Implications for the Wells earthquake fault and adjacent structures: Nevada Bureau of Mines and Geology Open-File Report 09-XX, p. x–y.

Henry, C.D., and Faulds, J.E., 1999, Geologic map of the Emigrant Pass Quadrangle, Lander County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 99-9.

Henry, C.D., Faulds, J.E., Boden, D.R., and Ressel, M.W., 2001, Timing and styles of Cenozoic extension near the Carlin trend, northeastern Nevada: Implications for the formation of Carlin-type gold deposits: Geological Society of Nevada Special Publication No. 33, p. 115–128.

Henry, C.D., Ramelli, A.R., and Faulds, J.E., in press, Geologic map of the Seven Lakes Mountain Quadrangle, Washoe County, Nevada and Lassen County, California: Nevada Bureau of Mines and Geology Map 164, scale 1:24,000, XX p. text.

Hess, R.H., Fitch, S.P., and Warren, S.N., 2004, Nevada oil and gas well database: Nevada Bureau of Mines and Geology Open File Report 04-01.

Hickey, K., Tosdal, R., Haynes, S., and Moore, S., 2005, Tectonics, paleogeography, volcanic succession, and the depth of formation of Eocene sediment-hosted gold deposits of the northern Carlin trend, Nevada: Geological Society of Nevada Field Trip Guidebook #3, p. 97–105.

Hodges, K.V., Snoke, A.W., and Hurlow, H.A., 1992, Thermal evolution of a portion of the Sevier hinterland: The northern Ruby Mountains–East Humboldt Range and Wood Hills, northeastern Nevada: Tectonics, v. 11, p. 154–164.

Hooper, P.R., Camp, V.E., Reidel, S.P., and Ross, M.E., 2007, The origin of the Columbia River flood basalt province; plume versus nonplume models, *in* Foulger, G.R., and Jurdy, D.M., eds., Plates, plumes, and planetary processes: Geological Society of America Special Paper 430, p. 635–668.

Horton, T.W., and Chamberlain, C.P., 2006, Stable isotopic evidence for Neogene surface downdrop in the central Basin and Range Province: Geological Society of America Bulletin, v. 118, p. 475–490.

Horton, T.W., Sjostrom, D.J., Abruzzese, M.J., Poage, M.J., Waldbauer, J.R., Hren, M., Wooden, J., and Chamberlain, C.P., 2004, Spatial and temporal variation of Cenozoic surface elevation in the Great Basin and Sierra Nevada: American Journal of Science, v. 304, p. 862–888.

Howard, K.A., 2003, Crustal structure in the Elko-Carlin region, Nevada, during Eocene gold mineralization: Ruby-East Humboldt metamorphic core complex as a guide to the deep crust: Economic Geology, v. 98, p. 249–268.

Hudec, M.R., 1990, The structural and thermal evolution of the central Ruby Mountains, Elko County, Nevada [Ph.D. Thesis]: Laramie, Wyoming, University of Wyoming, 272 p.

Hudec, M.R., 1992, Mesozoic structural and metamorphic history of the central Ruby Mountains metamorphic core complex, Nevada: Geological Society of America Bulletin, v. 104, p. 1086–1100.

Humphreys, E.D., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987–990.

Humphreys, E.D., Hessler, E., Dueker, K., Farmer, G.L., Erslev, E., and Atwater, T., 2003, How Laramide-age hydration of North American lithosphere by the Farallon slab controlled subsequent activity in the western United States: International Geology Review, v. 45, p. 575–595.

Jarboe, N.A., Coe, R.S., Renne, P.R., Glen, J.M.G., and Mankinen, E.A., 2008, Quickly erupted volcanic sections of the Steens Basalt, Columbia River Basalt Group: Secular variation, tectonic rotation, and the Steens Mountain reversal: Geochemistry, Geophysics, and Geosystems, v. 9, 24 p., doi:10.1029/2008GC002067.

