

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

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Abstract

The deep crustal rocks exposed in the Ruby-East Humboldt metamorphic core complex, northeastern Nevada, provide a guide for reconstructing Eocene crustal structure ~50 km to the west near the Carlin trend of gold deposits. The deep crustal rocks, in the footwall of a west-dipping normal-sense shear system, may have underlain the Piñon and Adobe Ranges about 50 km to the west before Tertiary extension, close to or under part of the Carlin trend. Eocene lakes formed on the hanging wall of the fault system during an early phase of extension and may have been linked to a fluid reservoir for hydrothermal circulation. The magnitude and timing of Paleogene extension remain indistinct, but dikes and tilt axes in the upper crust indicate that spreading was east-west to northwest-southeast, perpendicular to a Paleozoic and Mesozoic orogen that the spreading overprinted. High geothermal gradients associated with Eocene or older crustal thinning may have contributed to hydrothermal circulation in the upper crust. Late Eocene eruptions, upper crustal dike intrusion, and gold mineralization approximately coincided temporally with deep intrusion of Eocene sills of granite and quartz diorite and shallower intrusion of the Harrison Pass pluton into the core-complex rocks.

Stacked Mesozoic nappes of metamorphosed Paleozoic and Precambrian rocks in the core complex lay at least 13 to 20 km deep in Eocene time, on the basis of geobarometry studies. In the northern part of the complex, the presently exposed rocks had been even deeper in the late Mesozoic, to >30 km depths, before losing part of their cover by Eocene time. Nappes in the core plunge northward beneath the originally thicker Mesozoic tectonic cover in the north part of the core complex. Mesozoic nappes and tectonic wedging likely occupied the thickened midlevel crustal section between the deep crustal core-complex intrusions and nappes and the overlying upper crust. These structures, as well as the subsequent large-displacement Cenozoic extensional faulting and flow in the deep crust, would be expected to blur the expression of any regional structural roots that could correlate with mineral belts. Structural mismatch of the mineralized upper crust and the tectonically complex middle crust suggests that the Carlin trend relates not to subjacent deeply penetrating rooted structures but to favorable upper crustal host rocks aligned within a relatively coherent regional block of upper crust.

Introduction

THE COMPLEX history of Cenozoic extensional faulting in the Basin and Range province has dismembered older structures, but in doing so has exposed different parts of preexisting over-thickened crustal sections. Metamorphic core complexes (Fig. 1), because they juxtapose upper crustal rocks against deeper rocks unroofed by extensional processes, offer opportunities to investigate and integrate structure and processes of the deep and shallow crust. Of special interest are the conditions below areas such as the Elko-Carlin area of northeastern Nevada, with its oil and gas accumulations (Garside et al., 1988; Flanagan et al., 1990) and Carlin-type gold deposits (Ilchik and Barton, 1997; Hofstra and Cline, 2000). The nearby Ruby-East Humboldt metamorphic core complex affords a view into crustal levels that were at one time as deep as ≥ 30 km and may shed light on the structural foundation below the Elko-Carlin area at the time of Carlin-type gold mineralization.

Carlin-type gold deposits are epigenetic, disseminated, auriferous pyrite deposits, typically hosted in calcareous sedimentary rocks (Hofstra and Cline, 2000). Along the northwest-striking Carlin gold trend (Fig. 2), the deposits formed at crustal depths of about 1 to 5 km (Kuehn and Rose, 1995; Henry and Ressel, 2000; Hofstra and Cline, 2000). Mineral deposits at several sites have been dated or tied chronologically to intrusions within a few million years of 40 Ma, late Eocene

(Seedorff, 1991; Henry and Boden, 1998; Hofstra et al., 1999, 2000; Chakurian et al., 2000; Henry and Ressel, 2000; Ressel et al., 2000; Arehart et al., 2003).

The deep crustal rocks in the Ruby-East Humboldt core complex have been proposed to have structurally underlain upper crustal rocks that now lie tens of kilometers to the west before late Cenozoic crustal extension (Jansma and Speed, 1990; Howard, 1992; Newman and Witter, 1992). In order to

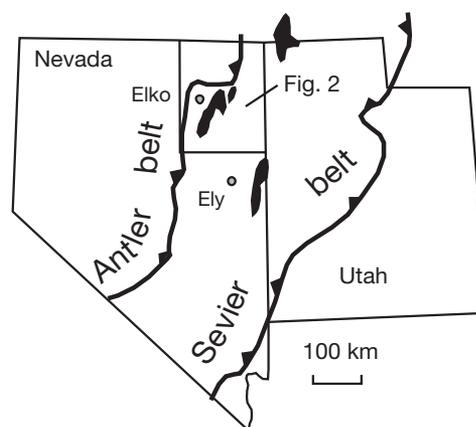


FIG. 1. Index map of Nevada and Utah showing metamorphic core complexes (black), the Mesozoic Sevier fold and thrust belt, and the eastern limit of allochthonous deep-water western-facies rocks of the Antler orogenic belt.

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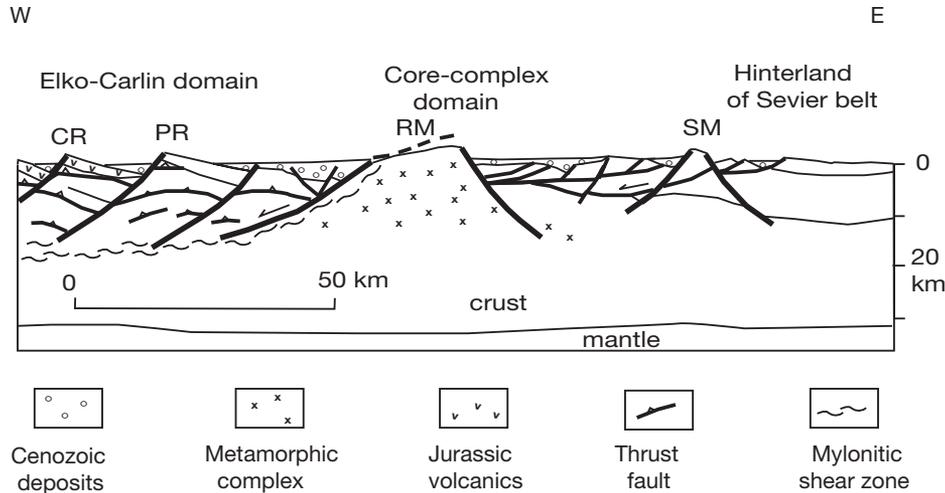


FIG. 3. Schematic modern-day cross section across the Elko-Carlin domain, core-complex domain, and west part of the hinterland domain of Figure 2. No vertical exaggeration. This section highlights post-Eocene tilting and normal faulting related to movement on a major west-rooted normal fault system from its eastern breakaway zone (SM area). Older features include abundant Mesozoic granite (crosses) under the metamorphic core complex, allochthons of western-facies Paleozoic rocks near the top of the upper crustal section in the Elko-Carlin domain, and deeper inferred thrust duplications of miogeoclinal and basement rocks concealed under the Elko-Carlin domain. CR = Cortez Range; PR = Piñon Range; RM = Ruby Mountains; SM = Spruce Mountain and southern Pequop Mountains.

(1968) included the southeastern domain in the hinterland of the thin-skinned Sevier fold and thrust belt, which reaches the surface 200 km to the east (Fig. 1). The hinterland domain exposes a 10- to 13-km-thick miogeoclinal, continental shelf sequence of Neoproterozoic siliciclastic strata and Paleozoic and lower Mesozoic marine strata capped by Jurassic eolian sandstone. Siliciclastic rocks dominate the Neoproterozoic and Lower Cambrian rocks, and carbonate rocks dominate the overlying section. Paleoproterozoic and Archean crystalline rocks, which are basement to the miogeoclinal sequence, crop out to the east in Utah, and locally in a nappe in the East Humboldt Range (Lush et al., 1988). The hinterland domain shown in Figure 2 includes parts of metamorphic core complexes on its east side along the Utah border, which are not discussed here. Upper Paleozoic and lower Mesozoic strata near the surface in the hinterland domain were in gentle folds after being thrust eastward during the Sevier orogeny in Cretaceous and early Tertiary time; they exposed generally less than 2 km of stratigraphic relief in the eroded stratigraphy below a Paleogene unconformity (Armstrong, 1968; Allmendinger and Jordan, 1981).

In the central domain of Figure 2, the Ruby-East Humboldt metamorphic core complex exposes metamorphosed and intruded equivalents of the miogeoclinal Paleozoic strata, as well as Proterozoic and Archean rocks. The metamorphic grade reaches upper amphibolite facies in the Ruby Mountains and adjoining East Humboldt Range. To the east it reaches lower amphibolite facies in the Wood Hills and greenschist facies in the Pequop Mountains (Thorman, 1970; Camilleri et al., 1997). Jurassic, Cretaceous, Eocene, and Oligocene granitoids intrude the higher-grade metamorphic rocks (Hudec and Wright, 1991; Wright and Snoko, 1993; McGrew et al., 2000). Extensional tectonic processes unroofed the metamorphic rocks during Tertiary time (Snoko et al., 1997). Mylonitization caused by normal-sense shearing

during this unroofing overprinted Mesozoic metamorphic textures and structures (Wright and Snoko, 1993). Cenozoic low-angle extensional faults placed allochthons of less metamorphosed or unmetamorphosed rocks onto the metamorphic core complexes (Coney, 1980; Armstrong, 1982). These faults dismembered and attenuated an overthickened crustal section.

The Elko-Carlin domain forms a western region where pre-Cenozoic thrust sheets of deep-water, western-facies Paleozoic strata overrode the miogeoclinal rocks. Lead and strontium isotopic ratios indicative of source regions for plutonic rocks signal that concealed North American basement thins westward beneath this domain (Tosdal et al., 2000). This domain hosts the Carlin-type gold deposits of the Carlin trend and the Independence district (Fig. 2). The thrust faults and associated middle to upper Paleozoic orogenic and overlap strata resulted from a series of shortening events along the western margin of North America, including the Antler (Devonian-Mississippian), Sonoma (Permian-Triassic), Elko (Jurassic), and Sevier (Cretaceous and early Tertiary) orogenies. By the time of final marine deposition in the Triassic, the shortening events apparently thickened the crust sufficiently that the entire region subsequently emerged as a persistent highland. All younger strata in northeastern Nevada are non-marine. Mesozoic thrust faults then reshuffled Paleozoic thrust sheets, complicating the dating of specific thrust movements and determination of the relative importance of Paleozoic and Mesozoic thrusting events (Coats and Riva, 1983; Jansma and Speed, 1990; Ketner, 1998; Taylor et al., 2000).

Major overthrusting in northeastern Nevada was directed east, southeast, and south (Coats and Riva, 1983; Camilleri and Chamberlain, 1997; Taylor et al., 2000). However, thrusts and folds of opposite transport directions also form a notable element of the crustal architecture and suggest backthrusting.

Backthrusting in the Elko-Carlin domain is suggested by Paleozoic(?) northward-overtained folds in the Bull Run Mountains (Ehman, 1985), Cretaceous(?) northwest-directed thrusting proposed near Carlin (Jansma and Speed, 1990), and mid-Mesozoic westward-overtained folds and thrusts in the Piñon and Cortez Ranges (Smith and Ketner, 1977; interpreted as part Eocene by Ketner and Alpha, 1992). In the core complex domain, the premetamorphic (pre-Cretaceous[?]) west-directed Ogilvie thrust in the Ruby Mountains (Fig. 4; Howard et al., 1979), Mesozoic northwestward-overtained folds in the Wood Hills (Thorman, 1970), and a reverse fault in the Pequop Mountains (Camilleri and Chamberlain, 1997) all suggest backthrusting.

Mesozoic magmatism in northeastern Nevada resulted in numerous Jurassic and less abundant Early Cretaceous intrusions, a 2.7-km thickness of Upper Jurassic volcanic rocks in the Cortez Range near the west side of the area of Figures 2 and 3, and Late Cretaceous granites that are voluminous in the deep crustal metamorphic complex but scarce at upper

crustal levels (Muffler, 1964; Coats, 1987; Elison, 1995; Lee and Barnes, 1997; Snoke et al., 1997; McGrew et al., 2000; Mortensen et al., 2000).

Eocene Position of Deep Crustal Rocks Exposed in the Core Complex

Paleodepth

Geochronology and geobarometric studies of mineral assemblages in the Ruby-East Humboldt metamorphic core complex indicate Mesozoic structural burial to depths two to three times the stratigraphic thickness, metamorphism, and Cenozoic tectonic exhumation (Hodges et al., 1992; McGrew and Snee, 1994; Camilleri and Chamberlain, 1997; McGrew et al., 2000; Table 1). The history of burial and unroofing are central to reconstructing the Eocene crustal section. A west-dipping Tertiary shear zone, exposed as a mylonitic carapace (0.03–2 km thick) forming the western side of the Ruby Mountains and East Humboldt Range (Fig. 4), overprinted

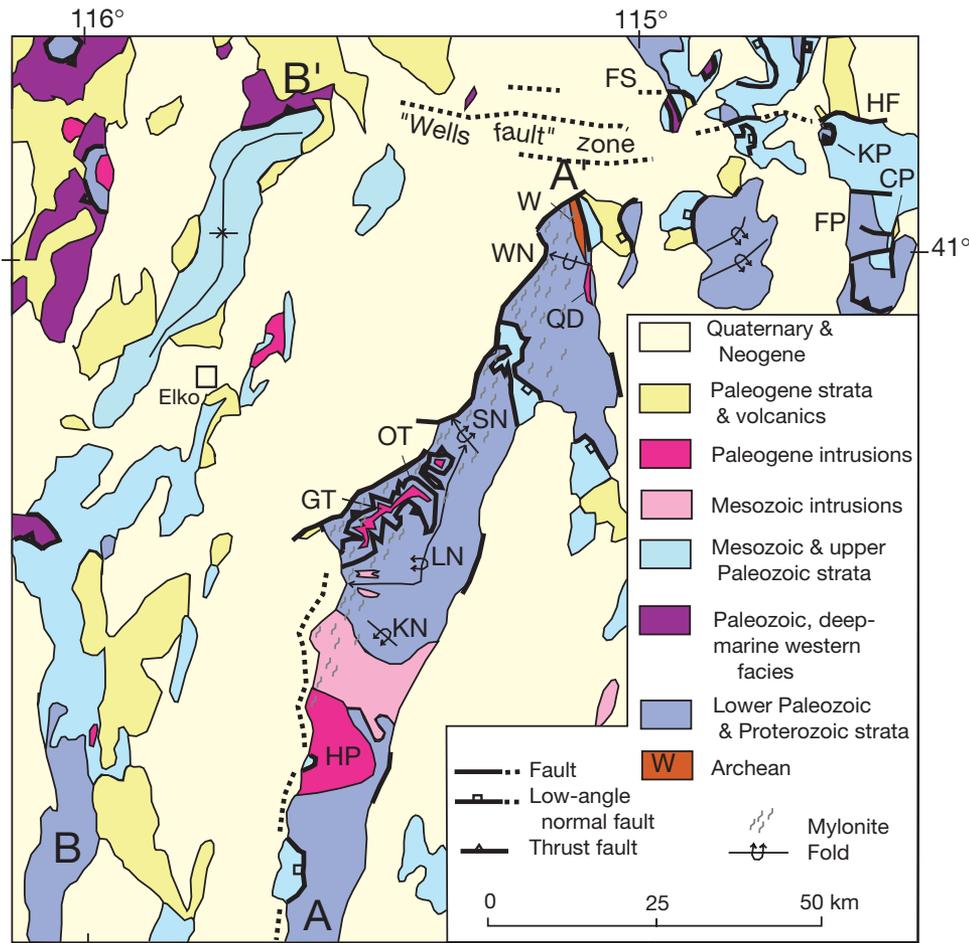


FIG. 4. Geologic map of part of the area of Figure 2, centered on the Ruby-East Humboldt Range. See Figure 2 for names of mountain ranges. A-A' and B-B' are ends of cross section lines. In the Ruby Mountains, GT = gneiss of Thorpe Creek, HP = Harrison Pass pluton, KN = King Peak nappe, LN = Lamoille Canyon nappe, OT = Ogilvie thrust fault, QD = Eocene quartz diorite sheet, SN = Secret Creek nappe. In the East Humboldt Range, W = Archean rocks, WN = Winchell Lake nappe. In the Snake Mountains, FS = Tertiary east-striking fault. In the Pequop Mountains, CP = conglomerate and overlying Eocene volcanic rocks that overlie an east-striking fault, FP = east-striking faults, HF = Holborn fault, and KP = klippe that places Ordovician over Permian rocks.

the metamorphic rocks during extensional exhumation (Snoke and Lush, 1984; Wright and Snoke, 1993; Mueller and Snoke, 1993a).

