Comparative anatomy of core-complex development in the northeastern Great Basin, U.S.A.

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ABSTRACT

Three metamorphic core complexes, Ruby Mountains-East Humboldt Range (R-EH), Albion Mountains-Raft River Mountains-Grouse Creek Mountains (A-RR-GC), and Snake Range (SR) are exposed in the northeastern Great Basin (Nevada, Utah, and Idaho). Their structural, magmatic, and metamorphic histories are synthesized and compared to evaluate fundamental tectonic processes in this area in which large-magnitude crustal contraction was followed by large-magnitude crustal extension. Throughout the region, contraction and magmatism began in the Late Jurassic, and in the R-EH and SR areas culminated at ~80–90 Ma. The A-RR-GC core complex experienced multiple episodes of Late Cretaceous tectonic denudation beginning at ~105 Ma, and it records no Mesozoic magmatism, apparently due to an infertile lower crust. The R-EH core complex also underwent tectonic denudation in latest Cretaceous/early Tertiary time. This illustrates the importance of syncontractional adjustments to thickened orogenic wedges and that these adjustments need not occur simultaneously throughout an orogen. Syncontractional extension and denudation in the A-RR-GC and R-EH areas also limited the amount, extent, and distribution of subsequent Tertiary extension.

Eocene magmatism was immediately followed by an intense pulse of crustal extension in all three areas. However, late Oligocene and early Miocene extension throughout the region was diachronous and was not always coincident with a widespread mid-Oligocene magmatic event, suggesting that Oligocene magmatism and extension are not entirely linked. The magnitude of tectonic denudation in the R-EH and SR core complexes varies along the strike of the core complex. In the R-EH area, this variation may be due to the restriction of Late Cretaceous(?) and middle Eocene episodes of extension to the northern part of the core complex. In the SR core complex this variation may be the result of a lateral ramp in the structural surface of the Snake Range décollement. These intra-core complex variations in tectonic denudation appear to be partly accommodated by solid-state flow of the lower crust into regions of high mid- to upper-crustal extension, and they require a complex, three-dimensional pattern of lower-crustal redistribution and magmatism. Oppositely vergent extensional fault systems in the A-RR-GC metamorphic core complex may have developed because the rigid Archean lower crust in this area could not flow into highly extended domains.

KEY WORDS: metamorphic core complex, crustal contraction and extension, hinterland, Sevier orogenic belt, Albion Mountains, East Humboldt Range, Grouse Creek Mountains, Raft River Mountains, Ruby Mountains, Northern Snake Range, Southern Snake Range, Great Basin, Basin and Range province.

INTRODUCTION

Metamorphic core complexes occur in oceanic and continental settings and are found in orogenic belts around the world (e.g., Crittenden et al., 1980; Lister et al., 1984; Dalziel and Brown, 1989; Doblas and Oyarzun, 1989; Tucholke et al., 1998; Ranero and Reston, 1999; Whitney et al., 2004). These terranes provide geoscientists with important opportunities to examine exposures of middle and lower crustal rocks within areas that have undergone large-magnitude extension commonly preceded by large-magnitude contraction in continental settings. Metamorphic core complexes are exposed throughout the North American Cordillera (Crittenden et al., 1980; Armstrong, 1982). In the northeastern

Great Basin (Nevada, Utah, and Idaho), they provide unique opportunities to examine middle and lower crustal rocks from the hinterland of the Sevier orogenic belt (Armstrong, 1968a; DeCelles, 2004) as well as the axis of the Basin and Range extensional province (Dickinson, 2002, 2007). In this area, three broad tracts of metamorphic and associated intrusive plutonic rocks have long been recognized as classic examples of Cordilleran metamorphic core complexes (Coney, 1979, 1980; Armstrong, 1982). These are the Ruby Mountains-East Humboldt Range (R-EH), Albion Mountains-Raft River Mountains-Grouse Creek Mountains (A-RR-GC), and Snake Range (SR) metamorphic core complexes (Fig. 1). These terranes are the product of a complex history involving: (1) Mesozoic crustal shortening, magmatism, and metamorphism; and (2) younger crustal extension, which locally began in the Late Cretaceous, became regional in extent during the Eocene and Miocene epochs, and continues as part of the on-going development of the Basin and Range province (Dickinson, 2002, 2007).