Johnson, J.G., and Visconti, R., 1992, Roberts Mountain thrust relationships in a critical area, northern Sulphur Spring Range, Nevada: Geological Society of America Bulletin, v. 104, p. 1208–1220.

John, D.A., Wallace, A.R., Ponce, D.A., Fleck, R.B., and Conrad, J.E., 2000, New perspectives on the geology and origin of the northern Nevada rift, *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., and Morris, C.L., eds., Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium Proceedings, May 15–18, p. 127–154.

John, D.A., Henry, C.D., and Colgan, J.P., 2008, Magmatic and tectonic evolution of the Caetano caldera, north-central Nevada: A tilted mid-Tertiary eruptive center and source of the Caetano Tuff: Geosphere, v. 4, p. 75–106, doi: 10.1130/GES00116.1.

Jones, C.H., Sonder, L.J., and Unruh, J.R., 1998, Lithospheric gravitational potential energy and past orogenesis: Implications for conditions of initial Basin and Range and Laramide deformation: Geology, v. 26, p. 639–642.

Ketner, K.B., 2008, The Inskip Formation, the Harmony Formation, and the Havallah Sequence of Northwestern Nevada – An Interrelated Paleozoic Assemblage in the Home of the Sonoma Orogeny: US Geological Survey Professional Paper 1757, 18 p.

Ketner, K.B., and Alpha, A.G., 1992, Mesozoic and Tertiary rocks near Elko, Nevada – Evidence for Jurassic to Eocene folding and low-angle faulting: US Geological Survey Bulletin, 13 p.

Ketner, K.B., and Smith, J.F., Jr., 1974, Folds and overthrusts of Late Jurassic or Early Cretaceous age in northern Nevada: US Geological Survey: Journal of Research, v. 2, p. 417–419.

Kistler, R.W., Ghent, E.D., and O'Neil, J.R., 1981, Petrogenesis of garnet two-mica granites in the Ruby Mountains, Nevada: Journal of Geophysical Research, v. 86, p. 10,591–10,606.

Klemperer, S.L., Hauge, T.A., Hauser, E.C., Oliver, J.E., and Potter, C.J., 1986, The Moho in the northern Basin and Range Province, Nevada, along the COCORP 40 degrees N seismic-reflection transect: Geological Society of America Bulletin, v. 97, no. 5, p. 603–618.

Kohn, M.J., 2007, Paleoaltimetry: Geochemical and thermodynamic approaches: Reviews in Mineralogy and Geochemistry, v. 66, 278 p.

Lee, S.Y., Barnes, C.G., Snoke, A.W., Howard, K.A., and Frost, C.D., 2003, Petrogenesis of Mesozoic, peraluminous granites in the Lamoille Canyon area, Ruby Mountains, Nevada, USA: Journal of Petrology, v. 44, p. 713–732.

Lee, J., Stockli, D.F., Owen, L.A., Finkel, R.C., and Kislitsyn, R., 2009, Exhumation of the Inyo Mountains, California: Implications for the timing of extension along the western boundary of the Basin and Range Province and distribution of dextral fault slip rates across the eastern California shear zone: Tectonics, v. 28, TC1001, doi:10.1029/2008TC002295.

Magill, J.R., Cox, A., and Duncan, R., 1981, Tillamook volcanic series: Further evidence for tectonic rotation of the Oregon Coast Range: Journal of Geophysical Research, v. 86, p. 2953–2970.

McCrory, P.A., Wilson, D.S., and Stanley, R.G., 2009, Continuing evolution of the Pacific-Juan de Fuca-North America slab window system – A trench-ridge-transform example from the Pacific Rim: Tectonophysics, v. 464, p. 30–42.

McGrew, A.J., and Snee, L.W., 1994, $^{40}Ar/^{39}Ar$ thermochronologic constraints on the tectonothermal evolution of the northern East Humboldt Range metamorphic core complex, Nevada: Tectonophysics, v. 238, p. 425–450.