Paleodepths of the metamorphic complex compiled from mineral-assemblage geobarometry studies (Table 1) show that maximum calculated pressures and depths of burial increase northward in the complex (Fig. 5). Pressures up to 9 kbars corresponding to depths >30 km, calculated for prograde metamorphic mineral assemblages in Neoproterozoic miogeoclinal strata in the East Humboldt Range and Clover Hill, are two to three times the load of stratigraphic burial (McGrew et al., 2000). The amount of tectonic burial and subsequent denudation exceeds that of most other Cordilleran core metamorphic complexes. The overload is

thought to apply to times of maximum crustal thickening in the Late Cretaceous or earlier (Hodges et al., 1992; Camilleri and Chamberlain, 1997; McGrew et al., 2000). Geobarometric pressure determinations, and inferred tectonic burial of Cambrian and Neoproterozoic strata, decrease both southward in the Ruby Mountains and eastward to the Wood Hills. Indicated maximum metamorphic temperatures decrease eastward to the Pequop Mountains and southward to Spruce Mountain, where lower Paleozoic strata contain only lower greenschist facies effects, and higher strata are subgreenschist facies (Thorman, 1970; Harris et al., 1980; Camilleri and Chamberlain, 1997).

Pressures determined for mineral assemblages formed during Tertiary mylonitization range from 3.1 to 5 kbars (Table 1;

TABLE 1. Mineral Geobarometry in the Ruby Mountains Metamorphic Complex¹

Locality and rock	Km NNE of A (Figs. 2, 4, 5, 6)	P (kbars)	Depth equivalent (km)	T (°C)	Event	Estimated age (Ma)	Reference
<u>Ruby Mountains-East Humboldt Range</u>							
Harrison Pass pluton ²	25	~3	~10–12	~250–500 ³	Intrusion	36	Barnes et al., 2001
Dawley Canyon area							
Neoproterozoic(?) pelite	30–32	(2.6)–3.7 3.5–4.7	(>10)–14 13–18	400–570 540–660	1st metamorphism (M1) 2nd metamorphism (M2)	~153 ~153 ⁴	Hudec, 1992 Hudec, 1992
Mahew Creek area							
Neoproterozoic pelite	42	4–4.5	15–17	500–550	2nd metamorphism (M2)	~85 ⁴	Jones, 1999
Ruby Mountains	30–85	3.4–6.5	12–24	365–700	Metamorphism	?various	Kistler et al., 1981; Hudec, 1992
Upper Lamoille Canyon							
Granitoids ⁵	57	5.5–6.5	21–25	~300 ⁶	Intrusion	29	Snoke et al., 1999
<u>Northern Ruby Mountains and southern East Humboldt Range</u>							
Unmylonitized schist	78–92	5.9–6.7 3.6–4.3	22–25 13–16	680–780 550–600	Metamorphism Mylonitization nearby	~75 40–20 [?]	Hodges et al., 1992 Hodges et al., 1992
<u>Southern East Humboldt Range</u>							
Mylonite	95	3.1–3.7	13–14	600	Mylonitization	40–20 [?]	Hurlow et al., 1991
<u>Eastern East Humboldt Range</u>							
Mafic rock ⁷	110	9.5	36	800	Metamorphism	>85 [?]	McGrew et al., 2000
Pelite (shallow level)	104–110	6.0–8.5	22–32	630–700	Progressive retrogression	85–50 [?]	McGrew et al., 2000
Pelite (deep level)	104–110	5.0–9.4	18–33	650–750	Retrogression and new metamorphism	85–30 [?]	McGrew et al., 2000
Pelite (mylonitic)	94	5 ± 1.4	19 ± 5	630 ± 100	Mylonitization	~40–20 [?]	McGrew et al., 2000
Quartz diorite sill ⁵	102–110	4.5–5.5	17–21	~500	Intrusion	40	McGrew and Snee, 1994
<u>East of East Humboldt Range</u>							
<u>Clover Hill</u>							
Neoproterozoic pelite	115	~9.7–10.5	~37–40	~500–540	Metamorphism	>115 [?]	Hodges et al., 1992
	115	4.2–5.8	16–22	580–620	Overprint	<45 ^{??}	Hodges et al., 1992
<u>Wood Hills</u>							
Cambrian pelite	110	5.5–6.4	20–24	530–650	Retrogression	<115	Hodges et al., 1992

¹Estimated pressure and ambient temperature determined from metamorphic mineral assemblage compositions in pelitic and quartzfeldspathic rocks except where noted

²Miarolitic cavities present; authors estimated pressure as lower than indicated (3.6 ± 0.3 to 5.4 ± 0.6 kbar) by Al-in-hornblende barometry

³Temperature of subgreenschist- to amphibolite-facies host rocks (Burton, 1997)

⁴Hudec (1992) and Jones (1999) differed in their interpretations of the age of their M2 metamorphic event

⁵Pressure determined by Al-in-hornblende technique for granitoids; temperature shown is for host rocks

⁶Temperature of host rocks at biotite Ar closure temperature based on 25–30 Ma biotite K-Ar dates (Armstrong and Hansen, 1966; Kistler et al., 1981)

⁷Pressure-temperature conditions determined from mafic metamorphic mineral assemblage

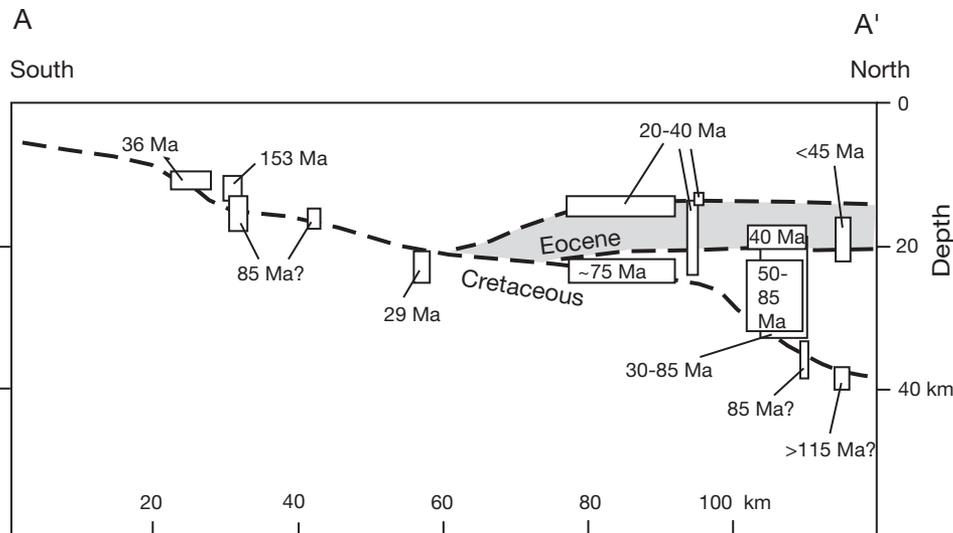


FIG. 5. Burial depths along A-A' (Figs. 2, 4) estimated from rocks in the Ruby Mountains metamorphic core complex from mineral geobarometry, showing age estimates for the mineral assemblage used (Table 1). Depth determinations refer to currently exposed rocks, mostly at Neoproterozoic and Cambrian stratigraphic levels but locally higher, whose maximum stratigraphic overburden ranged from about 5 to 13 km. Possible depth profiles (dashed) of the current level of exposure are shown both for the time of maximum burial (Late Cretaceous?) and during formation of secondary mineral assemblages related to mylonitization (Eocene?-Miocene). Maximum burial depths were greatest in the north. By the time of mid-Tertiary mylonitization, indicated burial depths are more uniform, implying that the most overthickened northern region had already experienced partial denudation.

Hurlow et al., 1991; Hodges et al., 1992; McGrew et al., 2000). A preliminary aluminum-in-hornblende pressure estimate of 4.5 to 5.5 kbars was reported for a late Eocene sill in the East Humboldt Range (McGrew and Snee, 1994), and similar estimates were reported for late Oligocene (29 Ma) intrusions in the Ruby Mountains (Snoko et al., 1999). Intrusion of the circa 36 Ma Harrison Pass pluton at the south end of the metamorphic core was shallower, estimated by Barnes et al. (2001) to be at pressures of about 3 kbar.

Timing of exhumation

Decompression and exhumation of the core complex included an early stage dated uncertainly as before late Eocene(?) or older and a better-dated late Oligocene-Miocene stage (McGrew and Snee, 1994). Metamorphic rocks in the East Humboldt Range show a clockwise pressure-temperature path with decompression indicating that they may have experienced as much as 10 km of unroofing in the first stage (McGrew and others, 2000). This unroofing may have occurred by middle Eocene time or earlier, on the basis of complex hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra that suggest a range of early Tertiary cooling ages (Dallmeyer et al., 1986; McGrew and Snee, 1994). Thermochronologic studies of these and other metamorphic core-complex rocks in and near northeastern Nevada have attributed early Tertiary ages to Eocene cooling by extensional unroofing (Dallmeyer et al., 1986; McGrew and Snee, 1994; Lee, 1995; McGrew et al., 2000; Wells et al., 2000; Wells, 2001). Apparent hornblende ages in the East Humboldt Range young downward, from ~60 to ~30 Ma within an exposed altitude interval of ~0.5 km (McGrew and Snee, 1994). This observation could be interpreted to suggest that the first stage of major exhumation was

older and that this Paleocene to Oligocene interval reflects very slow (~0.02 mm/yr) unroofing. The timing of early unroofing of the East Humboldt Range therefore remains uncertain.

The burial depths at various times (summarized in Fig. 5) suggest that the north part of the core complex lost one third to one half of its load in the first stage of exhumation (McGrew et al., 2000). Rocks in the central part of the core complex lack kyanite and were never buried so deeply as in the north, and yet magmatic hornblende geobarometry suggests they were still at apparent depths of 21 to 25 km in late Oligocene time (Snoko et al., 1999). This suggests that first-stage exhumation primarily involved the overthickened northern area, in accord with the idea that extensional collapse in the Basin and Range province was focused in the most overthickened areas (Coney and Harms, 1984; Spencer and Reynolds, 1990). The climactic second stage of exhumation affected the entire Ruby-East Humboldt core complex and peaked in the Miocene, when rapid denudation is documented by quenched mineral ages and clasts that were shed into sedimentary basins (Smith and Ketner, 1976b; Dokka et al., 1986). Other core complexes in the Great Basin also show evidence of Miocene quenching attributed to a phase of rapid extensional denudation (Dumitru et al., 2000).

West-rooted extensional shear zone

Structures listed in Table 2 all point to westward rooting of the fault zone and major west-directed tectonic unroofing of the core complex. These features include westward dip of the mylonitic shear zone, top-to-west shear indicators such as mylonitic stretching lineation and foliation and shear (S-C) fabrics as well as disharmonic folds, westward younging of

TABLE 2. Evidence That West-Rooted Extensional Shear and Faulting Unroofed the Core Complex

Feature	Evidence
Mylonite-zone dip	The mylonitic shear-zone carapace dips and roots dominantly westward or northwestward except where locally domed (Snoke, 1980, 1992; Howard, 1987, 2000; Mueller and Snoke, 1993a)
Mylonite fabric	The stretching lineation in the mylonites, indicating shear azimuth, strikes consistently to the west-northwest (275°–290° azimuth) throughout the northern Ruby Mountains and East Humboldt Range (Howard, 1980; Snoke and Lush, 1984); structural indicators in the mylonites such as S-C intersections indicate dominantly top-to-west shear, only locally top-to-the-east (Snoke and Lush, 1984)
Disharmonic folds	The disharmonic Soldier Creek nappe and most outcrop-scale disharmonic folds in the mylonitic shear zone show top-to-west drag directly down the azimuth of the stretching lineation (Howard, 1966, 1968, 1980)
Cooling ages	Biotite K-Ar and apatite and zircon fission-track cooling ages in the infrastructure and mylonitic carapace range from about 35 to 9 Ma in the Ruby Mountains-East Humboldt Range and consistently young westward, indicating an eastward-tilted section, or progressive quenching beneath a west-moving upper plate (Kistler et al., 1981; Blackwell et al., 1985; Reese, 1986; Hudec, 1990; McGrew and Snee, 1994)
Tilted Tertiary beds	Tertiary strata flanking the core complex and in several ranges on either side dip dominantly eastward into a series of west-dipping normal faults (Muffler, 1964; Hope, 1972; Smith and Howard, 1977; Stewart and Carlson, 1977; Smith and Ketner, 1978; Snoke, 1980, 1992; Fink and van de Kamp, 1992; Hazlett et al., 1992; Schalla, 1992); hanging-wall Eocene strata on the west flank of the Ruby Mountains dip more steeply than upper Miocene strata (Smith and Howard, 1977), suggesting that tilting progressed before and after the late Miocene
Fault striae	Fault striae at the base of extensional klippen trend 310° near Harrison Pass (Burton, 1997); semi-ductile “hot slickenlines” below klippen on the west side of the Ruby Mountains 25 km to the north trend an average 270°; slickenside striae there are more variable in orientation; Smith and Howard’s (1977) earlier interpreted the klippen as thrust faulted, but the faults superpose nonmylonitic, low-grade, lower Paleozoic strata onto higher-grade mylonites and thus attenuate structural section; some of the faults place older over younger strata and so can be inferred to excise parts of older structures (such as the King Peak or Lamoille Canyon nappes)
Normal faults at north flank of core complex	Mueller (1993), Mueller and Snoke (1993a), and Mueller et al. (1999) concluded there are three systems of low-angle normal faults at the north end of the core complex: an early Tertiary one and a Neogene-Quaternary one both down to west, and an intermediate-age one (mapped only north of the core complex) down to east
Dip of west-flanking normal faults	Mapped west- or northwest-dipping normal faults showing movement into the late Quaternary bound the west flank of the Ruby-East Humboldt Range (Sharp, 1939; Mueller and Snoke, 1993a; Howard, 2000); seismic reflection profiles across the range-front fault system suggest it dips about 20° NW off the Ruby Mountains and East Humboldt Range below a half graben of southeast-dipping strata (Effimoff and Pinezich, 1981; Reese, 1986; Smith et al., 1989; Hazlett et al., 1992; Sartaruga and Johnson, 2000)

cooling ages in the footwall, eastward-tilted Tertiary strata in allochthonous fault striae, and mapped and seismically imaged west-rooted faults. Cooling ages of 20 to 25 Ma that record climactic quenching of the core complex rocks (Dokka et al., 1986) imply that an Eocene reconstruction of the Ruby-East Humboldt Range should restore much of the unroofing.