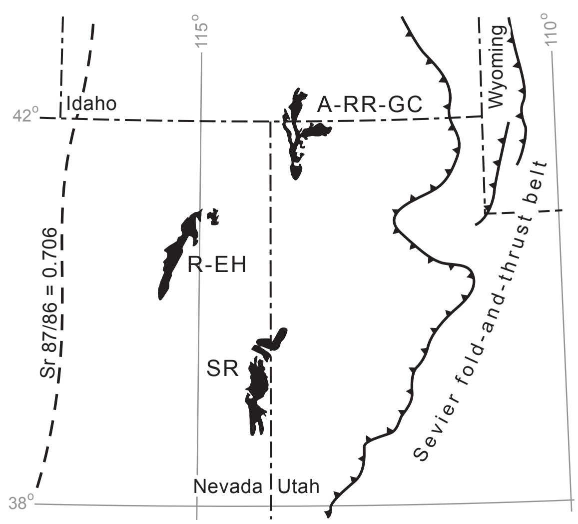

Figure 1. Map showing locations of the Ruby Mountains-East Humboldt Range (R-EH), Albion Mountains-Raft River Mountains-Grouse Creek Mountains (A-RR-GC), and Snake Range (SR) metamorphic core complexes and Sevier fold-and-thrust belt. Adapted from Coney (1980).

Numerous detailed studies have helped unravel the structural, metamorphic, and geochronologic/thermochronologic histories of these core complexes (e.g., R-EH: Howard, 1971, 1980; Snoke, 1980; Snoke et al., 1990, 1997; McGrew and Snee, 1994; MacCready et al., 1997; McGrew et al., 2000; Howard, 2003; A-RR-CG: Armstrong, 1968b; Compton et al., 1977; Miller, 1980, Todd, 1980; Wells, 1997, 2001; Hoisch et al., 2002; SR: Miller et al., 1983, 1988, 1999a; Lee et al., 1987; Lee and Sutter, 1991; Lee, 1995; Lewis et al., 1999). However, no detailed, comparative analysis of these three core complexes has been published. The publication of considerable new data, especially thermobarometric and geochronological/thermochronological data, suggests that a comparative study is appropriate and should indicate important directions for future research. In this paper we have attempted to provide such a "comparative anatomy" of these core complexes by compiling detailed tectonic maps and time lines for each core complex and by systematically comparing their structural, magmatic, metamorphic, and geochronological/thermochronological histories.

Previously, Snoke and Miller (1988) and Miller et al. (1988) provided concise summaries of the structural, metamorphic, and magmatic histories of the R-EH and A-RR-GC metamorphic core complexes and SR metamorphic core complex, respectively. These summaries outline a basic tectonic model that involves the formation of a thick tectonic wedge during the Late Jurassic and Early Cretaceous followed by mid-Tertiary crustal-scale extension. This basic tectonic model is still viable. However, during the past two decades numerous studies have added to and refined our understanding of these metamorphic core complexes. These refinements include: (1) new isotopic ages that further constrain the timing of deformational, magmatic, and metamorphic events; (2) abundant thermobarometric data that better define the pressure-temperature evolution of these complexes; (3) the recognition of a multiphase Precambrian history; (4) improvements in our understanding of the style, geometry, and significance of Cenozoic extensional structural features; (5) the recognition of Cretaceous episodes of extension; and (6) new, detailed geologic mapping. Therefore, the goals of this paper are: (1) to provide an up-to-date, detailed synthesis of the structural, magmatic, and metamorphic evolution of the R-EH, A-RR-GC, and SR metamorphic core complexes; (2) to integrate the new data and interpretations of these core complexes that have appeared in the past two decades; and (3) to use these data to develop new interpretations concerning the nature and timing of tectonothermal events in the region. Our results allow us to correlate tectonic events both along and across strike in the hinterland of the Sevier orogenic belt, Basin and Range province, and, presumably, the Neoproterozoic rifted continental margin of North America. This regional history also allows us to make important inferences about the nature of the Sevier orogenic wedge and mechanisms operating during the collapse of this wedge and the initial development of the Basin and Range extensional province.