McGrew, A.J., Peters, M.T., and Wright, J.E., 2000, Thermobarometric constraints on the tectonothermal evolution of the East Humboldt Range metamorphic core complex, Nevada: Geological Society of America Bulletin, v. 112, p. 45–60.

McKee, E.H., 1970, Fish Creek Mountains tuff and volcanic center, Lander County, Nevada: US Geological Survey Professional Paper 681, 17 p.

McQuarrie, N., and Chase, C.G., 2000, Raising the Colorado Plateau: Geology, v. 28, p. 91–94.

Miller, E.L., and Gans, P.B., 1989, Cretaceous crustal structure and metamorphism in the hinterland of the Sevier thrust belt, western US Cordillera: Geology, v. 17, p. 59–62.

Miller, E.L., Gans, P.B., Wright, J.E., and Sutter, J.F., 1988, Metamorphic history of the east-central Basin and Range province: Tectonic setting and relationship to magmatism, *in* Ernst, W.G., ed., Metamorphism and crustal evolution, western coterminous United States, Rubey, Prentice-Hall, Englewood Cliffs, New Jersey, vol. 7, p. 649–682.

Miller, D.M., Nakata, J.K., and Glick, L.J., 1990, K–Ar ages of Jurassic to Tertiary plutonic and metamorphic rocks, northwestern Utah and northeastern Nevada: US Geological Survey Bulletin 1906, 18 p.

Miller, D.M., Nilsen, T.H., and Bilodeau, W.L., 1992, Late Cretaceous to early Eocene geologic evolution of the US Cordillera, *in* Burchfield, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous US, Decade of North American Geology, Geological Society of America, Boulder, Colorado, vol. G-3, p. 205–260.

Miller, E.L., Dumitru, T.A., Brown, R.W., and Gans, P.B., 1999, Rapid Miocene slip on the Snake Range–Deep Creek Range fault system, east-central Nevada: Geological Society of America Bulletin, v. 111, p. 886–905.

Molnar, P., and Lyon-Caen, H., 1988, Some simple aspects of the support, structure and evolution of mountain belts, *in* Clark, S.P., Jr., *et al.*, eds., Processes in continental lithosphere deformation: Geological Society of America Special Paper 218, p. 179–207.

Moore, T.E., O'Sullivan, P.B., Murchey, B.L., Moring, B.C., Harris, A.G., Blodgett, R.B., and Fleck, R.J., 2005, Geologic map of The Cedars quadrangle, southern Shoshone Range, Nevada: Window to The World: Geological Society of Nevada Symposium Proceedings, May 14–18, Reno, NV, p. 67.

Morgan, J.W., 1972, Deep mantle convection plumes and plate motions: American Association of Petroleum Geologists Bulletin, v. 56, p. 203–213.

Mueller, K.J., and Snoke, A.W., 1993, Progressive overprinting of normal fault systems and their role in Tertiary exhumation of the East Humboldt–Wood Hills metamorphic complex, northeast Nevada: Tectonics, v. 12, p. 361–371.

Muffler, L.J.P., 1964, Geology of the Frenchie Creek Quadrangle, north-central Nevada: US Geological Survey Bulletin 1179.

Mulch, A., Graham, S.A., and Chamberlain, C.P., 2006, Hydrogen isotopes in Eocene river gravels and paleoelevation of the Sierra Nevada: Science, v. 313, p. 87–89.

Muntean, J.L., and Henry, C.D., 2007, Preliminary geologic map of the Jerritt Canyon mining district, Elko County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 07-3, 1:24,000.

Murphy, M.A., McKee, E.H., Winterer, E.L., Finney, S.C., Matti, J.C., and Dunham, J.B., 2007, Geologic map of the Cooper Peak Quadrangle, Eureka County, Nevada: Nevada Bureau of Mines and Geology Map 159, 1:24,000.