In the mylonitic shear zone, rock units and lithologic layering thin markedly (Howard, 1980; Snoke, 1980; Snoke and Lush, 1984). Mylonitization, although it possibly began in Eocene or earlier time, affected 29 Ma intrusive rocks and was finished by 25 to 20 Ma as determined from cooling ages. It thus operated between 29 and 20 Ma (Dallmeyer et al., 1986; Dokka et al., 1986; Wright and Snoke, 1993; McGrew and Snee, 1994; McGrew et al., 2000).

Superposed low-angle normal faults further attenuated the crustal section, forming a series of klippen that place mostly younger above older rocks and displace rocks as young as 13 Ma (Smith and Howard, 1977; Snoke, 1980, 1992). The mylonites and the low-angle faults record a plastic-to-brittle sequence of shoaling depths of extensional shearing, preserved as the shear zone and deeper infrastructure rose updip to shallower and cooler levels as the core complex was being

unroofed (Snoke et al., 1997). Down-to-west normal faults in the Pequop Mountains and in Spruce Mountain, about 50 km east of the Ruby-East Humboldt Range, suggest the site of major breakaway for the extensional allochthons (Hope, 1972; Camilleri and Chamberlain, 1998). Normal faults in the core complex were domed to shallow dips, a typical feature of core complexes that results from unloading and isostatic doming (Buck, 1988). West-dipping faults as young as Holocene have continued the sequential unroofing of the core complex.

North boundary of the core complex—A transfer zone?

The north boundary of the core complex forms a significant element in the extensional picture (Mueller and Snoke, 1993a). Below I speculate that an extensional transfer fault occurs at this boundary, which could bear on restoring the amount of separation on the extensional fault system.

The exposed core complex plunges northward beneath cover rocks in the vicinity of Wells, Nevada, near a zone of east-striking faults (Mueller and Snoke, 1993a; Camilleri and Chamberlain, 1997). Cenozoic extension appears greater south of this zone, which may mark a boundary in the extensional pattern (Newman and Witter, 1992; Mueller and

Snoke, 1993a). Thorman (1970), Poole et al. (1977), and Thorman and Ketner (1979) proposed that a west-northwest-striking "Wells fault" zone projects through this area and offsets allochthons and facies in a dextral sense for roughly 70 km. Some authors disagreed that facies offsets were systematically this great or that a fault was needed to explain them (Coats and Riva, 1983; Coats, 1987). However, Paleozoic and Triassic stratigraphic facies exposed in the northern Adobe Range match closely to the facies in the southern Snake Mountains about 65 km in a dextral sense to the east (Thorman and Brooks, 1988). The dextral offset appears to postdate Jurassic or Cretaceous folding of the Adobe syncline, but its timing is not well constrained (Stewart, 1980).

East-striking faults in or near the proposed "Wells fault" zone include the Holborn fault (HF in Fig. 4). It bounds the north end of the core complex in the northern Pequop Mountains and Windermere Hills (Mueller et al., 1999). The Holborn fault displaces, with a normal component, Tertiary rocks that were deposited after 35 Ma, and 15 Ma strata lap across the fault. Its east strike and shallow-to-steep northward dip contrast with two west-rooted and one east-rooted nearby faults that Mueller (1993) inferred as extensional faults that unroofed the core complex. A west-northwest-striking fault that cuts Paleozoic rocks in the Snake Mountains (FS in Fig. 4) bends abruptly around exposures of Paleogene volcanic and sedimentary rocks (Thorman and Brooks, 1988) in a manner that suggests it is a dextral tear fault in a postvolcanic extensional fault system. An east-striking fault in the northern Pequop Mountains predates 41 Ma Eocene volcanic rocks (CP in Fig. 4; Brooks et al., 1995; Camilleri and Chamberlain, 1997). The synextensional age of some of these faults is the basis for the interpretation that the "Wells fault" may be a long-lived east-striking transfer fault zone in the Cenozoic extensional pattern, bounding the highly extended core-complex domain to the south. If so, the estimated 60 to 70 km dextral offset of the "Wells fault" zone may mark the offset of hanging-wall blocks across the fault zone and may approximate their offset above the metamorphic footwall on the south side of the zone. The "Wells fault" zone is cut by the youngest Neogene part of the west-dipping normal fault system that fronts the west side of the core complex (Mueller and Snoke, 1993a). The "Wells fault" zone possibly is reactivated from Mesozoic structures, but in any case it parallels other synextensional transfer faults and accommodation zones of similar length produced during Cenozoic extension of the Basin and Range province (Stewart, 1998; Faulds and Stewart, 1998; Dubendorfer and Black, 1992).

Separation of hanging wall and core-complex footwall

If dominant westward-directed unroofing is assumed (Table 2), the metamorphic rocks of the core complex once were overlain by rocks exposed somewhere to the west. How far west these rocks were transported depends on the total separation on the detachment fault system, on whether any of the unroofing sequence was east directed, as Mueller (1993) indicated for areas north of the Holborn fault, and on the partition of extension into post-Eocene and earlier phases. The northward increase of maximum structural burial depths in the core complex (Fig. 5) and the northward increase in thickness of the mylonitic shear zone (Mueller and Snoke, 1993a)

both imply that early tectonic unroofing was greatest in the north. Perhaps detachment-fault displacement was greatest there too. As extensional faults in the Basin and Range province appear to sole in plastic middle crust at depths of about 10 to 15 km (e.g., Wernicke, 1992), it is unclear how rocks were exhumed structurally from >30 km depth. Either cold geotherms allowed initial fault systems to penetrate this deep, or sequential exhumation proceeded in stages along multiple fault systems. The early phase of exhumation, which halved the tectonic load above the north part of the core complex before Miocene(?) time (Fig. 5), therefore may have been along structures other than the now-prominent west-rooted shear zone.

Table 3 calculates partial estimates of horizontal separation or net heave on the detachment system using a variety of approaches and assumptions, although none is definitive. The 50-km width of the metamorphic belt beneath extensional klippen suggests a net horizontal separation of at least 50 km. This separation includes any contributions from eastward-directed or northward-directed unroofing (Mueller and Snoke, 1993a). An approach using shear-strain rate in the mylonite, as estimated from the grain size, requires many assumptions about texture-strain relations, mylonite thickness, fault throw, and initial fault dip; and any estimate of net slip rate is highly uncertain (Hacker et al., 1990, 1992). Another approach attempted in Table 3 incorporates my earlier speculation that the "Wells fault" is a Tertiary transfer zone whose offset (~60–70 km) may approximate the extensional separation.

Yet another approach to finding the horizontal separation makes use of the westward-younging patterns of biotite and apatite mineral dates observed by Kistler et al. (1981) and Reese (1986) across the footwall metamorphic rocks. The patterns may simply reflect an east-tilted section through a zone of partial age retention (Kistler et al., 1981; Blackwell et al., 1985). If instead the westward younging patterns record sequential quenching below an unroofing fault (McGrew and Snee, 1994), the indicated net rate of horizontal separation are ~0.5 to ~1.2 km/m.y. (Table 3). This rate is a half to a whole order of magnitude slower than at core complexes in the Colorado River extensional corridor or the Aegean Sea (Foster et al., 1993; John and Foster, 1993; John and Howard, 1995). Thermochronologic transect studies in progress across the core complex are attempting to test further for any fast early Miocene spurt of westward-directed unroofing. Otherwise the present evidence is consistent with a rate of lateral unroofing that was slower than for other core complexes. The various results in Table 3 are consistent with net separation of the Ruby-East Humboldt metamorphic core from its roof rocks of 50 km or more, comparable to the core complexes in the Colorado River extensional corridor (Reynolds and Spencer, 1985; Howard and John, 1987; Hillhouse and Wells, 1991). Location of the hanging wall of the Ruby-East Humboldt metamorphic complex ~50 km westward or west-northwestward would suggest that the high-grade rocks once lay approximately beneath the upper crustal rocks exposed in the Piñon Range and Adobe Range as earlier suggested (Jansma and Speed, 1990; Howard, 1992; Newman and Witter, 1992). The following discussion assumes this possible restoration as a guide to integrating the geology of the upper and middle crust.

TABLE 3. Possible Amounts of East-West Separation across Ruby Mountains Detachment Fault System Using Different Assumptions

Evidence	Assumptions	Horizontal rate (km/m.y.)	Time interval	Calculated net westward heave of upper plate (km)
Footwall metamorphic belt, 53 km exposed width (Camilleri and Chamberlain, 1997)	Minimum separation indicated by footwall width; ignore postdetachment Basin and Range extension	—	Cenozoic	≥53
Paleozoic facies separated 65 to 70 km dextrally across east-west “Wells fault” zone; individual east-west faults in zone range from pre-41 Ma to between 35 and 15 Ma (Thorman and Brooks, 1988; Brooks et al., 1995; Camilleri and Chamberlain, 1997; Mueller et al., 1999)	“Wells fault” bounds the Ruby Mountains core complex as an extensional transfer zone; all slip is east-west	—	Tertiary	65–70
Grain size of mylonite in Ruby Mountains and East Humboldt Range	Strain rates postulated to be calculable from grain size; example rate assumes mylonite zone 1.5 km thick, 15° original dip, 15 km throw (Hacker et al., 1990); inferred strain rate increased ~2.6 times by Hacker et al. (1992)	~57	Tertiary	
Apatite fission-track ages young westward across Ruby Mountains at rate of 1–2 m.y./km (data from Reese, 1986)	Dates are cooling ages; rock quenched by west-directed unroofing	0.5–1	18–10 Ma	4–8
K-Ar biotite ages young westward across Ruby Mountains and East Humboldt Range at ~0.8 m.y./km (Kistler et al., 1981; McGrew and Snee, 1994)	Dates are cooling ages; rocks quenched by west-directed unroofing (cf. Foster et al., 1993); cooling slightly lags displacement (Ketchum, 1996); invalid if dates instead record oblique section through a zone of partial argon retention	~1.2	35–20 Ma	18

Integrated Crustal Section

Two stacked sections

A suggested Eocene north-south cross section (Fig. 6) uses a section of the Piñon Range and Adobe Range to portray the upper crust and a section along the exposed core complex for the deeper crust. Vertical separation is greater in the north than in the south, but for this simple restoration no north-south variation in horizontal separation is assumed. The two sections portrayed in Figure 6 may not have been exactly stacked, but they likely typify the crustal levels portrayed. The Carlin gold trend lies mostly west of the Piñon and Adobe Ranges and obliquely intersects section B-B' in Figure 6.

Eocene depths of the metamorphic and igneous rocks in section A-A' (Fig. 6) were assumed from the geobarometric estimates graphed in Figure 5. Important caveats are that an Eocene timing for the geobarometry of the mylonitic mineral assemblages (in the northern third of the core complex) is uncertain, and that the geobarometric results yield a broad range of depth estimates.

Extensional unroofing was least in the southern area depicted in Figures 5 and 6, so the southern Piñon Range may not restore as far east as the Ruby Mountains. Sinistral faulting and counterclockwise rotation in the southernmost Ruby Mountains and the hanging wall to the west may reflect accommodation to the differential extension (Palmer et al., 1991; Nutt and Good, 1998).

Eocene depths as shown for the East Humboldt Range (northern end of A-A') correspond to about half of the maximum calculated pressures (Fig. 5), following the conclusion

of McGrew et al. (2000) that sequentially lower pressures resulted from partial unroofing by late Eocene time. Crustal thickness in the Eocene before thinning to the present thickness is unknown. Stoerzel and Smithson (1998) modeled present crustal structure below the Ruby Mountains as a series of deep and middle crustal layers that thicken northward at the expense of shallower, lower-velocity layers, and a Moho that deepens northward from 32 to 35 km. Sataruga and Johnson (1998) offered a less asymmetric velocity model. Such models probably serve as poor guides to the Eocene crustal structure, because the deep crust likely experienced major change during accommodation to post-Eocene extension (Gans, 1987; Wernicke, 1992; MacCready et al., 1997).

Structure in the deep Eocene crust

The late Eocene Harrison Pass granodiorite pluton in the central Ruby Mountains intruded a boundary zone separating a homoclinal section of low metamorphic grade Paleozoic strata to the south from deformed metamorphosed strata and leucogranite to the north (Fig. 6). Mesozoic andalusite and sillimanite metamorphic assemblages in Cambrian and Neoproterozoic rocks in the central Ruby Mountains pass northward to sillimanite assemblages in the northern Ruby Mountains and to kyanite-bearing assemblages in the East Humboldt Range, Clover Hill, and Wood Hills (Thorman, 1970; Hodges et al., 1992; Hudec, 1992; Snoke, 1992; Jones, 1999; McGrew et al., 2000). Mesozoic leucogranites inflate the exposed infrastructure by a factor of two, decreasing upward (Howard et al., 1979; Howard, 1980, 2000; McGrew et al., 2000). The leucogranites were derived by crustal anatexis

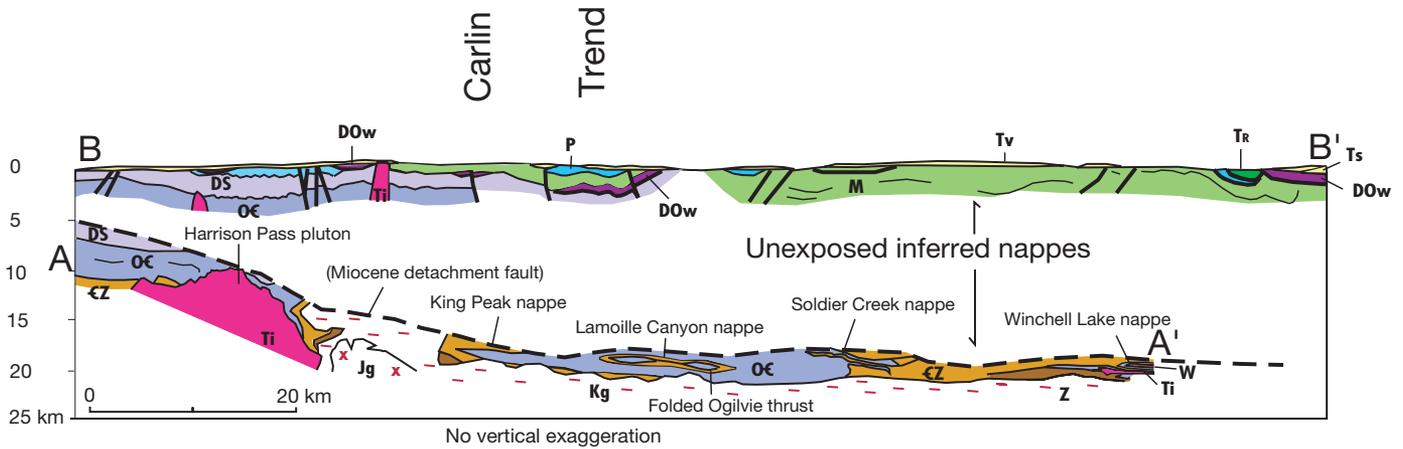


FIG. 6. North-south structure section through possible Eocene restoration of the crust along line B-B', integrated with section A-A' below it (Figs. 2, 4), guided by depths for A-A' indicated in Figure 4. A-A' and B-B' are here considered to provide representative sections of their crustal levels whether or not B-B' restores directly above A-A'. The miogeoclinal section is duplicated at A-A' and B-B' levels, and further structural duplications are inferred to occupy the mostly unexposed intervening interval. Strata shown in the northern two thirds of A-A' are inflated 30 to 70 percent by Cretaceous leucogranite. The upper part of section (B-B') is interpreted from a cross section of the Piñon Range by Smith and Ketner (1978), and maps and sections of the Adobe Range by Ketner (1973), Silitonga (1974), Solomon and Moore (1982), Coats (1987), and Ketner and Alpha (1992). Lower part of section (A-A') is interpreted from cross sections of the Ruby Mountains by Howard et al. (1979), of the East Humboldt Range by Snoke et al. (1997), and from a projection of the Harrison Pass pluton (assuming the pluton is tilted west 30°) after Burton et al. (1997). Rock units are as follows: EZ = Cambrian and Neoproterozoic quartzite, DOw = allochthonous Devonian to Ordovician western and transitional facies, DS = Devonian and Silurian eastern facies, Jg = Jurassic leucogranite, Kg = Cretaceous leucogranite gneiss and rafts of country rock, M = Pennsylvanian and Mississippian, OC = Ordovician and Cambrian eastern-facies carbonates and shale, P = Permian and Pennsylvanian strata, Ti = Eocene to early Oligocene intrusions, Ts = Eocene sedimentary rocks (folded and eroded from view in the left part of the section), Tr = Triassic, Tv = Eocene to lower Oligocene volcanic rocks, W = Archean and Paleoproterozoic(?) basement gneisses, Z = Neoproterozoic pelite and quartzite.