RUBY MOUNTAINS-EAST HUMBOLDT RANGE, NEVADA

Introduction

The Ruby Mountains-East Humboldt Range (R-EH) metamorphic core complex encompasses the Ruby Mountains and East Humboldt Range in northeastern Nevada (Figs. 1, 2) and exposes rocks ranging in age from Archean to Tertiary (Howard, 1966, 1971, 1980; Howard et al., 1979; Snoke, 1980; Snoke et al., 1990, 1997; Hudec, 1992; McGrew and Snee, 1994; McGrew et al., 2000). Snoke et al. (1990) recognized two basic structural tiers within the R-EH core complex (Figs. 2, 3A; Table 1). These tiers are delineated by Tertiary extensional architecture, but each displays different aspects of Mesozoic deformational, metamorphic, and magmatic history. The structurally highest level, the upper tier, consists of a nonmetamorphosed to weakly metamorphosed, brittlely attenuated Lower Triassic to mid-Miocene stratified rocks that lie above the frictional/brittle, range-scale, west-rooted, normal-sense Ruby-East Humboldt detachment fault system. Throughout most of the R-EH core complex, the Ruby-East Humboldt detachment fault system is underlain by a km-thick, west-rooted, Tertiary mylonitic shear zone, which yields a top-to-the-west-northwest sense-of-shear. In the northern Ruby Mountains and East Humboldt Range, the lower structural tier beneath the Tertiary mylonitic zone consists of Archean through mid-Paleozoic high-grade, migmatitic metasedimentary rocks (Howard, 1971) that have been extensively intruded by Mesozoic and Tertiary dikes, sheets, and small plutons (Fig. 3A). Throughout the literature, the migmatitic metasedimentary rocks and associated intrusive igneous rocks of this lower structural tier are commonly referred to as the "metamorphic infrastructure" (Armstrong and Hansen, 1966). In sharp contrast, in the southern Ruby Mountains, the lower structural tier consists of nonmetamorphosed to weakly metamorphosed Cambrian to Carboniferous rocks of the Cordilleran miogeocline (Sharp, 1942; Willden and Kistler, 1969, 1979). This basic structural outline serves as the framework for the structural, metamorphic, and magmatic events described in geochronological order below.

Precambrian Through Paleozoic History

A fragmentary Precambrian history is recorded in rocks of the lower tier of the R-EH core complex. The westernmost exposure of Archean basement rocks in the United States, potentially part of the Wyoming province (Lush et al., 1988), lies in the core of the Winchell Lake fold-nappe in the northern East Humboldt Range (Fig. 2). The Archean rocks consist of a mappable body of migmatitic orthogneiss and associated rocks (paragneiss and amphibolite) with a minimum igneous crystallization age of ~2520 Ma (based on U-Pb zircon). A distinctive sequence of Paleoproterozoic(?) metasedimentary rocks is closely associated with the gneissic rocks, interpreted as the original cover for the Archean rocks (Lush et al., 1988; McGrew, 1992; Snoke, 1992). These field relationships suggest a history of Late Archean granitic magmatism and subsequent deposition of a Paleoproterozoic(?) continental-margin sequence. Sr, Nd, and Pb isotopic data reported by Wright and Snoke (1993) suggested to those authors that the boundary between the southwestern margin of the Archean Wyoming province and Proterozoic Mojave province (Bennett and DePaolo, 1987) lies near the intersection of the East Humboldt Range and Ruby Mountains (Fig. 2). However, recent geochronological and isotopic data from the southwestern portion of the Wyoming province indicate a mixed terrane, including both Archean and Proterozoic rocks (Mueller and Frost, 2006). Consequently, the boundary delineated by Wright and Snoke (1993) is problematic. The Neoproterozoic rifting of the western margin of North America and subsequent formation of a passive continental margin, which existed from Neoproterozoic to mid-Paleozoic time (Stewart and Poole, 1974), is recorded by the deposition of the Cordilleran miogeoclinal sequence, although the base of this ~10-km-thick sequence is not exposed.