Namson, J., and Davis, T.L., 1990, Late Cenozoic fold and thrust belt of the southern Coast Ranges and Santa Maria Basin, California: American Association of Petroleum Geologists Bulletin, v. 74, p. 467–492.

Nichols, K.M., and Silberling, N.J., 1977, Stratigraphy and depositional history of the Star Peak Group (Triassic), northwestern Nevada: Geological Society of America Special Paper 178, 73 p.

Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., and Luyendyk, B.P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system: Geology, v. 22, p. 491–495, doi: 10.1130/0091-7613(1994)022 <0491:MCROTW> 2.3.CO;2.

Noble, D.C., McKee, E.H., Smith, J.G., and Korringa, M.K., 1970, Stratigraphy and geochronology of Miocene volcanic rocks in northwestern Nevada: US Geological Survey Professional Paper 700D, p. D23–D32.

Nosker, S.A., 1981, Stratigraphy and structure of the Sou Hills, Pershing County, Nevada [M.S. Thesis]: Reno, University of Nevada.

Nutt, C.J., and Hart, K.S., 2004, Geologic map of the Big Bald Mountain and part of the Tognini Spring quadrangle, White Pine County, Nevada: Nevada Bureau of Mines and Geology Map 145, scale 1:24,000.

Page, B.M., Coleman, R.G., and Thompson, G.A., 1998, Late Cenozoic tectonics of the central and southern Coast Ranges of California: Geological Society of America, v. 110, p. 846–876, doi: 10.1130/0016-7606(1998)110 <0846:OLCTOT> 2.3.CO;2.

Pierce, L.A., and Morgan, K.L., 1992, The track of the Yellowstone hotspot: Volcanism, faulting, and uplift, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 1–53.

Potter, C.J., Liu, C.-S., Huang, J., Zheng, L., Hauge, T.A., Hauser, E.C., Allmendinger, R.W., Oliver, J.E., Kaufman, S., and Brown, L., 1987, Crustal structure of north-central Nevada; results from

COCORP deep seismic profiling: Geological Society of America Bulletin, v. 98, no. 3, p. 330–337.

Proffett, J.M., Jr., 1977, Cenozoic geology of the Yerington District, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266.

Reiners, P.W., Brady, R., Farley, K.A., Fryxell, J.E., Wernicke, B., and Lux, D., 2000, Helium and argon thermochronometry of the Gold Butte Block, south Virgin Mountains, Nevada: Earth and Planetary Science Letters, v. 178, p. 315–326, doi:10.1016/S0012-821X(00) 00080-7.

Ressel, M.W., and Henry, C.D., 2006, Igneous geology of the Carlin trend, Nevada: Development of the Eocene plutonic complex and significance for Carlin-type Gold deposits: Economic Geology, v. 101, p. 347–383.

Rey, P., Vanderhaeghe, O., and Teyssier, C., 2001, Gravitational collapse of the continental crust: Definition, regimes and modes: Tectonophysics, v. 342, p. 435–449.

Roberts, R.J., Montgomery, K.M., and Lehner, R.E., 1967, Geology and mineral resources of Eureka County, Nevada: Nevada Bureau of Mines Bulletin, 64, 152 p.

Rytuba, J.J., and McKee, E.H., 1984, Peralkaline ash flow tuffs and calderas of the McDermitt volcanic field, southeast Oregon and north central Nevada: Journal of Geophysical Research, v. 89, p. 8616–8628.

Satarugsa, P., and Johnson, R.A., 1998, Crustal velocity structure beneath the eastern flank of the Ruby Mountains metamorphic core complex: Results from normal-incidence to wide-angle seismic data: Tectonophysics, v. 295, p. 369–395.

Satarugsa, P., and Johnson, R.A., 2000, Cenozoic tectonic evolution of the Ruby Mountains metamorphic core complex and adjacent valleys, northeastern Nevada: Rocky Mountain Geology, v. 35, p. 205–230.