(Kistler et al., 1981; Lee and Barnes, 1997; Batum, 1999; McGrew et al., 2000). Stable isotope and petrologic studies indicate that high-temperature, H₂O-rich fluid infiltration and metasomatism affected the marbles (Peters and Wickham, 1994, 1995). Silver-bearing skarns are associated with Mesozoic granites in the metamorphic complex, but they contain no gold that might be suggestive of roots to the Carlin-type gold deposits (Berger and Oscarson, 1998).

Tectonic complexity in the Ruby-East Humboldt Range infrastructure increases northward (Fig. 6). Northward structural plunges and the presence of stacked nappes in the north that include Precambrian basement are consistent with the greater tectonic loading in the north that is implied by mineral assemblage data (Fig. 5).

The exposed structures in the metamorphic complex include thrusts, fold nappes, and recumbently folded thrusts involving miogeoclinal strata (Fig. 6). The structures show strikingly diverse vergence. During metamorphism, Late Cretaceous(?) folding produced the southeastward overturned Lamoille Canyon fold nappe and the north-northeastward-overturned King Peak fold nappe in the Ruby Mountains, and northwestward-overturned folds in the Wood Hills (Fig. 4; Thorman, 1970; Howard, 1980, 1987; Camilleri and Chamberlain, 1997; Jones, 1999; McGrew et al., 2000). The initially Mesozoic(?) Soldier Creek fold-thrust nappe (SN in Fig. 4) and the next-higher recumbent synclines in the northern Ruby Mountains (Howard, 1980; Snoke, 1980) are stretched owing to Tertiary extensional shearing, but they show westward vergence that is probably inherited from

Mesozoic folds. Metamorphosed thrust(?) slices that duplicate the section a few kilometers north of the Secret Creek nappe (Snoke, 1980; Valasek et al., 1989), and the Archean basement-cored Winchell Lake fold nappe (Fig. 4) together with fault sheets that it folds (Lush et al., 1988; McGrew et al., 2000), are so modified by Tertiary extensional shearing that the original vergence, facing, and attenuated thicknesses are indeterminate.

A middle crust inflated by pre-Eocene tectonic thickening

Figure 5 portrays the overthickened north part of the section as substantially attenuated by Eocene(?) time (McGrew and Snee, 1994; McGrew et al., 2000). McGrew et al. (2000) deduced that pressures and depths for rocks in the East Humboldt Range had by 40 to 50 Ma decreased by a factor of two or more from their maxima. Mesozoic tectonic loading was less for rocks to the south in the Ruby Mountains, which are not known to have undergone attenuation by Eocene time, because hornblende barometry implies that rocks exposed in Lamoille Canyon were still at substantial depth when late Oligocene granitoids were emplaced.

The tectonic load resulted from episodic crustal thickening by telescoping from mid-Paleozoic through Mesozoic time, especially in the Cretaceous (Riva, 1970; Smith and Ketner, 1976a, 1978; Thorman et al., 1991; Hodges et al., 1992; Smith et al., 1993; Miller and Hoisch, 1995; Camilleri et al., 1997; Jones, 1999; Taylor et al., 2000). The abundance of Mesozoic granites is greatest on the north side of the Harrison Pass pluton, decreases northward, and decreases structurally upward

in the northern Ruby Mountains and East Humboldt Range; it decreases eastward into the lower-amphibolite facies rocks of the Wood Hills, which contain only isolated pegmatites. This abundance pattern suggests that granites contributed only a fraction of the now-removed tectonic load from above the Ruby Mountains core complex. Instead, the regional geology suggests that this tectonic load consisted dominantly of cryptic Mesozoic thrust sheets and other nappes.

Extensional klippen that structurally overlie the deep crustal rocks of the core complex provide glimpses of the now-dismembered crustal interval that once overlay the deep rocks. These klippen include stacks of thin slivers in the southern East Humboldt Range, each placing lower-grade rocks on higher-grade rocks (Snoke, 1980, 1998; Snoke et al., 1997). Most place younger strata above older strata, but some show the opposite relation, suggestive of preextension thrust-duplicated sections. The klippen probably are displaced westward many kilometers relative to the metamorphic footwall they overlie. Incomplete stratigraphic sections and the scarcity of allochthonous granites beheaded from the migmatitic footwall indicate that these klippen record only a small, fragmentary sample of the preextension load that geobarometry results imply was above the metamorphic complex. Camilleri and McGrew (1997) pointed out that preextension structural duplication is required in the Wood Hills where an extensional fault separates a klippe of unmetamorphosed Devonian to Permian strata from a footwall where the same strata are metamorphosed. Mueller et al. (1999) interpreted a klippe of Ordovician miogeoclinal rocks, faulted in the northern Pequop Mountains onto Permian rocks in the core-complex footwall (KP in Fig. 4), to be superposed by means of extensional faulting from an inferred higher, older-above-younger thrust plate of Ordovician and younger rocks.

The core-complex domain lacks thick, up-ended, intact, allochthonous tilt blocks that at other highly extended corridors in the Basin and Range province commonly expose sections throughout 8 to 15 km of the upper crust (Anderson, 1971; Proffett, 1977; Howard and John, 1987; Fryxell et al., 1992; Howard and Foster, 1996; Howard et al., 2000). In their absence, I conclude that upper crust denuded from the Ruby-East Humboldt core complex remains largely upright and hidden, and it underpins exposed hanging-wall rocks to the west.

Camilleri and Chamberlain (1997, 1998) proposed from facies evidence that the deep burial of core-complex rocks occurred during Cretaceous east-transported thrusting. They judged that a limey facies of the Devonian Roberts Mountains Formation, now in a Tertiary extensional klippe in the Pequop Mountains, had first been deposited farther west and thrust eastward over a correlative dolomitic facies in the underlying metamorphosed footwall (but see Wise, 1998, for a different interpretation). Cryptic preextension east-directed thrusting can similarly explain a possible western provenance for facies of Carboniferous rocks that occupy west-transported extensional klippen in the central and southern Ruby Mountains (Willden et al., 1967; Armstrong, 1972; Burton, 1997).

Any structural load over rocks in the central Ruby Mountains was small by late Eocene time if the ~36 Ma Harrison

Pass pluton was emplaced at ~3 kbars as suggested by Barnes et al. (2001). This value may be a minimum for the upper part of the exposed pluton, given conflicting geobarometric evidence. Geobarometric estimates for plutonic hornblende average ~5.4 kbar for some subunits of the pluton and ~3.6 kbars for others. Possible miarolitic cavities identified near the pluton's roof could imply pressures less than 2 kbars; and metamorphic andalusite in adjacent wall rocks imply intrusion pressures less than 4 kbars if the andalusite is due to contact metamorphism (Barnes et al., 2001), although Burton (1997) cited textural evidence that the andalusite may predate the pluton. If the pluton intruded at ≥ 10 km depth, the cover for its roof would include about 5 to 7 km of tectonic load added to the normal stratigraphic sequence (Fig. 6).

If the complexity of thrust and fold nappes exposed in the metamorphic rocks is any guide to structural style in the denuded roof, many telescoping structures, not just one thick sheet, provided the tectonic burial required to explain the geobarometric results. The northward increase in Mesozoic geobarometric burial depth implies that a larger structural load was present there, perhaps by more or thicker nappes than were piled above southern parts of the metamorphic complex. Northward plunges of exposed structures (Fig. 6, A-A') support the presence of a greater structural load to the north.

Camilleri and Chamberlain (1997) hypothesized an unexposed, large-throw, east-directed thrust-fault plate to explain the deep tectonic burial in the East Humboldt Range. They also implied in cross section that the basal fault of this plate dives eastward beneath the Goshute-Toano Range (Fig. 2). The small stratigraphic relief of pre-Cretaceous strata unconformably below Paleogene deposits in the hinterland domain (Armstrong, 1968), however, argues against exposure in the Eocene of such a prominent thrust fault. The base of the Paleogene section unconformably overlies Mesozoic strata in the southern Pequop Mountains area, which seem structurally tied to the metamorphic complex as it was mapped by Camilleri and Chamberlain (1997). Furthermore, no clear regional thrust having tens of kilometers displacement is obvious in the exposed hinterland upper crustal section.

Models of tectonic wedging or blind structures (Snoke and Miller, 1988, Fig. 7), or duplexes or a steeply downthrust prong (Miller and Hoisch, 1995; Lewis et al., 1999) have been proposed to explain structural thickening in the region and at the same time attempt to avoid large stratigraphic relief at the surface. Tectonic wedging and associated backthrusting (Wentworth et al., 1984; Price, 1986; Wentworth and Zoback, 1989; Jamison, 1993) could be consistent with the multiple directions of Jurassic and Cretaceous structural transport. As an example, Price's (1986) model for the Mesozoic Canadian Cordillera explained shortening, thickening, and structures showing opposing vergence as caused by a wedge pushed eastward into and under North American sedimentary rocks (Fig. 7).

Eocene Landscape and Upper Crust

To develop an integrated crustal framework for the late Eocene entails a survey of upper crustal features and processes, followed by analysis of processes in the deep crust.

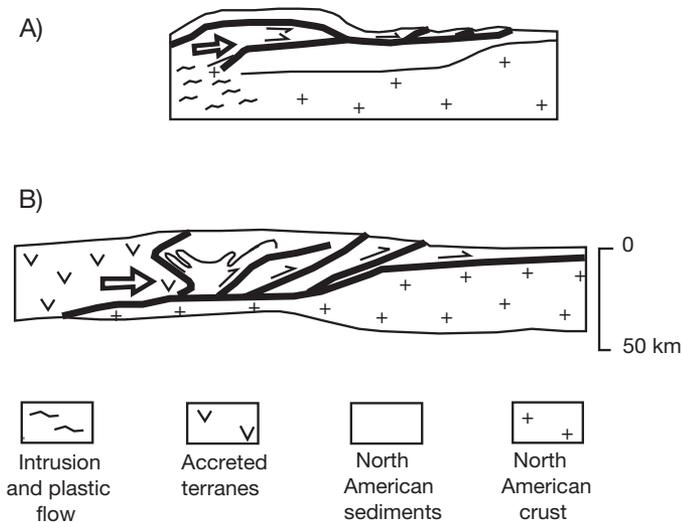


FIG. 7. Two representative wedge models for the Mesozoic Cordillera. A. Snoke and Miller's (1988) model, here modified, for the eastern Great Basin. B. Price's (1986) model of the Canadian Cordillera illustrating how tectonic wedging can develop shortening structures of opposing vergence in the Selkirk structural fan (after Price and Monger, 2000).

Eocene substrate

In middle and late Eocene time, northeastern Nevada exposed a substrate of Paleozoic and Mesozoic rocks onto which Eocene sedimentary rocks and volcanic rocks were deposited in broad alluvial plains and lake basins. In the hinterland domain, Paleogene deposits rest exclusively with little angularity on upper stratigraphic levels of the eastern-facies miogeoclinal sequence (Armstrong, 1968, 1972; Coats, 1987; Brooks et al., 1995). In the core complex domain, the substrate unconformably below Eocene rocks ranges 2 to 4 km in stratigraphic level, from allochthonous Triassic strata in the East Humboldt Range to Devonian strata in the Pequop Mountains (Brooks et al., 1995; Camilleri and Chamberlain, 1997).

In contrast, the Eocene deposits in much of the Elko-Carlin domain lap over a substrate of eroded thrust sheets and folds—mostly of western-facies Paleozoic deep-water and continental-slope deposits and locally of upper Paleozoic overlap facies (Riva, 1970; Oversby, 1972; Smith and Ketner, 1976a, 1978; Miller et al., 1981; Ehman, 1985; Coats, 1987; Ketner and Evans, 1988; Thorman and Brooks, 1988; Smith and Miller, 1990; Ketner and Alpha, 1992). The pre-Eocene substrate in the Cortez Range area consists of Jurassic volcanic rocks and Cretaceous lacustrine and fluvial deposits (Muffler, 1964; Smith and Ketner, 1976b). The Peko Hills (Fig. 2), which likely restore above the northern part of the core complex, expose Eocene(?) strata resting on Paleozoic strata that were complexly folded and thrust faulted in the Mesozoic (Ketner and Evans, 1988; Thorman et al., 1991). Thin-skinned, Mesozoic thrust sheets that carried siliceous, western-facies strata east or south may have capped the northern part of the crustal section—judging, for instance, by the five thin sheets present in the Snake Mountains and the five in the HD Range just north of the section in Figure 6 (Riva, 1970; Coats and Riva, 1983; Thorman and Brooks, 1988; Smith et al., 1990). Such sheets in the Adobe and Piñon

Ranges were eroded by Eocene time and overlapped by Eocene sedimentary rocks (Fig. 6; Smith and Ketner, 1978; Ketner and Ross, 1983).

The upper-crustal substrate to Eocene deposits in north-eastern Nevada is little metamorphosed in the hinterland domain and in the area between the Ruby-East Humboldt core complex and the Piñon and Adobe Ranges. West and north of Elko and Carlin, some Paleozoic strata record paleotemperatures of 300°C or more (Harris et al., 1980; Poole et al., 1983; Cunningham, 1985; Ransom and Hansen, 1990), which may indicate that a substantial cover was eroded before the Eocene. Strata in the area of the Independence district yielded Precambrian fission-track ages on clastic zircon grains that indicate that Phanerozoic paleotemperatures remained less than 200°C (Hofstra et al., 1999).