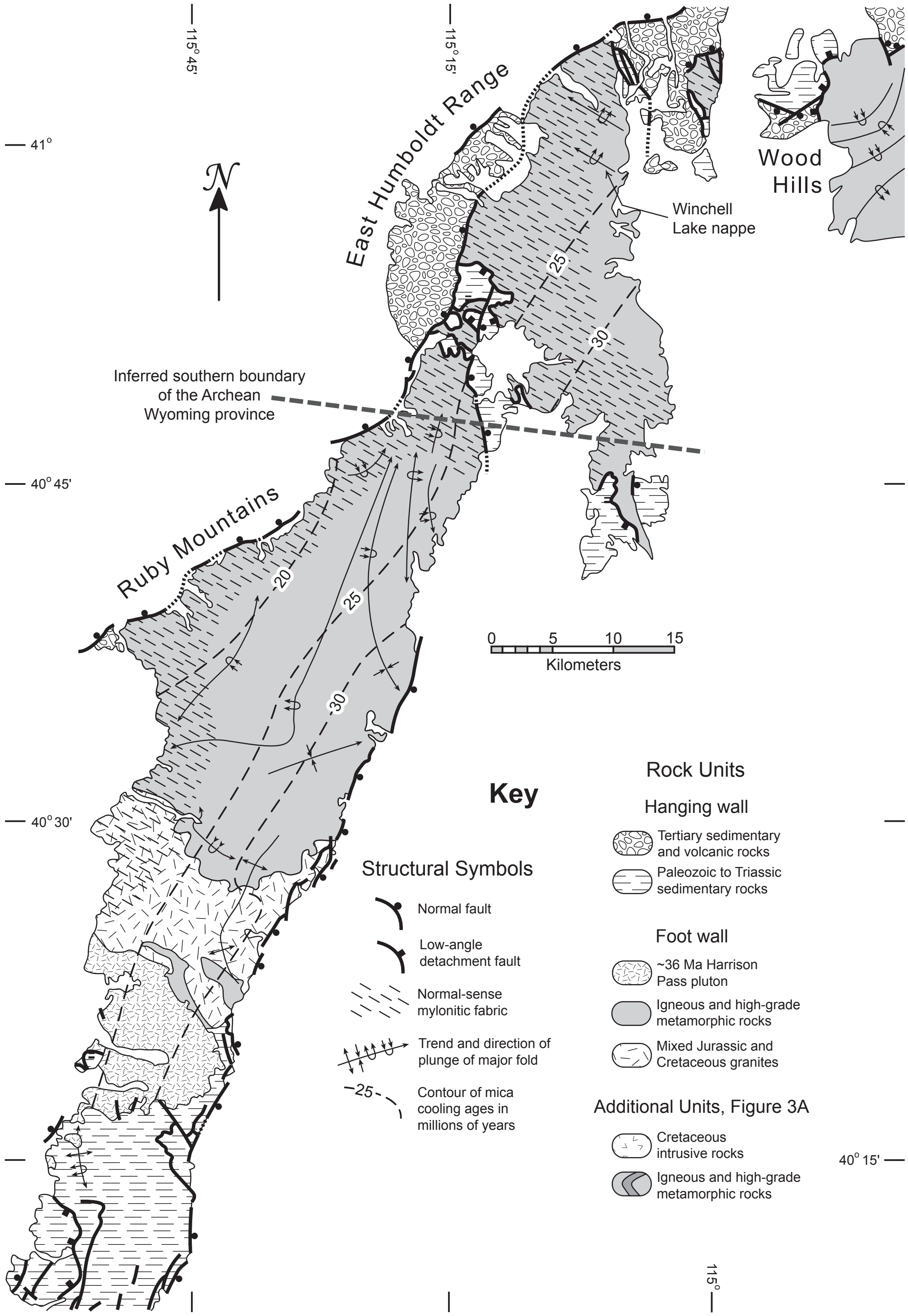

Figure 2. Geologic map of the Ruby Mountains-East Humboldt Range metamorphic core complex showing major structures, intrusive bodies, contours of biotite-cooling ages, and the inferred southern boundary of the Archean Wyoming province. Adapted and compiled from Howard et al. (1979), Hudec (1992), Wright and Snoke (1993), McGrew and Snee (1994), and Camilleri and Chamberlain (1997).