Scarberry, K.C., 2007, Extension and volcanism: Tectonic development of the northwestern margin of the Basin and Range Province in southern Oregon [Ph.D. thesis]: Corvallis, Oregon State University, 168 p.

Schmauder, G.C., Arehart, G.B., and Donelick, R.A., 2005, Thermal and chemical profiling of the Bald Mountain district, White Pine County, Nevada, *in* Rhoden, H.N., Steininger, R.C., and Vikre, P.G., eds., Geological Society of Nevada Symposium 2005: Window to the World, Reno, Nevada, May, p. 531–542.

Sharp, R.P., 1942, Stratigraphy and structure of the southern Ruby Mountains, Nevada: Geological Society of America Bulletin, v. 53, p. 647–690.

Smith, K., Pechman, J., Meremonte, M., and Pankow, K., 2009, Preliminary analysis of the Mw6.0 Wells, Nevada earthquake sequence: Nevada Bureau of Mines and Geology Open-File Report 09-XX (in press).

Smith, J.F., and Ketner, K.B., 1975, Stratigraphy of Paleozoic rocks in the Carlin–Piñon Range Area, Nevada: US Geological Survey Professional Paper 867-A, 87 p.

Smith, J.F., and Ketner, K.B., 1976, Stratigraphy of post-Paleozoic rocks and summary of resources in the Carlin–Piñon Range area, Nevada: US Geological Survey Professional Paper 867-B, 48 p.

Smith, J.F., and Ketner, K.B., 1978, Geologic map of the Carlin-Piñon Range area, Elko and Eureka Counties, Nevada: US Geological Survey Miscellaneous Investigations Map I-1028, scale 1:62,500.

Smith, D.L., Gans, P.B., Miller, E.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., 1991, Palinspastic restoration of Cenozoic extension in the central and eastern Basin and Range Province at latitude 30–40 degrees N, *in* Raines, G.L., Lisle, R.F., Schafer, R.W., and Wilkinson, W.H., eds., Geology and ore deposits of the Great Basin: Reno, Nevada: Geological Society of Nevada, p. 75–86.

Smith, D.L., Miller, E.L., Wyld, S.J., and Wright, J.E., 1993, Progression and timing of Mesozoic crustal shortening in the northern Great Basin, Western USA, *in* Dunne, G.C., and McDougall, K.A., eds., Mesozoic paleogeography of the Western United States II, Field Trip Guidebook: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 71, p. 389–405.

Snoke, A.W., and Miller, D.M., 1988, Metamorphic and tectonic history of the northeastern Great Basin, *in* Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States, Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 606–648.

Snoke, A.W., Howard, K.A., McGrew, A.J., Burton, B.R., Barnes, C.G., Peters, M.T., and Wright, J.E., 1997, The grand tour of the Ruby-East Humboldt metamorphic core complex, northeastern Nevada: Brigham Young University Geological Studies, v. 42, p. 1, p. 225–269.

Solomon, B.J., McKee, E.H., and Andersen, D.W., 1979, Stratigraphy and depositional environments of Paleogene rocks near Elko, Nevada, *in* Cenozoic paleogeography of the western United States Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, v. 3, p. 75–88.

Sonder, L.J., and Jones, C.H., 1999, Western United States extension: How the West was widened: Annual Review of Earth and Planetary Sciences, v. 27, p. 417–462.

Stewart, J.H., 1980, Geology of Nevada: A discussion to accompany the geologic map of Nevada: Nevada Bureau of Mines and Geology Special Publication, v. 4, 136 p.

Stewart, J.H., McKee, E.H., and Stager, H.K., 1977, Geology and mineral deposits of Lander County, Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 88, 106 p.

Stewart, J.H., Murchey, B., Jones, D.L., and Wardlaw, B.R., 1986, Paleontologic evidence for complex tectonic interlayering of Mississippian to Permian deep-water rocks of the Golconda allochthon in the Tobin Range, north-central Nevada: Geological Society of America Bulletin, v. 97, p. 1122–1132.