Eocene lakes and volcanism

Lacustrine deposits of the Elko Formation record a broad Eocene lake system in the Elko-Carlin domain (Fig. 2; Smith and Ketner, 1976a; Solomon et al., 1979; Ketner and Alpha, 1992; Schalla, 1992; Solomon, 1992). The deposits contain oil shale and limestone and are up to 1 km or more thick. Small lakes containing flora indicative of adjacent forested hills were present in the northern part of the Elko-Carlin domain (Axelrod, 1966). Eocene lakes in the hinterland domain formed depocenters for the White Sage Formation along the Utah border and the Sheep Pass Formation in east-central Nevada near Ely (Fig. 1; Fouch, 1979; Dubiel et al., 1996). The Elko Formation mostly is found in the Elko-Carlin domain west and north of the Ruby Mountains. An exception is where the Sohio Ruby Valley no. 1 well encountered a comparable oil-shale-bearing section 20 km east of the Ruby Mountains (Fink and van de Kamp, 1992) and ~20 km west of a breakaway zone of the west-rooted extensional fault system. Vandervoort and Schmidt (1990) suggested that extension following the Sevier orogeny provided the basins for Cretaceous to Eocene lakebeds in eastern Nevada. The Elko Formation thins westward from the Ruby Mountains (Satarugsa and Johnson, 2000), it occupies the hanging wall of the west-dipping Ruby-East Humboldt detachment-fault system, and its basin may mark an early phase of extensional faulting (Henry et al., 2001).

Conglomerate at a similar stratigraphic level underlies Eocene volcanic rocks and laps across faulted upper and middle Paleozoic strata in the northeast part of the core complex domain. In the Pequop Mountains (Brooks et al., 1995; Camilleri and Chamberlain, 1997) the conglomerate is earlier than 41 Ma, and it contains ostracod-bearing siltstone and large boulders derived from granodiorite and the Diamond Peak Formation (Carboniferous). Prevolcanic conglomerate dated between 41 and 39 Ma in the southeastern East Humboldt Range also contains ostracod-bearing clasts derived from lakebeds (Brooks et al., 1995). The stratigraphic and geographic position of these conglomerates suggests they may record Eocene scarps that developed along the eastern border of the Elko Formation lake system.

Calc-alkalic volcanic flows and tuffs dated as late middle Eocene and late Eocene overlie and are interbedded with the Eocene lacustrine strata (Brooks et al., 1995; Henry and Boden, 1998; Henry and Ressel, 2000). The volcanic rocks

and their numerous eruptive centers—the Tuscarora magmatic belt of Christiansen and Yeats (1992) and northeast Nevada volcanic field of Brooks et al. (1995)—mark a midpoint in the early Eocene to Miocene migration of arc-like magmatism southward from British Columbia to southern Nevada (Armstrong and Ward, 1991; Christiansen and Yeats, 1992). The southward migration may relate to steepening or delamination of a formerly shallow-dipping subducting slab (Humphreys, 1995; Sonder and Jones, 1999).

Although the widespread lake deposits suggest that broad basins and low prevolcanic Eocene topographic relief were present in much of eastern Nevada, local unconformities within Eocene sections suggest that active faulting occurred at basin margins (Ehman, 1985; Potter et al., 1995; Mueller et al., 1999). Sedimentary breccias near the East Humboldt Range record late Eocene or Oligocene landslides derived from incipient unroofing of low-grade metamorphic rocks (but not mylonites) in the core complex (Snoko et al., 1990, 1997; Mueller and Snoko, 1993b).

Eocene upper-crustal deformation and dike orientation

Structural and stratigraphic evidence of Eocene to early Oligocene extensional faulting and associated unconformities is scattered through northeastern Nevada (Zoback et al., 1981; Ehman, 1985; Miller, 1990; Seedorff, 1991; Smith et al., 1991; Brooks et al., 1995; Potter et al., 1995; Mueller et al., 1999; Gans et al., 2001; Henry et al., 2001; Muntean et al., 2001). Steep to moderate westward to northwestward pre-Miocene dips of Eocene rocks in the Mount Velma, Bull Run, and Copper Basin areas north of Elko (Coash, 1967; Ehman, 1985; Coats, 1987; Rahl et al., 2002), and a southeastward pre-Miocene dip of Eocene rocks on the west flank of the Ruby Mountains (Smith and Howard, 1977) indicate the strike of Paleogene tilt axes and imply that Paleogene extension was oriented east-west to northwest-southeast. Eocene north- to northwest-trending folds were described near Elko, in the Piñon Range, and in the southernmost Ruby Mountains area (Ketner and Alpha, 1992; Nutt and Good, 1998); they may include local transpressional structures related to extension (Nutt et al., 2000) and drag folds along extensional faults.

Eocene dikes near Tuscarora strike mostly northeastward, whereas Eocene to early Oligocene dikes in the Piñon Range and Emigrant Pass areas strike mostly northward (Smith and Ketner, 1978; Henry and Ressel, 2000; Henry et al., 2001). These orientations suggest that in the Eocene the least compressive stress was oriented northwest-southeast to east-west in the Elko-Carlin domain.

In summary, the regional extent and magnitude of late Eocene extension in northeast Nevada remain indistinct (Seedorff, 1991). Crustal thinning may have included broad subsidence (Henry et al., 2001) and eventual partial dismemberment. The evidence, including cooling-age hints of a Paleogene stage of core-complex exhumation, is consistent with the idea that crust that had been shortened and overthickened by Mesozoic telescoping began to collapse in Late Cretaceous or Paleogene time (Coney, 1987; Vandervoort and Schmidt, 1990; Livaccari, 1991; Hodges and Walker, 1992; Costenius, 1996; Sonder and Jones, 1999). Extensional faulting in the Bull Run and Copper Basin areas north of Elko

accompanied Eocene volcanism (Ehman, 1985; Rahl et al., 2002). The northwest-southeast to east-west orientation of late Eocene to Oligocene extension implied by tilt axes and by dikes was approximately perpendicular to the older Paleozoic and Mesozoic contractional orogen.

Deep Eocene Processes

Magmatism and fluid flow

Deep counterparts to the Eocene calc-alkaline volcanic rocks in the Elko-Carlin area were intruded at depths ≥ 10 km into the metamorphic rocks of the core complex. The bell-jar-shaped ~ 36 Ma Harrison Pass pluton of granodiorite and granite (Fig. 6) partly downfolded its wall rocks, and magmatic stoping partly engulfed its roof of Paleozoic strata (Wright and Snoko, 1993; Burton et al., 1997). Granodiorite magma may have accumulated at a depth ~ 20 km (5.4 ± 0.6 kbars) before rising to the site of the pluton's emplacement at perhaps 10 to 15 km depth (~ 3 kbars?; Barnes et al., 2001). The composite pluton evidently collected several other batches of magma from partial melting sites in Mojave-province crust, mixed in some cases with mantle-derived magmas that provided heat for melting (Barnes et al., 2001). Downfolded wall rocks (Fig. 6) suggest that the pluton's rise may have been matched by return flow in the wall rocks. The pluton's intrusion was close to the time of the first erupted tuffs exposed in adjacent ranges (Palmer et al., 1991; Nutt and Good, 1998; Gordee et al., 2000). Any future evidence that volcanic rocks and shallow intrusions exposed in the Piñon Range were physically connected to the pluton would improve estimates of the extensional fault displacement and would inspire reconstructions of an Eocene magmatic plumbing system.

Farther north in the core complex, sills dated as Eocene by U-Pb methods intruded the metamorphic rocks. The two widest sheets are peraluminous granite (gneiss of Thorpe Creek, 36–39 Ma) and quartz diorite (40 ± 3 Ma), each many kilometers broad (Fig. 4); smaller quartz diorite and granodiorite bodies are dated as ~ 35 to 38 Ma (Howard et al., 1979; McGrew, 1992; Wright and Snoko, 1993; MacCready et al., 1997). The intrusions correlate temporally with eruption of volcanic rocks from widespread centers in the region (Brooks et al., 1995; Henry and Ressel, 2000). In contrast, younger, widespread, and small late Oligocene (~ 29 Ma) granites in the core complex lack many nearby volcanic or intrusive correlates. The dated Eocene sheets in the core complex are attenuated and mylonitized by postintrusion deformation. The gneiss of Thorpe Creek (located in the northern Ruby Mountains) averages less than 100 m thick, and the less extensive largest quartz diorite sheet (in the East Humboldt Range) may average 200 m. Together their bulk is less than an order of magnitude that of the Harrison Pass pluton. Assuming that the pluton averages 3 km thick, a rough volume estimate suggests it is ~ 30 times as voluminous as each of the two sheet intrusions. If the average thickness of crustal section exposed in the metamorphic complex of the Ruby and East Humboldt Ranges is taken as 3 to 4 km, the dated Eocene intrusions account for roughly 10 vol percent.

Stable isotope data from the core complex provide evidence that mantle-derived fluids isotopically homogenized

the deepest exposed metasedimentary rocks during magmatism, and that exchange with meteoric water affected rocks down to the levels of mylonitic rocks close below detachment faults (Grunder and Wickham, 1991; Fricke et al., 1992; Wickham et al., 1993; McGrew and Peters, 1997). The timing of these processes and how they relate to Eocene events remain uncertain.

Flow, extension, shear, and thermal gradient

The subhorizontal Eocene sills that intruded into the metamorphic rocks contrast in their orientation to the steep, commonly north-south dikes in the upper crust. The high Eocene temperatures ($\geq 500^{\circ}\text{C}$) of deep rocks in the East Humboldt Range (McGrew et al., 2000) suggests that they were less prone than the upper crust to maintain elastic stresses for dike intrusion.

MacCready et al. (1997) proposed from fabric evidence that rocks in the Ruby Mountains were undergoing north-south plastic flow below and simultaneously with mid-Tertiary west-directed extensional shearing, which is best dated as younger than 29 Ma. They interpreted the proposed flow as accommodation to isostatic rise in response to greater unroofing in the north than in the south part of the core complex. Such flow may also be consistent with bulging of the middle crust below the northern part of the exposed infrastructure as modeled from seismic data by Stoerzel and Smithson (1998). Whether such plastic flow operated in Eocene time is unknown.

Pressure-temperature conditions, fabrics, and mineral dates established for rocks in the East Humboldt Range suggested to several authors, however, that both crustal attenuation and extensional mylonitic shearing may have been operating there by Eocene time (Dallmeyer et al., 1986; Hurlow et al., 1991; Hodges et al., 1992; Wright and Snoke, 1993; McGrew and Snee, 1994; McGrew et al., 2000). McGrew et al. (2000), using $^{40}\text{Ar}/^{39}\text{Ar}$ data on hornblende and mineralogic pressure-temperature calculations, found a hot and increasing geothermal gradient and proposed its timing to be 50 to 30 Ma, about 30° to $50^{\circ}\text{C}/\text{km}$ at ~ 40 Ma. Those authors pointed out that their clockwise pressure-temperature path, which lowered temperature little during decompression, resembles the path expectable for areas undergoing extension and thinning of the lower crust.

The Eocene intrusive magmas were evidently 300° to 400°C hotter than their host rocks in the core complex, and they brought much more magmatic advective heat to rocks in the Harrison Pass area than to elsewhere in the core complex. A hot Paleogene geothermal gradient as inferred for the East Humboldt Range by McGrew et al. (2000), whether it resulted from Eocene magmatism or exhumation, would be expected to affect Eocene thermal conditions, hydrothermal circulation, and mineralization processes in the upper crust.

Discussion

Late Eocene magmatism and mineralization in northeastern Nevada overlapped temporally with east-west to southeast-northwest extension of the structurally overthickened crust. Earlier Eocene magmatism and coincident extension affected northern parts of the Cordillera before sweeping

southward to Nevada (e.g., Janecke et al., 1997). If the inception of magmatism marks steepening of the underlying subduction zone, slab rollback may have helped to drive the extension (Humphreys, 1995; Sonder and Jones, 1999), or upwelling asthenosphere behind a delaminated slab may have driven magmatism and thermally weakened the overthickened crust to the point of extensional collapse (Muntean et al., 2001).

Dispersed Eocene igneous activity and a geotherm further warmed by crustal thinning can be expected to have powered geothermal circulation of fluids in the upper crust. Down-dropping or sagging in the hanging wall of an early phase of the west-rooted fault system that eventually unroofed the Ruby-East Humboldt core complex may have helped form the Eocene basin into which the Elko Formation was deposited. Eocene lakes signal availability of water for hydrothermal circulation systems with a potential for mineralization.

The Carlin trend of gold deposits (Fig. 2) is mostly west of the section portrayed in Figure 6. No recognized major Cenozoic structure clearly controls the north-northwest orientation of the entire Carlin trend. The trend may instead follow a favorable distribution of facies of Paleozoic host strata (Armstrong et al., 1998), perhaps related to the shape of the Paleozoic continental margin (Tosdal et al., 2000), and capped by impermeable Paleozoic allochthons or strata. The crustal depths of gold mineralization lay well above the structural level of rocks now exposed in the core complex, but late Eocene magmas that ponded in the middle crust could have provided regional deep-seated magmatic or metamorphic fluids for upper crustal mineralization (Hofstra and Cline, 2000).

Nearly isothermal depressurization, raising of geothermal gradients, and some mylonitic shearing in the middle crust all have been attributed to Eocene or older crustal thinning. If this equivocal timing is correct, Figure 8 suggests how some of these conditions may be related to processes in the upper crust. Faulting in the upper crust would be expected to be compatible with an east-west to northwest-southeast direction of Eocene upper crustal extension. Fluid circulation systems driven by normal faulting, by an elevated geotherm, and by heat from intrusions may have interacted with favorable host strata and structures to enhance mineralization at shallow crustal depths.

To the extent that the rocks in the core complex are representative, middle crustal rocks under the Elko region include metamorphosed and structurally duplicated miogeoclinal sections consisting of carbonate, quartzite, and pelite that were shuffled structurally with underlying Archean and Proterozoic basement gneisses and invaded by abundant Mesozoic granite generated by crustal anatexis at depth. None of these rocks has been well documented as providing a source for metals involved in Carlin-type gold deposits.

The Mesozoic crustal thickening required by the large burial depths of rocks in the core complex suggests that a complex of fold and thrust nappes was present, perhaps involving crustal wedging. These structures would be expected to greatly complicate the geometry and blur the expression of any old, deeply penetrating or persistent crustal flaws such as are commonly assumed to form steep electrical conductors or to be responsible for mineral alignments such as the Carlin trend (Rodriguez, 1998; Crafford and Grauch, 2002;

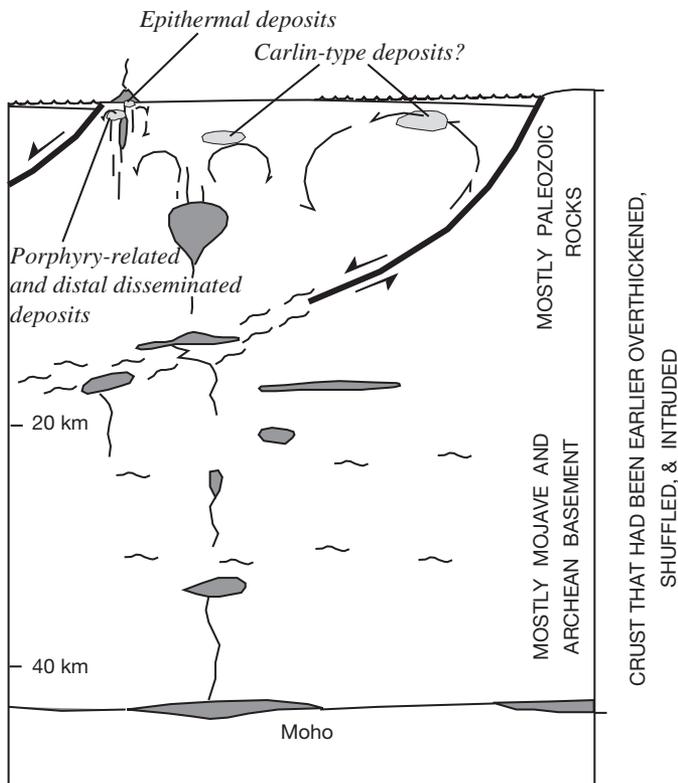


FIG. 8. Possible conditions in the crust in Eocene time in the Elko-Carlin domain. Eocene(?) or earlier partial thinning by normal faulting, shearing, and flow resulted in collapse of crustal isotherms and increase of the thermal gradient. In this model, mafic melts from the mantle interacted with and partly melted deep crust to produce late Eocene calc-alkaline magmas that rose into the middle and upper crust. The magmatic products (shaded dark) formed sheets in the middle crust; formed plutons, necks, and dikes in the upper crust; and erupted as lava and ash that disrupted surface lakes. Deformational episodes had largely detached the upper crust from any ancient crustal roots. Hydrothermal circulation driven by enhanced geothermal gradient, attenuation faulting, and heat of intrusions may have interacted with favorable host strata to help set the stage for various types of mineralization at shallow crustal depths.