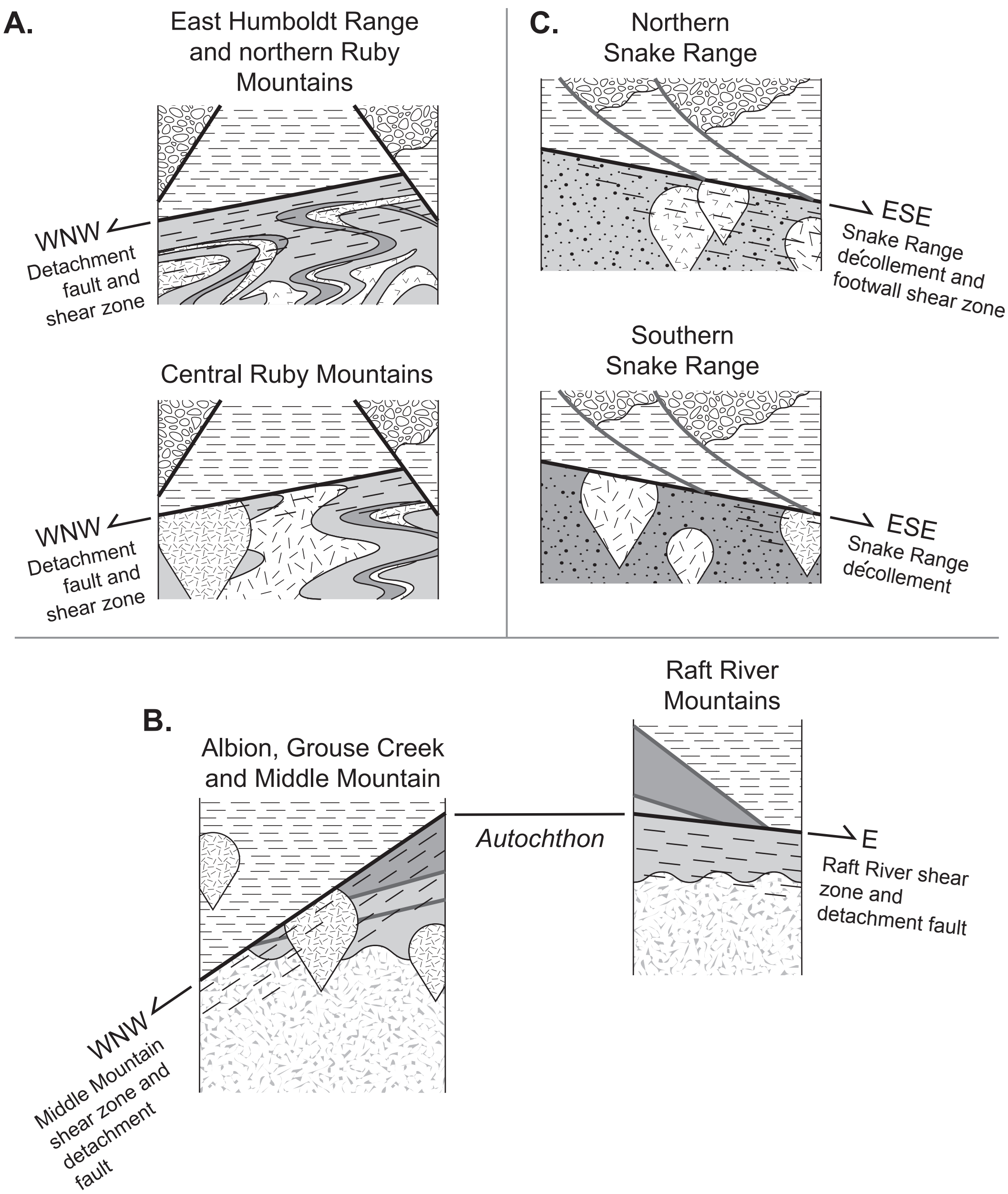

Figure 3. ***A***, Tectonostratigraphic columns of the Ruby Mountains-East Humboldt Range core complex. See Figure 2 for key to rock types and structural symbols. ***B***, Tectonostratigraphic columns of the Albion Mountains-Raft River Mountains-Grouse Creek Mountains core complex. See Figure 4 for key to rock types and structural symbols. ***C***, Tectonostratigraphic columns of the Snake Range core complex. See Figure 5 for key to rock types and structural symbols.

Mesozoic History

A complex sequence of Mesozoic deformational, metamorphic, and magmatic events affected the Archean through mid-Paleozoic rocks now exposed in the lower tier of the R-EH core complex. At least two distinct metamorphic episodes, numerous Jurassic and Cretaceous intrusions, and three penetrative deformation fabrics are recognized. The earliest recognizable episode of Mesozoic(?) deformation involves thrust faulting inferred from an apparent duplication of strata in the lower tier of the northern Ruby Mountains (Howard, 1966, 1980; Smith and Howard, 1977; Howard, 2000; Howard and MacCready, 2004) and the tectonic emplacement of an inverted Neoproterozoic to early Paleozoic metased-

Table 1. Correlation of tectonostratigraphic terminology used in this article with that used in the literature.

Terminology used in this article	Terminology used in the literature
Ruby-East Humboldt core complex	
Upper tier	Suprastructure (Snoke, 1980; Howard, 1980)
Lower tier	Infrastructure (Snoke, 1980; Howard, 1980)
Albion-Raft River-Grouse Creek core complex	
Allochthon	Upper allochthon in the Grouse Creek and Albion Mountains (Compton et al., 1977; Miller, 1980; Todd, 1980); all of the allochthonous sheets in the Raft River Mountains (Compton et al., 1977)
Autochthon	Autochthon (Compton et al., 1977)
Snake Range core complex	
Upper tier	Upper plate (Miller et al., 1983)
Lower tier	Lower plate (Miller et al., 1983)

imentary sequence on top of Paleoproterozoic(?) and Archean rocks in the northern East Humboldt Range and Clover Hill (Lush et al., 1988; McGrew, 1992; Snoke, 1992). These episodes of low-angle faulting are interpreted to have occurred before Late Jurassic/Early Cretaceous metamorphism and folding and likely represent early shortening associated with the Sevier orogeny (DeCelles, 2004).

Hudec (1992) recognized two episodes of Jurassic metamorphism and three episodes of Jurassic deformation roughly synchronous with intrusion of the ~153-Ma (U-Th-Pb monazite) (Hudec and Wright, 1990) Dawley Canyon granite in the central Ruby Mountains (Fig. 2). This interpretation was refined by Jones (1999), who showed that the second phase of metamorphism was Late Cretaceous and recognized two Jurassic deformation fabrics, an initial vertical shortening and subsequent tight folding, in the central Ruby Mountains. The temperature and pressure of the mid-Jurassic metamorphic event are estimated at 425–575°C and 2.6–3.7 kb, respectively. This metamorphism was closely associated with intrusion of the Dawley Canyon granite (Hudec, 1992; Jones 1999). No definitive evidence for mid-Jurassic metamorphism or deformation has been recognized in the northern part of the core complex, although Dallmeyer et al. (1986) reported an ~154-Ma muscovite granite porphyry (their sample I, 197-8) intruded into nonmetamorphosed upper Paleozoic cover rocks near Secret Valley, in the southwestern East Humboldt Range. Furthermore, an episode of kyanite growth documented in metapelitic rocks from the East Humboldt Range (McGrew, 1992; McGrew et al., 2000), Clover Hill (Snoke, 1992), and Wood Hills (Thorman, 1970) predates the widespread Late Cretaceous metamorphism. This moderately high-pressure metamorphism has been tentatively attributed to significant Late Jurassic and/or Early Cretaceous tectonic burial (Hodges et al., 1992; Snoke, 1992; Camilleri and Chamberlain, 1997; McGrew et al., 2000).