Stock, J.M., and Hodges, K.V., 1989, Pre Pleistocene extension around the Gulf of California and the transfer of Baja California to the Pacific Plate: Tectonics, v. 8, p. 99–115.

Stock, J.M., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and tertiary positions of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339–1384.

Stockli, D.F., 2005, Application of low-temperature thermochronometry to extensional tectonic settings, *in* Reiners, P., and Ehlers, T., eds., Thermochronometry: Reviews in Mineralogy and Geochemistry, v. 58, p. 420–461.

Stockli, D.F., Linn, J.K., Walker, J.D., and Dumitru, T.A., 2001, Miocene unroofing of the Canyon Range during extension along the Sevier Desert Detachment, west-central Utah: Tectonics, v. 20, p. 289–307.

Stockli, D.F., Surpless, B.E., Dumitru, T.A., and Farley, K.A., 2002, Thermochronological constraints on the timing and magnitude of Miocene and Pliocene extension in the central Wassuk Range, western Nevada: Tectonics, v. 21, doi: 10.1029/2001TC001295.

Stoerzel, A., and Smithson, S.B., 1998, Two-dimensional travel time inversion for the crustal P and S wave velocity structure of the Ruby Mountains metamorphic core complex, NE Nevada: Journal of Geophysical Research, v. 103, p. 21,121–21,143.

Surpless, B.E., Stockli, D.F., Dumitru, T.A., and Miller, E.L., 2002, Two-phase westward encroachment of Basin and Range extension into the northern Sierra Nevada: Tectonics, v. 21, doi: 10.1029/2000TC001257.

Taylor, W.J., Bartley, J.M., Martin, M.W., Geissman, J.W., Walker, J.D., Armstrong, P.A., and Fryxell, J.E., 2000, Relations between hinterland and foreland shortening: Sevier orogeny, central North American Cordillera, v. 19, p. 1124–1143.

Trexler, J.H., Cashman, P.H., Henry, C.D., Muntean, T., Schwartz, K., TenBrink, A., Faulds, J.E., Perkins, M., and Kelly, T., 2000, Neogene basins in western Nevada document the tectonic history of the Sierra Nevada – Basin and Range transition zone for the last 12 Ma, *in* Lageson, D.R., Peters, S.G., and Lahren, M.M., eds., Great Basin and Sierra Nevada: Boulder, Colorado, Geological Society of America Field Guide 2, p. 97–116.

US Geological Survey and Nevada Bureau of Mines and Geology, 2006, Quaternary fault and fold database for the United States, accessed July 24, 2008 from USGS website: http//earthquakes.usgs.gov/regional/qfaults/

Vandervoort, D.S., and Schmitt, J.G., 1990, Cretaceous to Early Tertiary paleogeography in the hinterland of the Sevier thrust belt, east-central Nevada: Geology, v. 18, p. 567–570.

Wallace, A.R., 1977, Geology and ore deposits, Kennedy mining district, Pershing County, Nevada [M.S. Thesis]: Colorado, University of Colorado.

Wallace, R.E., 1984, Fault scarps formed during the earthquakes of October 2, 1915, in Pleasant Valley, Nevada, and some tectonic implications, *in* Faulting related to the 1915 Earthquakes in Pleasant Valley, Nevada, US Geological Survey Professional Paper 1274-A, A1–A33.

Wallace, A.R., Perkins, M.E., and Fleck, R.J., 2008, Late Cenozoic paleogeographic evolution of northeastern Nevada: Evidence from the sedimentary basins: Geosphere, v. 4, p. 36–74, doi: 10.1130/GES00114.1.

Watt, J.T., Glen, J.M.G., John, D.A., and Ponce, D.A., 2008, Three-dimensional geologic model of the northern Nevada rift and the Beowawe geothermal system, north-central Nevada: Geosphere, v. 3, p. 667–682, doi: 10.1130/GES00100.1.