Wannamaker and Doerner, 2002; Grauch et al., 2003). Radiogenic isotopes signal the underlying presence of Archean basement in the northern East Humboldt Range, in contrast to most of the Ruby Mountains where isotopic values suggest an underlying more heterogeneous basement province of mixed Archean and Paleoproterozoic heritage (Wright and Snoke, 1993; Barnes et al., 2001). Whether or how the basement-cored nappe, deeper Mesozoic burial, and greater early denudation in the East Humboldt Range compared with the Ruby Mountains may reflect this indistinct relict boundary between provinces is unknown.

Regional isotopic, gravity, and magnetic maps have been interpreted as showing deep crust boundaries aligned along and parallel to the Carlin trend and reflecting the continental edge resulting from Proterozoic rifting (Tosdal et al., 2000; Grauch et al., 2003). Those authors suggested that these features have persisted through time and influenced younger structures and mineralization. The structural shuffling demonstrated in the exposed core complex and its involvement of allochthonous basement, however, predicts much

disruption of any such old regional crustal boundaries and detachment from their roots.

The surface position of any old, deep structures that could have influenced Eocene mineralization would be expected to be displaced or blurred not only by contractional and extensional allochthons but also by flow and melting deep in the crust. The nearly flat Moho observed throughout the Basin and Range province requires deep crustal flow to accommodate large geographic variations in amount of upper crustal extension (Gans, 1987; Wernicke, 1992). In light of the structural shuffling and flow, it is no surprise that proposed isotopic and geophysical crustal boundaries that might relate to mineral belts (Tosdal et al., 2000; Grauch et al., 2003) appear to be gradational through widths of tens of kilometers.

The tectonically shuffled character of the Eocene middle crust implies that the upper-crustal Carlin gold trend did not and does not root in any simple structure or rock body at middle crustal depth. The Carlin trend furthermore strikes obliquely relative to regional Eocene extensional or igneous structures in the upper crust. These structural mismatches could be explained if the structural setting for the Carlin trend of mineralized rocks relates not so much to deeply penetrating Eocene structures but to a relict northwest-striking belt of favorable host-rock conditions in the upper crust. Favorable host rocks may relate to deposition along a Paleozoic continental margin the roots of which have since been disrupted. Low Tertiary dips and low degrees of tectonic extension in the Elko-Carlin domain suggest that it and its contained linear Carlin trend occupy an upper crustal block that, although detached from the middle crust, is relatively little disrupted internally. Regional Eocene magmatic intrusion, normal faulting, enhanced geothermal gradient, crustal thinning, and ponding of surface water in active structural basins are all processes that can be inferred to have helped drive Eocene hydrothermal systems and mineralization in an upper crustal belt of favorable host rocks.

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REFERENCES

- Allmendinger, R.W., and Jordan, T.E., 1981. Mesozoic evolution, hinterland of the Sevier orogenic belt: *Geology*, v. 9, p. 308–313.
 Anderson, R.E., 1971. Thin-skinned distension of Tertiary rocks of southeastern Nevada: *Geological Society of America Bulletin*, v. 82, p. 43–58.
 Arehart, G.B., Chakurian, A.M., Tretbar, D.R., Christensen, J.N., McInnes, B.A., and Donelick, R.A., 2003. Review of radioisotope dating of Carlin-type deposits in the Great Basin, western North America, and implications for deposit genesis: *ECONOMIC GEOLOGY*, v. 98, p. 235–248.
 Armstrong, A.K., Theodore, T.G., Oscarson, R.L., Kotlyar, B.B., Harris, A.G., Bettles, K.H., Lauha, E.A., Hipsley, R.A., Griffen, G.L., Abbot, E.W., and

- Cluer, J.K., 1998, Preliminary facies analysis of Silurian and Devonian rocks that host gold along the Carlin trend, Nevada, in Tosdal, R.M., ed., Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report 98-338, p. 38-63.
- Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429-458.
- 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.
- 1982, Cordilleran metamorphic core complexes from Arizona to southern Canada: Annual Reviews of Earth and Planetary Sciences, v. 10, p. 129-154.
- Armstrong, R.L., and Hansen, Edward, 1966, Cordilleran infrastructure in the eastern Great Basin: American Journal of Science, v. 264, p. 112-127.
- 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.
- Axelrod, D.I., 1966, The Eocene Copper Basin flora of northeastern Nevada: University of California Publications in Geological Sciences, v. 59, 125 p.
- 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, northeastern Nevada: Journal of Petrology, v. 42, p. 901-929.
- Batum, M.A., 1999, Petrology of Late Cretaceous and Cenozoic granitic rocks, East Humboldt Range, northeastern Nevada: Unpublished M.S. thesis, Lubock, Texas Tech University, 167 p.
- Berger, V.L., and Oscarson, R.L., 1998, Tungsten-polymetallic-and barite-mineralized rocks in the Ruby Mountains, Nevada, in Tosdal, R.M., ed., Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report 98-338, p. 151-175.
- Blackwell, D.D., Reese, N.M., and Kelly, S.A., 1985, Evolution of Basin and Range structure in the Ruby Mountains and vicinity, Nevada, in Lucchitta, I., Morgan, P., and Soderblom, L. A., eds., Conference on Heat and Detachment in Crustal Extension on Continents and Planets, Sedona, AZ, Oct. 10-12, 1985, Proceedings: Houston, Texas, Lunar and Planetary Institute, p. 12-14.
- Brooks, W.E., Thorman, C.H., and Snee, L.W., 1995, the $^{40}\text{Ar}/^{39}\text{Ar}$ ages and tectonic setting of the middle Eocene northeast Nevada volcanic field: Journal of Geophysical Research, v. 100, p. 10,403-10,416.
- Buck, W.R., 1988, Flexural rotation of normal faults: Tectonics, v. 7, p. 959-973.
- Burton, B.R., 1997, Structural geology and emplacement history of the Harrison Pass pluton, central Ruby Mountains, Elko County, Nevada: Unpublished Ph.D. dissertation, Laramie, University of Wyoming, 295 p.
- Burton, B.R., Barnes, C.G., Burling, Trina, and Wright, J.E., 1997, Grand tour part 4: Geology and geochemistry of the Harrison Pass pluton, central Ruby Mountains, Nevada, in Link, P.K., and Kowalis, B.J., Proterozoic to Recent stratigraphy, tectonics, and volcanology—Utah, Nevada, southern Idaho, and central Mexico: Brigham Young University Geology Studies, v. 42, Part I, p. 283-292.
- Camilleri, P.A., and Chamberlain, K.R., 1997, Mesozoic tectonics and metamorphism in the Pequoop Mountains and Wood Hills region, northeast Nevada: Implications for the architecture and evolution of the Sevier orogen: Geological Society of America Bulletin, v. 109, p. 74-94.
- 1998 Mesozoic tectonics and metamorphism in the Pequoop Mountains and Wood Hills region, northeast Nevada: Implications for the architecture and evolution of the Sevier orogen; Reply: Geological Society of America Bulletin, v. 110, p. 680-684.
- Camilleri, Phyllis, and McGrew, Allen, 1997, The architecture of the Sevier hinterland: A crustal transect through the Pequoop Mountains, Wood Hills, and East Humboldt Range, Nevada, in Link, P.K., and Kowalis, 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 I, p. 310-324.
- Camilleri, P., Yankee, A., Coogan, J., Decelles, P., McGrew, A., and Wells, M., 1997, Hinterland to foreland transect through the Sevier orogen, northeast Nevada to north central Utah: Structural style, metamorphism, and kinematic history of a large contractional orogenic wedge, in Link, P.K., and Kowalis, 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 I, p. 297-309.
- Chakurian, A., Arehart, G.B., and Donelick, R.A., 2000, Regional apatite fission-track dating of the Carlin trend: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-250.
- 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 Cordilleran orogen, Conterminous U.S.: Geological Society of America, The Geology of North America, v. G-3, p. 261-406.
- Coash, J.R., 1967, Geology of the Mount Velma Quadrangle, Elko County, Nevada: Nevada Bureau of Mines Bulletin 68, 20 p.
- Coats, R.R., 1987, Geology of Elko County, Nevada: Nevada Bureau of Mines and Geology Bulletin 101, 112 p.
- Coats, R.R., and Riva, J.F., 1983, Overlapping overthrust belts of late Paleozoic and Mesozoic ages, northern Elko County, Nevada: Geological Society of America Memoir 157, p. 305-327.
- Coney, P.J., 1980, Cordilleran metamorphic core complexes, an overview: Geological Society of America Memoir 153, p. 7-31
- 1987, The regional tectonic setting and possible causes of Cenozoic extension in the North American Cordillera, in Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 177-186.
- Coney, P.J., and Harms, T.A., Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550-554.
- Costenius, K.N., 1996, Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20-39.
- Crafford, A.E.J., and Grauch, V.J.S., 2002, Geologic and geophysical evidence for the influence of deep crustal structures on Paleozoic tectonics and the alignment of world-class gold deposits, north-central Nevada, USA: Ore Geology Reviews, v. 21, p. 157-184.
- Cunningham, C.G., 1985, Relationship between disseminated gold deposits and a regional paleothermal anomaly in Nevada: U.S. Geological Survey Open-File Report 85-722, 20 p.
- 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.
- Dokka, R.K., Mahiggie, 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.
- Dubendorfer, E.M., and Black, R.A., 1992, Kinematic role of transverse structures in continental extension: An example from the Las Vegas Valley shear zone, Nevada: Geology, v. 20, p. 1107-1110.
- Dubiel, R.F., Potter, C.J., Good, S.C., Snee, L.W., 1996, Reconstructing an Eocene extensional basin: The White Sage Formation, eastern Great Basin, in Beratan, K.K., ed., Reconstructing the history of Basin and Range extension using sedimentology and stratigraphy: Geological Society of America Special Paper 303, p. 1-14.
- Dumitru, T.A., Miller, E.L., Surpluss, B.E., Martinez, C.M., Egger, A.E., and Stockli, D.F., 2000, Large structural domains of synchronous Miocene extension in the northern Basin and Range province: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-43.
- Effimoff, I., and Pinezich, A.R., 1981, Tertiary structural development of selected valleys based on seismic data, Basin and Range province, northeastern Nevada: Royal Society of London Philosophical Transactions, Series A, v. 300, p. 435-442.
- Ehman, K.D., 1985, Paleozoic stratigraphy and tectonics of the Bull Run Mountains, Elko County, northern Nevada: Unpublished Ph.D. dissertation, Davis, University of California, 174 p.
- Elison, M.W., 1995, Causes and consequences of Jurassic magmatism in the northern Great Basin: Implications for tectonic development: Geological Society of America Special Paper 299, p. 267-294.
- Faulds, J.E., and Stewart, J.H., eds., 1998, Accommodation zones and transfer zones: The regional segmentation of the Basin and Range province: Geological Society of America Special Paper 323, 257 p.
- Fink, R.A., and van de Kamp, P.C., 1992, Summary of SOHIO #1 Ruby Valley Federal, Elko County, Nevada, in Trexler, J.H., Flanigan, T.E., Flanigan, D.M.H., Hansen, M., and Garside, L., eds., Structural geology and petroleum potential of southwest Elko County, Nevada: Nevada Petroleum Society Field Trip Guidebook, 1992, p. 86-87.
- Flanigan, D.M.H., Garside, L.J., and Hansen, Mike, eds., 1990, Oil fields and geology of the Pine Valley, Eureka County area, Nevada: Nevada Petroleum Society 1990 Field Trip Guidebook, 74 p.
- Foster, D.A., Gleadow, A.J.W., Reynolds, S.J., and Fitzgerald, P.G., 1993, The denudation of metamorphic core complexes and the reconstruction of the