The northern Ruby Mountains and East Humboldt Range are characterized by clockwise prograde pressure-temperature-time (P-T-t) paths beginning with Late Jurassic or Early Cretaceous tectonic burial (Hodges et al., 1992; Camilleri and Chamberlain, 1997; McGrew et al., 2000). Peak metamorphic conditions in the R-EH metamorphic core complex were reached during Late Cretaceous time and are associated with the development of map-scale recumbent fold-nappes (Fig. 2), extensive migmatization, and voluminous peraluminous magmatism (Snoke et al., 1979, 1992, 1997; Howard et al., 1979; Howard, 1980; Snoke and Miller, 1988; Hodges et al., 1992; McGrew, 1992; McGrew et al., 2000; Lee et al., 2003). In the northern East Humboldt Range, peak metamorphic conditions approached 800ºC and 9 kb in the lower structural tier of the parautochthonous core (McGrew, 1992; McGrew et al., 2000; Snoke, 1992). This metamorphism was accompanied by emplacement of the Winchell Lake fold-nappe (Lush et al., 1988; McGrew, 1992). A syntectonic leucogranite sill within the Winchell Lake fold-nappe has been dated at 84.8±2.8 Ma (U-Pb zircon) (McGrew et al., 2000). Map-scale fold-nappes in the northern Ruby Mountains originated in the Late Cretaceous (Howard, 1966, 1980, 2000; Howard et al., 1979; Howard and MacCready, 2004), and a syntectonic, sillimanite-bearing leucogranite body associated with the Lamoille Canyon fold-nappe yielded an U-Pb (monazite) age of ~84 Ma (Wright and Snoke, 1993; Lee et al., 2003). Late Cretaceous deformation in this area is associated with upper amphibolite-facies metamorphism and migmatization (Howard, 1980, 1987; Snoke, 1980; Snoke and Miller, 1988). To the south, in the central Ruby Mountains, Late Cretaceous metamorphic assemblages record temperatures of 500–550°C and pressures of 4–4.5 kb, and are associated with upright tight to isoclinal folding and subsequent vertical shortening and subhorizontal simple shearing forming the recumbent King Peak fold-nappe (Hudec, 1992; Jones, 1999).

Several workers have postulated that extensional deformation in the R-EH core complex began during the Late Cretaceous (Hodges et al., 1992; McGrew and Snee, 1994; Camilleri, 1994; Camilleri and Chamberlain, 1997; McGrew et al., 2000). This conclusion is based on thermobarometric/chronologic data from the East Humboldt Range and Wood Hills. In the East Humboldt Range, metamorphic assemblages record peak pressures near 9 kb and peak temperatures near 800°C that are intimately associated with emplacement of the Winchell Lake fold-nappe at ~84 Ma (Hodges et al., 1992; McGrew et al., 2000). By Eocene time, these rocks had cooled to ~630°C and decompressed to ~5 kb (McGrew et al., 2000). Samples of hornblende from structurally higher levels of the core complex yield $^{40}Ar/^{39}Ar$ cooling ages ranging from 50–63 Ma (Dallmeyer et al., 1986; McGrew and Snee, 1994). This evidence indicates that tectonic denudation may have began during the Late Cretaceous. In the Wood Hills to the east, up to 10 km of crustal thinning occurred along the Pequop fault (Camilleri, 1996), and this deformation is associated with ~75-Ma sphene cooling ages (~580ºC for grain size analyzed) (Camilleri and Chamberlain, 1997).