Wells, R.E., 1990, Paleomagnetic rotations and the Cenozoic tectonics of the Cascade Range, Washington, Oregon, and California: Journal of Geophysical Research, v. 95, p. 19,409–19,417.
Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Geology of North America, The Cordilleran Region: Geological Society of America Decade in North American Geology Series, v. G-3, p. 553–581.
Wernicke, B.P., and Getty, S.R., 1997, Intracrustal subduction and gravity currents in the deep crust: Sm–Nd, Ar–Ar, and thermobarometric constraints from the Skagit Gneiss Complex, Washington: Geological Society of America Bulletin, v. 109, p. 1149–1166.
Wernicke, B., and Snow, J.K., 1998, Cenozoic tectonism in the central Basin and Range; motion of the Sierran–Great Valley block: International Geology Review, v. 40, p. 403–410.
Wesnousky, S.G., Barron, A.D., Briggs, R.W., Caskey, S.J., Kumar, S., and Owen, L., 2005, Paleoseismic transect across the northern Great Basin: Journal of Geophysical Research, v. 110, B05408, doi:10.1029/2004JB003283.
Whitebread, D.H., and Sorensen, M.L., 1980, Preliminary geologic map of the Granite Quadrangle, SE quarter Kyle Hot Springs Quadrangle, Pershing County, Nevada: US Geological Survey, Open-File Report: OF 85–715.
Whitney, D.L., Teyssier, C., and Vanderhaeghe, O., 2004, Gneiss domes and crustal flow, *in* Whitney, D.L., Tessyier, C., and Siddoway, C.S., eds., Gneiss domes in orogeny: Geological Society of America Special Paper 380, p. 15–33.
Willden, R., and Kistler, R.W., 1979, Precambrian and Paleozoic stratigraphy in central Ruby Mountains, Elko County, Nevada: Rocky Mountain Association of Geologists, Great Basin and Great Basin Field Conference, p. 221–243.
Wilson, D.S., McCrory, P.A., and Stanley, R.G., 2005, Implications of volcanism in coastal California for the Neogene deformation history of North America: Tectonics, v. 24, TC3008, doi:10.1029/2003TC001621.
Wolfe, J.A., Schorn, H.E., Forest, C.E., and Molnar, P., 1997, Paleobotanical evidence for high altitudes in Nevada during the Miocene: Science, v. 276, p. 1672–1675.
Wolfe, J.A., Forest, C.E., and Molnar, P., 1998, Paleobotanical evidence of Eocene and Oligocene paleoaltitudes in midlatitude western North America: Geological Society of America Bulletin, v. 110, p. 664–678.
Wolff, J.A., Ramos, F.C., Hart, G.L., Patterson, J.D., and Brandon, A.D., 2008, Columbia River flood basalts from a centralized crustal magmatic system: Nature Geoscience, v. 1, p. 177–180.
Wright, J.E., and Snoke, A.W., 1993, Tertiary magmatism and mylonitization in the Ruby-East Humboldt metamorphic core complex, northeastern Nevada: U–Pb geochronology and Sr, Nd, and Pb isotope geochemistry: Geological Society of America Bulletin, v. 105, p. 935–952.
Wyld, S.J., 2002, Structural evolution of a Mesozoic backarc fold-and-thrust belt in the US Cordillera: New evidence from northwestern Nevada: Geological Society of America Bulletin, v. 114, p. 1452–1486.
Zoback, M.L., and Thompson, G.A., 1978, Basin and Range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets: Geology, v. 6, p. 111–116.
Zoback, M.L., McKee, E.H., Blakely, R.J., and Thompson, G.A., 1994, The northern Nevada rift: Regional tectono-magmatic relations and middle Miocene stress direction: Geological Society of America Bulletin, v. 106, p. 371–382.