- Transition zone, west-central Arizona: *Journal of Geophysical Research*, v. 98, p. 2167–2186.
- Fouch, T.D., 1979, Character and paleogeographic distribution of Upper Cretaceous(?) and Paleogene nonmarine sedimentary rocks in east-central Nevada, *in* Armentrout, J.M., Cole, M.R., and TerBest, H., eds., *Cenozoic Paleogeography of the Western United States*, Pacific Coast Paleogeography Symposium, 3rd, 1979: Society of Economic Paleontologists and Mineralogists Pacific Section, p. 97–111.
- Fricke, H.C., Wickham, S.M., and O'Neil, J.R., 1992, Oxygen and hydrogen isotope evidence for meteoric water infiltration during mylonitization and uplift in the Ruby Mountains-East Humboldt Range core complex, Nevada: *Contributions to Mineralogy and Petrology*, v. 111, p. 203–221.
- Fryxell, J.E., Salton, G.G., Selverstone, J., and Wenicke, B., 1992, Gold Butte crustal section, south Virgin Mountains, Nevada: *Tectonics*, v. 11, p. 1099–1120.
- Gans, P.B., 1987, An open-system, two-layer crustal stretching model for the eastern Great Basin: *Tectonics*, v. 6, p. 1–12.
- Gans, P.B., Seedorff, E., Fahey, P.L., Hasler, R.W., Maher, D.J., Jeanne, R.A., and Shaver, S.A., 2001, Rapid Eocene extension in the Robinson district, White Pine County, Nevada: Constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ dating: *Geology*, v. 29, p. 475–478.
- Garside, L.J., Hess, R.H., Fleming, K.L., and Weimer, B.S., 1988, Oil and gas developments in Nevada: Nevada Bureau of Mines and Geology Bulletin 104, 136 p.
- Gordee, S.M., Dettloff, C.L., and Burton, B.R., 2000, Geologic and geochemical comparison of late Eocene-Oligocene volcanic and intrusive rocks, Carlin-Piñon Range and central Ruby Mountains, Elko County, Nevada: *Geological Society of America, Abstracts with Programs*, v. 32, no. 7, p. A-159.
- Grauch, V.J.S., Rodriguez, B.D., and Wooden, J.L., 2003, Geophysical and isotopic constraints on crustal structure related to mineral trends in north-central Nevada and implications for tectonic history: *ECONOMIC GEOLOGY*, v. 98, p. 269–286.
- Grunder, A.L., and Wickham, S.M., 1991, Homogenization and lowering of $^{18}\text{O}/^{16}\text{O}$ in mid-crustal rocks during extension-related magmatism in eastern Nevada: *Earth and Planetary Science Letters*, v. 107, p. 416–431.
- Hacker, B.R., Yin, An, Christie, J.M., and Snoke, A.W., 1990, Differential stress, strain rate, and temperatures of mylonitization in the Ruby Mountains, Nevada: Implications for the rate and duration of uplift: *Journal of Geophysical Research*, v. 95, p. 8569–8580.
- Hacker, B.R., Yin, An, Christie, J.M., and Davis, G.A., 1992, Stress magnitude, strain rate, and rheology of extended middle continental crust inferred from quartz grain sizes in the Whipple Mountains, California: *Tectonics*, v. 11, p. 36–46.
- Harris, A.G., Wardlaw, B.R., Rust, C.C., and Merrill, G.K., 1980, Maps for assessing thermal maturity (conodont color alteration index maps) in Ordovician through Triassic rocks in Nevada and Utah and adjacent parts of Idaho and California: U.S. Geological Survey Map I-1249.
- Hazlett, D.P., Bregar, J.E., and Hersch, J.B., 1992, Petroleum potential of southern Huntington Valley and results of the Anadarko Cherry Spring Federal 30–44, White Pine County, Nevada, *in* Trexler, J.H., Flanigan, T.E., Flanigan, D.M.H., Hansen, M., and Garside, L., eds., *Structural geology and petroleum potential of southwest Elko County, Nevada*: Nevada Petroleum Society Field Trip Guidebook, 1992, p. 61–70.
- Henry, C.D., and Boden, D.R., 1998, Eocene magmatism: The heat source for Carlin-type gold deposits of northern Nevada: *Geology*, v. 26, p. 1067–1070.
- Henry, C.D., and Ressel, M.W., 2000, Eocene magmatism of northeastern Nevada: The smoking gun for Carlin-type gold deposits, *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, Reno, 2000, Proceedings, v. 1, p. 365–388.
- 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 deposits, *in* Shaddrick, D.R., and Mathewson, D.C., eds., *Regional tectonics and structural control of ore: The major gold trends of northern Nevada*: Geological Society of Nevada, Special Publication 33, p. 115–128.
- Hillhouse, J.W., and Wells, R.E., 1991, Magnetic fabric, flow directions, and source area of the lower Miocene Peach Springs Tuff in Arizona, California, and Nevada: *Journal of Geophysical Research*, v. 96, p. 12,443–12,460.
- Hodges, K.V., and Walker, J.D., 1992, Extension in the Cretaceous orogen, North America: *Geological Society of America Bulletin*, v. 104, p. 560–569.
- 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.
- Hofstra, A.H., and Cline, J.S., 2000, Characteristics and models for Carlin-type gold deposits: Reviews in *ECONOMIC GEOLOGY*, v. 13, p. 163–220.
- Hofstra, A.H., Snee, L.W., Rye, R.O., Folger, H.W., Phinisey, J.D., Loranger, R.J., Dahl, A.R., Naeser, C.W., Stein, H.J., and Lewchuk, M., 1999, Age constraints on Jerritt Canyon and other Carlin-type gold deposits in the western United States—Relationship to mid-Tertiary extension and magmatism: *ECONOMIC GEOLOGY*, v. 94, p. 769–802.
- Hofstra, A.H., Premo, W.R., Emsbo, P., Cline, J.S., and Alieimikoff, J.N., 2000, U-Th-Pb dating of hydrothermal minerals from Carlin-type gold deposits: Results and evaluation, *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, Reno, 2000, Proceedings, v. 1, p. 61–65.
- Hope, R.A., 1972, Geologic map of the Spruce Mountain Quadrangle, Elko County, Nevada: U.S. Geological Survey Map GQ-942, 1:62,500, 3 p.
- Howard, K.A., 1966, Structure of the metamorphic rocks of the northern Ruby Mountains, Nevada: Unpublished Ph.D. dissertation, New Haven, Conn., Yale University, 170 p.
- 1968, Flow direction in triclinic folded rocks: *American Journal of Science*, v. 266, no. 9, p. 758–765.
- 1980, Metamorphic infrastructure in the northern Ruby Mountains, Nevada, *in* Crittenden, M.D., Coney, P.J., and Davis, G.H., eds., *Cordilleran metamorphic core complexes*: Geological Society of America Memoir 153, p. 335–347.
- 1987, Lamoille Canyon nappe in the Ruby Mountains metamorphic core complex, Nevada, *in* Hill, M.L., ed., *Centennial Field Guide*, Geological Society of America, v. 1, p. 95–100.
- 1992, Ruby Mountains metamorphic core complex: Deep crustal exposures exhumed from beneath the Piñon Range?, *in* Trexler, J.H., Flanigan, T.E., Flanigan, D.M.H., Hansen, M., and Garside, L., eds., *Structural geology and petroleum potential of southwest Elko County, Nevada*: Nevada Petroleum Society Field Trip Guidebook, 1992, p. 57–60.
- 2000, Geologic map of the Lamoille Quadrangle, Elko County, Nevada: Nevada Bureau of Mines and Geology Map 125, scale 1:24,000, 4 p.
- Howard, K.A., and Foster, D.A., 1996, Thermal and unroofing history of a thick, tilted Basin and Range crustal section in the Tortilla Mountains, Arizona: *Journal of Geophysical Research*, v. 101, p. 511–522.
- Howard, K.A., and John, B.E., 1987, Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., *Continental extensional tectonics*: Geological Society of London Special Publication 28, p. 299–311.
- Howard, K.A., Kistler, R.W., Snoke, A.W., and Willden, Ronald, 1979, Geologic map of the Ruby Mountains, Nevada: U.S. Geological Survey Map I-1136, 1:125,000.
- Howard, K.A., Nielson, J.E., Wilshire, H.G., Nakata, J.K., Goodge, J.W., Reneau, S.L., John, B.E., and Hansen, V.L., 2000, Geologic map of the Mohave Mountains area, Mohave County, western Arizona: U.S. Geological Survey Map I-2308, 1:48,000.
- Hudec, M.R., 1990, The structural and thermal evolution of the central Ruby Mountains, Elko County, Nevada: Unpublished Ph.D. dissertation, Laramie, University of Wyoming, 272 p.
- 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.
- Hudec, M.R., and Wright, J.E., 1991, Mesozoic history of the central part of the Ruby Mountains-East Humboldt Range metamorphic core complex, Nevada [abs.]: *Geological Society of America Abstracts with Programs*, v. 22, no. 3, p. 30.
- Humphreys, E.D., 1995, Post-Laramide removal of the Farallon slab, western United States: *Geology*, v. 23, p. 987–990.
- Hurlow, H.A., Snoke, A.W., and Hodges, K.V., 1991, Temperature and pressure of mylonitization in a Tertiary extensional shear zone, Ruby Mountains-East Humboldt Range, Nevada: *Tectonic implications*: *Geology*, v. 19, p. 82–86.
- Ilchik, R.P., and Barton, M.D., 1997, An agmagmatic origin of Carlin-type gold deposits: *ECONOMIC GEOLOGY*, v. 92, p. 269–288.
- Jamison, W.R., 1993, Mechanical stability of the triangle zone: the backthrust wedge: *Journal of Geophysical Research*, v. 98, p. 20,015–20,032.

- Janecke, S.U., Hammond, B.F., Snee, L.W., and Geissman, J.W., 1997, Rapid extension in an Eocene volcanic arc: Structure and paleogeography of an intra-arc half graben in central Idaho: *Geological Society of America Bulletin*, v. 109, p. 253–267.
- Jansma, P.E., and Speed, R.C., 1990, Omission faulting during Mesozoic regional contraction at Carlin Canyon, Nevada: *Geological Society of America Bulletin*, v. 102, p. 417–427.
- John, B.E., and Foster, D.A., 1993, Structural and thermal constraints on the initiation angle of detachment faulting in the southern Basin and Range: The Chemehuevi Mountains case study: *Geological Society of America Bulletin*, v. 105, p. 1091–1108.
- John, B.E., and Howard, K.A., 1995, Rapid extension recorded by cooling-age patterns and brittle deformation, Naxos, Greece: *Journal of Geophysical Research*, v. 100, p. 9969–9979.
- Jones, J.V., 1999, Deformational, magmatic, and metamorphic history of the central Ruby Mountains, Elko County, Nevada: Unpublished M.S. thesis, Laramie, University of Wyoming, 166 p.
- Ketchum, R.A., 1996, Thermal models of core-complex evolution in Arizona and New Guinea: Implications for ancient cooling paths and present-day heat flow: *Tectonics*, v. 15, p. 933–951.
- Ketner, K.B., 1973, Preliminary geologic map of the Hunter Quadrangle, Elko County, Nevada: U.S. Geological Survey Map MF-539, 1:24,000.
- 1998, The nature and timing of tectonism in the western facies terrane of Nevada and California—An outline of evidence and interpretations derived from geologic maps of key areas: U.S. Geological Survey Professional Paper 1592, 19 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: U.S. Geological Survey Bulletin 1988-C, 13 p.
- Ketner, K.B., and Evans, J.G., 1988, Geologic map of the Peko Hills, Elko County, Nevada: U.S. Geological Survey Map I-1902, 1:24,000.
- Ketner, K.B., and Ross, R.J., 1983, Preliminary geologic map of the northern Adobe Range, Elko County, Nevada: U.S. Geological Survey Open-File Report 83–290, 1:24,000.
- Kistler, R.W., Ghent, E.D., and O'Neill, 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.
- Kuehn, C.A., and Rose, A.W., 1995, Carlin gold deposits, Nevada: Origin in a deep zone of mixing between normally pressured and overpressured fluids: *ECONOMIC GEOLOGY*, v. 90, p. 17–36.
- Lee, Jeffrey, 1995, Rapid uplift and rotation of mylonitic rocks from beneath a detachment fault: Insights from potassium feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology, northern Snake Range, Nevada: *Tectonics*, v. 14, p. 54–77.
- Lee, S.-Y., and Barnes, C., 1997, Grand tour part 3: Geology and petrology of Cretaceous and Tertiary granitic rocks, Lamoille Canyon, Ruby Mountains, Nevada, in Link, P.K., and Kowalis, 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 I, p. 276–282.
- Lewis, C.J., Wernicke, B.P., Selverstone, Jane, and Bartley, J.M., 1999, Deep burial of the footwall of the northern Snake Range decollement, Nevada: *Geological Society of America Bulletin*, v. 111, p. 39–51.
- Livaccari, R.F., 1991, Role of crustal thickening and extensional collapse in the tectonic evolution of the Sevier-Laramide orogeny, western United States: *Geology*, v. 19, p. 1104–1107.
- Lush, A.P., McGrew, A.J., Snoko, A.W., and Wright, J.E., 1988, Allochthonous Archean basement in the northern East Humboldt Range, Nevada: *Geology*, v. 16, p. 349–353.
- MacCready, Tyler, Snoko, A.W., Wright, J.E., and Howard, K.A., 1997, Mid-crustal flow during Tertiary extension in the Ruby Mountains core complex, Nevada: *Geological Society of America Bulletin*, v. 109, p. 1576–1594.
- McGrew, A.J., 1992, Tectonic evolution of the northern East Humboldt Range, Elko County, Nevada: Unpublished Ph.D. dissertation, Laramie, University of Wyoming, 190 p.
- McGrew, A.J., and Peters, M.T., 1997, Grand tour part 2: Petrogenesis and thermal evolution of deep continental crust: the record from the East Humboldt Range, Nevada, in Link, P.K., and Kowalis, 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 I, p. 270–276.
- McGrew, A.J., and Snee, L.W., 1994, $^{40}\text{Ar}/\text{Ar}$ 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.
- Miller, D.M., 1990, Mesozoic and Cenozoic tectonic evolution of the north-eastern Great Basin, in Shaddrick, D.R., Kizis, J.A., and Hunsaker, E.L., eds., *Geology and ore deposits of the northeastern Great Basin: Geological Society of Nevada Field Trip 5 Guidebook*, p. 43–73.
- Miller, D.M., and Hoisch, T.D., 1995, Jurassic tectonics of northeastern Nevada and northwestern Utah from the perspective of barometric studies: *Geological Society of America Special Paper 299*, p. 267–294.
- Miller, E.L., Bateson, T., Dinter, D., Dyer, R., Harbaugh, D., and Jones, D.C., 1981, Thrust emplacement of the Schoonover sequence, northern Independence Mountains, Nevada: *Geological Society of America Bulletin*, Part I, v. 92, p. 703–729.
- Mortensen, J.K., Thompson, F.H., and Tosdal, R.M., 2000, U-Pb age constraints on magmatism and mineralization in the northern Great Basin, Nevada, 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, Reno, 2000, Proceedings*, v. 1, p. 419–438.
- Mueller, K.J., 1993, Geologic map of the Windermere hills, northeastern Nevada: Nevada Bureau of Mines and Geology Field Studies Map 4, 1:48,000, 4 p.
- Mueller, K.J., and Snoko, A.W., 1993a, 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.
- 1993b, Cenozoic basin development and normal fault systems associated with the exhumation of metamorphic core complexes in northeast Nevada, in Lahren, M.M., Trexler, J.H., and Spinosa, C., eds., *Crustal evolution of the Great Basin and the Sierra Nevada: Cordilleran/Rocky Mountain Sections of the Geological Society of America*, University of Nevada Mackay School of Mines, Reno, 1993, *Field Trip Guidebook*, p. 1–34.
- Mueller, K.J., Cerveny, P.K., Perkins, M.E., and Snee, L.W., 1999, Chronology of polyphase extension in the Windermere Hills, northeast Nevada: *Geological Society of America Bulletin*, v. 111, p. 11–27.
- Muffler, L.J.P., 1964, Geology of the Frenchie Creek Quadrangle, north-central Nevada: U.S. Geological Survey Bulletin 1179, 99 p.
- Muntean, J., Tarnocai, C., Coward, M., Rouby, D., and Jackson, A., 2001, Styles and restorations of Tertiary extension in north-central Nevada, in Shaddrick, D.R., and Mathewson, D.C., eds., *Regional tectonics and structural control of ore: The major gold trends of northern Nevada: Geological Society of Nevada Special Publication 33*, p. 55–69.
- Newman, G.W., and Witter, G.G., 1992, The Silurian-Devonian shelf-margin, a late Paleozoic outer-shelf arch, and unique preservation of pre-Tertiary structures northwest of Elko, Nevada, in Trexler, J.H., Flanigan, T.E., Flanigan, D.M.H., Hansen, M., and Garside, L., eds., *Structural geology and petroleum potential of southwest Elko County, Nevada: Nevada Petroleum Society Field Trip Guidebook, 1992*, p. 4–23.
- Nutt, C.J., and Good, S.C., 1998, Recognition and significance of Eocene deformation in the Alligator Ridge area, central Nevada, in Tosdal, R.M., ed., *Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report 98–338*, p. 141–150.
- Nutt, C.J., Hofstra, A.H., Hart, K.S., and Mortensen, J.K., Structural setting and genesis of gold deposits in the Bald Mountain-Alligator Ridge area, east-central Nevada, 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, Reno, 2000, Proceedings*, v. 1, p. 513–537.
- Oversby, Brian, 1972, Thrust sequences in the Windermere Hills, northeastern Elko County, Nevada: *Geological Society of America Bulletin*, v. 83, p. 2677–2688.
- Palmer, H.C., MacDonald, W.D., and Hayatsu, A., 1991, Magnetic, structural and geochronologic evidence bearing on volcanic sources and Oligocene deformation of ash flow tuffs, northeast Nevada: *Journal of Geophysical Research*, v. 96, p. 2185–2202.
- Peters, M.T., and Wickham, S.M., 1994, Petrology of upper amphibolite facies marbles from the East Humboldt Range, Nevada: *Journal of Petrology*, v. 35, p. 205–238.
- 1995, On the causes of ^{18}O -depletion and $^{18}\text{O}/^{16}\text{O}$ homogenization during regional metamorphism: The East Humboldt Range core complex, Nevada: *Contributions to Mineralogy and Petrology*, v. 119, p. 68–82.