Tertiary History

A protracted history of Tertiary crustal-scale extension and magmatism is recorded in the tiers of the R-EH core complex. Tertiary plutonism within the core complex occurred in two discrete episodes (late Eocene and mid Oligocene). Plutons range in composition from quartz diorite to two-mica granites with biotite monzogranitic dikes and sheets representing a significant intrusive component (Wright and Snoke, 1993). The initial plutonic pulse was emplaced between 40–36 Ma and includes the ~36-Ma Harrison Pass pluton (Fig. 2) (Wright and Snoke, 1993; Barnes et al., 2001). This initial episode of magmatic activity has also been related to mineralization in the adjacent Carlin gold district (Howard, 2003). The second episode occurred at ~29 Ma and is characterized by monzogranitic magmas (Wright and Snoke, 1993). Intrusive rocks from both magmatic episodes are extensively deformed in the mylonitic shear zone and are involved in synextensional deformation within the lower tier of the core complex (Wright and Snoke, 1993; MacCready et al., 1997; McGrew et al., 2000). Hurlow et al. (1991) and McGrew et al. (2000) reported synmylonitic mineral assemblages in the East Humboldt Range that equilibrated at temperatures of 580–630°C and pressures of 3–4 kb. These data indicate a major Tertiary episode of metamorphic mineral growth accompanied exhumation. High-grade metamorphic conditions persisted in the R-EH core complex through the initiation of deformation along the km-thick mylonitic shear zone that flanks the western side of the core complex. This assertion is supported by the existence of: (1) early Oligocene $^{40}Ar/^{39}Ar$ hornblende cooling ages in the East Humboldt Range and late Oligocene $^{40}Ar/^{39}Ar$ and K-Ar hornblende cooling ages in the northern Ruby Mountains (Dallmeyer et al., 1986; McGrew and Snee, 1994); (2) high-temperature quartz *c*-axis fabrics within the mylonite zone (MacCready, 1996; McGrew and Casey, 1998); and (3) high-temperature microstructures in 40–29-Ma orthogneiss bodies in the East Humboldt Range (McGrew, 1992; McGrew and Snee, 1994).

Thermochronologic data from the East Humboldt Range suggest an episode of extension during the early to middle Eocene that likely involved the initial formation of the mylonitic shear zone (Mueller and Snoke, 1993; McGrew and Snee, 1994). Additionally, ~43–39-Ma volcanic rocks are deposited unconformably across normal faults that tilted early Eocene lacustrine deposits (Mueller and Snoke, 1993; Brooks et al., 1995). This relationship also indicates pre-late Eocene extension in northeastern Nevada. However, the bulk of $^{40}Ar/^{39}Ar$ and K-Ar cooling ages of hornblende, muscovite, and biotite show that significant tectonic denudation leading to core-complex development in the R-EH core complex began in mid-Oligocene time and continued through the late Oligocene (Kistler et al., 1981; Dallmeyer et al., 1986; McGrew and Snee, 1994). The bulk of Oligocene denudation was accomplished by the shallowly dipping, west-rooted, top-to-the-west-northwest, normal-sense detachment fault and associated mylonitic shear zone that flank the western side of the core complex (Fig. 2) (Howard et al., 1979; Howard, 1980; Snoke, 1980; Lister and Snoke, 1984; Snoke and Miller, 1988; Snoke et al., 1990; McGrew and Snee, 1994; MacCready et al., 1997; Snoke et al., 1997; McGrew et al., 2000). Mica $^{40}Ar/^{39}Ar$ and K-Ar cooling ages within the R-EH core complex range from ~33 Ma in the eastern part of the East Humboldt Range to ~21 Ma along the western edge of the core complex (Kistler et al., 1981; Dallmeyer et al., 1986; McGrew and Snee, 1994). McGrew and Snee (1994) have used these data to argue for a rolling-hinge type of normal-fault geometry (Wernicke and Axen, 1988) and east-to-west tectonic denudation of the core complex between 33–24 Ma, with the bulk of the exhumation occurring after emplacement of the ~29-Ma intrusive monzogranitic suite. Fission-track ages of sphene and apatite from the northern Ruby Mountains and East Humboldt Range are between 25.4 and 23.4 Ma. These ages are synchronous across the core complex and ages of the two minerals collected from the same localities are indistinguishable within error (Dokka et al., 1986). Apatite fission track and (U-Th)/He ages from the Harrison Pass pluton yield weighted-mean ages of 14.6±1.1 Ma and 14.8±1.5 Ma, respectively, and these ages also show no east-to-west change across the core complex (Colgan and Metcalf, 2006). All of these data indicate that final post-mylonitic exhumation of the R-EH core complex occurred very rapidly.

Based on the presence of stacked, oppositely vergent fold-nappes within the Ruby Mountains, Howard (1966) proposed that at least part of the intense folding in the metamorphic infrastructure of the R-EH core complex is extensional in origin. Subsequently, detailed geochronological and structural studies have provided extensive evidence for reworking of Cretaceous fold-nappes during Tertiary extension (Howard, 1980; Wright and Snoke, 1993; MacCready et al., 1997; McGrew et al., 2000). MacCready et al. (1997) provided compelling evidence for north–south-oriented plastic flow of material in the lower tier into the area beneath the core-complex detachment system during extension. They also documented in detail the transition between distributed pure-shear-dominated flow in the lower tier and localized simple shear in the mylonitic shear zone (Fig. 3A). Reconstructions of the Tertiary basins that flank the R-EH metamorphic core complex show that basin-fill sedimentary rocks do not reflect the amount of exhumation recorded in the core complex. This additional evidence argues in favor of lower-crustal flow into the area of concentrated extensional denudation (Satarugsa and Johnson, 2000). Therefore, it seems that the record of solid-state flow and voluminous Tertiary magmatism within the lower tier of the R-EH metamorphic core complex reflects a complex lower-crustal response to localized middle- and upper-crustal extension.