- Poole, F.G., Sandberg, C.A., and Boucot, A.J., 1977, Silurian and Devonian paleogeography of the western United States, in Stewart, J.H., and Fritsche, A.E., eds., *Paleozoic Paleogeography of the Western United States: Pacific Coast Paleogeography Symposium: Society of Economic Paleontologists and Mineralogists Pacific Section*, p. 39–65.
- Poole, F.G., Claypool, G.E., and Fouch, T.D., 1983, Major episodes of petroleum generation in part of the northern Great Basin: Geothermal Resources Council Special Report 13, p. 207–213.
- Potter, C.J., Dubiel, R.F., Snee, L.W., and Good, S.C., 1995, Eocene extension of early Eocene lacustrine strata in a complexly deformed Sevier-Laramide hinterland, northwest Utah and northeast Nevada: *Geology*, v. 23, p. 181–184.
- Price, R.A., 1986, The southeastern Canadian Cordillera: Thrust faulting, tectonic wedging, and delamination of the lithosphere: *Journal of Structural Geology*, v. 8, p. 239–254.
- Price, R.A., and Monger, J.W.H., 2000, A transect of the southern Canadian Cordillera from Calgary to Vancouver, in *Cordilleran Section of Geological Association of Canada and Annual meeting of the Cordilleran Section of the Geological Society of America*, 96th, Vancouver, 2000, Proceedings, 164 p.
- Proffett, J.M., 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.
- Rahl, J.M., McGrew, A.J., and Foland, K.A., 2002, Transition from contraction to extension in the northeastern Basin and Range: New evidence from the Copper Mountains, Nevada: *Journal of Geology*, v. 110, p. 179–194.
- Ransom, K.L., and Hansen, J.B., 1990, Devonian Woodruff Formation at Cole Creek Canyon: A world class Devonian source rock, in Flanigan, D.M.H., Garside, L.J., and Hansen, Mike, eds., *Oil fields and geology of the Pine Valley, Eureka County area, Nevada: Nevada Petroleum Society Field Trip Guidebook*, 1990, p. 13.
- Reese, N.M., 1986, Cenozoic tectonic history of the Ruby Mountains and adjacent areas, northeastern Nevada: Constraints from radiometric dating and seismic reflection profiles: Unpublished M.S. thesis, Dallas, Texas, Southern Methodist University, 88 p.
- Ressel, M.W., Noble, D.C., Heizler, M.T., Volk, J.A., Lamb, J.B., Park, D.E., Conrad, J.E., and Mortensen, J.K., 2000, Gold-mineralized Eocene dikes at Griffen and Mickle: Bearing on the age and origin of deposits of the Carlin trend, Nevada, in Cluer, J.K., Price, J.G., Struhsacker, R.F., Hardyman, E.M., and Morris, C.L., eds., *Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium*, Reno, 2000, Proceedings, v. 1, p. 79–101.
- Reynolds, S.J., and Spencer, J.E., 1985, Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona: *Geology*, v. 13, p. 353–356.
- Riva, 1970, Thrusted Paleozoic rocks in the northern and central HD Range, northern Nevada: *Geological Society of America Bulletin*, v. 81, p. 2689–2715.
- Rodriguez, B.D., 1998, Regional crustal structure beneath the Carlin trend, Nevada, based on deep electrical geophysical measurements, in Tosdal, R.M., ed., *Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report 98-338*, p. 15–19.
- 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.
- 2000, Cenozoic tectonic evolution of the Ruby Mountains metamorphic core complex and adjacent valleys, northeastern Nevada: *Rocky Mountain Geology*, v. 35, p. 205–230.
- Schalla, R.A., 1992, Results of exploratory drilling in Humington Valley near Jiggs, Elko County, Nevada, in Trexler, J.H., Flanigan, T.E., Flanigan, D.M.H., Hansen, M., and Garside, L., eds., *Structural geology and petroleum potential of southwest Elko County, Nevada: Nevada Petroleum Society Field Trip Guidebook*, 1992, p. 71–85.
- Seedorff, Eric, 1991, Magmatism, extension, and ore deposits of Eocene to Holocene age in the Great Basin—Mutual effects and preliminary proposed genetic relationships, in Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., *Geology and Ore Deposits of the Great Basin Symposium: Geological Society of Nevada*, Reno, 1991, Proceedings, v. 1, p. 133–178.
- Sharp, R.P., 1939, Basin-Range structure of the Ruby-East Humboldt Range, northeastern Nevada: *Geological Society of America Bulletin*, v. 50, p. 881–920.
- Silitonga, P.H., 1974, Geology of part of the Kittridge Springs Quadrangle, Elko County, Nevada: Unpublished M.S. thesis, Golden, Colorado School of Mines, 88 p., map 1:24,000.
- Smith, D.L., and Miller, E.L., 1990, Late Paleozoic extension in the Great Basin, western United States: *Geology*, v. 18, p. 712–715.
- Smith, D.L., Gans, P.B., and Miller, E.L., 1991, Palinspastic restoration of Cenozoic extension in the central and eastern Basin and Range province at latitude 39°–40° N, in Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., *Geology and Ore Deposits of the Great Basin Symposium: Geological Society of Nevada*, Reno, 1991, Proceedings, v. 1, 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 U.S.A., in Dunne, G.C., and McDougall, K.A., eds., *Mesozoic paleogeography of the western United States, II: Society of Economic Paleontologists and Mineralogists Pacific Section, Field Trip Guidebook*, v. 71, p. 389–405.
- Smith, J.F., and Howard, K.A., 1977, Geologic map of the Lee Quadrangle, Elko County, Nevada: U.S. Geological Survey Map GQ-1393, 1:62,500.
- Smith, J.F., and Ketner, K.B., 1976a, Stratigraphy of Paleozoic rocks in the Carlin-Pinon Range area, Nevada: U.S. Geological Survey Professional Paper 867-A, 87 p.
- 1976b, Stratigraphy of post-Paleozoic rocks and summary of resources in the Carlin-Pinon Range area, Nevada: U.S. Geological Survey Professional Paper 867-B, 48 p.
- 1977, Tectonic events since early Paleozoic in the Carlin-Pinon Range area, Nevada: U.S. Geological Survey Professional Paper 867-C, 18 p.
- 1978, Geologic map of the Carlin-Piñon Range area, Elko and Eureka counties, Nevada: U.S. Geological Survey Map I-1028, 1:62,500.
- Smith, J.F., Ketner, K.B., Hernandez, G.X., Harris, A.G., Stamm, R.G., and Smith, M.C., 1990, Geologic map of the Summer Camp Quadrangle and part of the Black Butte Quadrangle, Elko County, Nevada: U.S. Geological Survey Map I-2097.
- Smith, R.B., Nagy, W.C., Julander, K.A.S., Viveiros, J.J., Barker, C.A., and Gants, D.G., 1989, Geophysical and tectonic framework of the eastern Basin and Range–Colorado Plateau–Rocky Mountain transition, in Pakiser, L.C., and Mooney, W.D., eds., *Geophysical framework of the continental United States: Geological Society of America Memoir 172*, p. 205–233.
- Snoke, A.W., 1980, Transition from infrastructure to suprastructure in the northern Ruby Mountains, Nevada, in Crittenden, M.D., Coney, P.J., and Davis, G.H., eds., *Cordilleran metamorphic core complexes: Geological Society of America Memoir 153*, p. 287–333.
- 1992, Clover Hill, Nevada: Structural link between the Wood Hills and East Humboldt Range, in Wilson, J.R., ed., *Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 92-3*, p. 107–122.
- 1998, Strain partitioning associated with a mylonitic shear-zone–detachment fault system, in Snoke, A.W., Tullis, J., and Todd, V.R., eds., 1998, *Fault-related rocks, a photographic atlas: Princeton, Princeton University Press*, p. 228–231.
- Snoke, A.W., and Lush, A.P., 1984, Polyphase Mesozoic–Cenozoic deformational history of the northern Ruby Mountains–East Humboldt Range, in Lintz, Joseph Jr., ed., *Western Geological Excursions, 1984: Reno, Nevada, Department of Geological Sciences of the MacKay School of Mines*, v. 4, p. 232–260.
- 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, Ruby Volume VII: Englewood Cliffs, New Jersey, Prentice Hall*, p. 606–648.
- Snoke, A.W., McGrew, A.J., Valasek, P.A., and Smithson, S.B., 1990, A crustal cross section for a terrain of superimposed shortening and extension: Ruby Mountains–East Humboldt Range metamorphic core complex, Nevada, in Salisbury, M.H., and Fountain, D.M., eds., *Exposed cross sections of the continental crust: The Netherlands, Kluwer Academic Publishers*, p. 103–135.
- 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, Part I—Introduction and road log, in Link, P.K., and Kowalis, 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 I, p. 225–269.
- Snoke, A.W., Barnes, C.G., Lee, S.-Y., Strike, A.T., and Howard, K.A., 1999, Emplacement, deformation, and exhumation of Tertiary (~29 Ma) sheet-like, monzogranitic intrusions in the Ruby Mountains core complex,

- Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 31, no. 6, p. A-96.
- Solomon, B.J., 1992, The Elko Formation of Eocene and Oligocene(?) age, source rocks and petroleum potential in Elko County, Nevada, *in*, Trexler, J.H., Flanigan, T.E., Flanigan, D.M.H., Hansen, M., and Garside, L., eds., Structural geology and petroleum potential of southwest Elko County, Nevada: Nevada Petroleum Society Field Trip Guidebook, 1992, p. 25–38.
- Solomon, B.J., and Moore, S.W., 1982, Geologic map and oil shale deposits of the Elko West Quadrangle, Elko County, Nevada: U.S. Geological Survey Map MF-1410, 1:24,000.
- Solomon, B.J., McKee, E.H., and Anderson, D.W., 1979, Stratigraphy and depositional environments of Paleogene rocks near Elko, Nevada, *in* Armentrout, J.M., Cole, M.R., and TerBest, H., eds., Cenozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium, 3rd, 1979: Society of Economic Paleontologists and Mineralogists Pacific Section, p. 75–88.
- Sonder, L.J., and Jones, C.H., 1999, Western United States extension: How the West was widened: *Annual Reviews Earth and Planetary Science*, v. 27, p. 417–462.
- Spencer, J.E., and Reynolds, S.J., 1990, Relationship between Mesozoic and Cenozoic tectonic features in west central Arizona and adjacent southeastern California: *Journal of Geophysical Research*, v. 95, p. 539–555.
- Stewart, J.H., 1980, Geology of Nevada: Nevada Bureau of Mines and Geology Special Publication 4, 136 p.
- 1998, Regional characteristics, tilt domains, and extensional history of the late Cenozoic Basin and Range province, western North America, *in* Faults, J.E., and Stewart, J.H., eds., Accommodation zones and transfer zones: The regional segmentation of the Basin and Range province: Geological Society of America Special Paper 323, p. 47–74.
- Stewart, J.H., and Carlson, J.E., 1977, Million-scale geologic map of Nevada: Nevada Bureau of Mines and Geology, Map 57.
- Stoerzel, Andreas, 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.
- 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: *Tectonics*, v. 19, p. 1124–1143.
- Thorman, C.H., 1970, Metamorphosed and nonmetamorphosed Paleozoic rocks in the Wood Hills and Pequoop Mountains, northeast Nevada: *Geological Society of America Bulletin*, v. 81, p. 2417–2448.
- Thorman, C.H., and Brooks, W.E., 1988, Preliminary geologic map of the Oxley Peak Quadrangle, Elko County, Nevada: U.S. Geological Survey Open-File Report 88–755, 1:24,000.
- Thorman, C.H., and Ketner, K.B., 1979, West-northwest strike-slip faults and other structures in allochthonous rocks in central and eastern Nevada and western Utah: Rocky Mountain Association of Geologists, Basin and Range Symposium, 1979, Proceedings, p. 123–133.
- Thorman, C.H., Ketner, K.B., Brooks, W.E., Snee, L.W., and Zimmerman, R.A., 1991, Late Mesozoic-Cenozoic tectonics in northeastern Nevada, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., *Geology and Ore Deposits of the Great Basin Symposium*: Geological Society of Nevada, Reno, 1991, Proceedings, v. 1, p. 25–45.
- Tosdal, R.M., Wooden, J.L., and Kistler, R.W., 2000, Geometry of the Neoproterozoic continental break-up, and implications for location of Nevadan mineral belts, *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, Reno, 2000, Proceedings, v. 1, p. 451–466.
- Valesek, P.A., Snoke, A.W., Hurich, C.A., and Smithson, S.B., 1989, Nature and origin of seismic reflection fabric, Ruby-East Humboldt metamorphic core complex, Nevada: *Tectonics*, v. 8, p. 391–415.
- Vandervoort, D.S., and Schmidt, 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.
- Wannamaker, P.E., and Doerner, W.M., 2002, Crustal structure of the Ruby Mountains and southern Carlin trend region, Nevada, from magnetotelluric data: *Ore Geology Reviews*, v. 21, p. 185–210.
- Wells, M.L., 2001, Rheological control on the initial geometry of the Raft River detachment fault and shear zone, western United States: *Tectonics*, v. 20, p. 435–457.
- Wells, M.L., Snee, L.W., and Blythe, A.L., 2000, Dating of major normal fault systems using thermochronology: An example from the Raft River Mountains, Basin and Range, western United States: *Journal of Geophysical Research*, v. 105, p. 16,303–16,327.
- Wentworth, C.M., and Zoback, M.D., 1989, The style of late Cenozoic deformation at the eastern front of the California coast: *Tectonics*, v. 8, p. 237–246.
- Wentworth, C.M., Blake, M.C., Jones, D.L., Walter, A.W., and Zoback, M.D., 1984, Tectonic wedging associated with emplacement of the Franciscan assemblage, California Coast Ranges, *in* Blake, M.C., Jr., ed., *Franciscan geology of northern California*: Society of Economic Paleontologists and Mineralogists Pacific Section, v. 43, p. 163–173.
- Wernicke, Brian, 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., *The Cordilleran orogen: Conterminous U.S.*: Boulder, Geological Society of America, *The Geology of North America*, v. G–3, p. 553–581.
- Wickham, S.M., Peters, M.T., Fricke, H.C., and O'Neil, J.R., 1993, Identification of magmatic and meteoric fluid sources and upward- and downward-moving infiltration fronts in a metamorphic core complex: *Geology*, v. 21, p. 81–84.
- Willden, R., Thomas, H.H., and Stern, T.W., 1967, Oligocene or younger thrust faulting in the Ruby Mountains, northeastern Nevada: *Geological Society of America Bulletin*, v. 78, p. 1345–1358.
- Wise, Jim, 1998, Mesozoic tectonics and metamorphism in the Pequoop Mountains and Wood Hills region, northeast Nevada: Implications for the architecture and evolution of the Sevier orogen; Discussion: *Geological Society of America Bulletin*, v. 110, p. 679–680.
- Wright, J.E., and Snoke, A.W., 1993, Tertiary magmatism and mylonitization in the Ruby-East Humboldt metamorphic core complex, northeastern Nevada: *Geological Society of America Bulletin*, v. 105, p. 935–952.
- Zoback, M.L., Anderson, R.E., and Thompson, G.A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: *Royal Society of London Philosophical Transactions, Part A*, v. 300, p. 407–434.