ALBION-RAFT RIVER-GROUSE CREEK MOUNTAINS, UTAH AND IDAHO

Introduction

The Albion Mountains-Raft River Mountains-Grouse Creek Mountains (A-RR-GC) metamorphic core complex encompasses the Albion, Raft River and Grouse Creek Mountains in northwestern Utah and southern Idaho and exposes rocks ranging in age from Archean to Tertiary (Figs. 1, 4) (Armstrong, 1968b; Compton, 1972, 1975; Compton et al., 1977; Wells, 1996). Several workers have divided rocks within the A-RR-GC metamorphic core complex into a series of allochthonous sheets bounded by low-angle faults and overlying an autochthon (Armstrong, 1968b; Compton et al., 1977; Todd, 1980; Miller, 1980). However, given the current level of understanding, it is not possible to correlate most of the allochthonous sheets across the A-RR-GC metamorphic core complex. Therefore, for the purposes of this paper, we recognize a two-tiered tectonostratigraphy consisting of a lower autochthon structurally overlain by a composite allochthon consisting of one or more fault-bounded sheets (Figs. 3B, 4; Table 1). Throughout the core complex, the structurally highest levels of the allochthon consist of nonmetamorphosed or weakly metamorphosed structurally attenuated Pennsylvanian to Permian strata (Figs. 3B, 4). Two normal-sense, low-angle detachment faults and associated footwall shear zones separate the allochthon from the underlying autochthon (Sabisky, 1985; Malavieille, 1987b; Saltzer and Hodges, 1988; Wells et al., 2000; Wells, 2001). The lowest structural level of the autochthon is composed of Late Archean adamellite orthogneiss that intrudes an assemblage of metatrondhjemite, schist, and amphibolite (Green Creek complex of Armstrong, 1968b) and is unconformably overlain by the Paleo- or Neoproterozoic(?) Elba Quartzite (Figs. 3B, 4) (Armstrong, 1968b; Compton et al., 1977; Todd, 1980; Miller, 1980; Wells et al., 1998). Within the Albion and Grouse Creek Mountains, fault-bounded Neoproterozoic through Ordovician rocks lie beneath the range-bounding detachment fault and are thus part of the autochthon as it is defined here (Figs. 3B, 4) (Armstrong, 1968b; Todd, 1980; Miller, 1980, 1983; Saltzer and Hodges, 1988). In contrast, in the Raft River Mountains, the deepest structural levels of the allochthon are comprised of Neoproterozoic through Ordovician metasedimentary rocks separated from Pennsylvanian–Permian strata by low-angle, normal-sense faults (Figs. 3B, 4) (Compton et al., 1977; Wells, 1997). This basic structural outline serves as the framework for the structural, metamorphic, and magmatic events described in geochronological order below.

Precambrian Through Paleozoic History

An incomplete and poorly understood Precambrian history is recorded in the rocks exposed in the autochthon of the A-RR-GC core complex. The adamellite orthogneiss has been dated at 2510±170 Ma (Rb-Sr whole-rock minimum age) by Compton et al. (1977) and cores of zircons have yielded an upper intercept on concordia of ~2620 Ma (Egger et al., 2003). This plutonic unit intrudes a complex polydeformed Archean assemblage of metatrondhjemite, metagabbro, mafic metavolcanic rocks, and metasedimentary rocks (Armstrong, 1968b; Compton, 1972, 1975; Compton et al., 1977; W. A. Sullivan, unpublished data). These rocks record at least two episodes of Late Archean magmatism. If the Elba Quartzite is interpreted as Paleoproterozoic (Compton et al., 1977; Crittenden, 1979), then this unit may be correlative with Paleoproterozoic quartzites exposed in the Medicine Bow Mountains in southeastern Wyoming (Karlstrom et al., 1983). In such case, the Elba Quartzite exposed in the A-RR-GC core complex would record deposition of a Paleoproterozoic passive-margin sequence associated with rifting of the Archean craton. Finally, Neoproterozoic rifting of the western margin of North America and formation of a Neoproterozoic to mid-Paleozoic passive margin is recorded by the deposition of the Cordilleran miogeoclinal sequence. Although, wherever the base of this sequence has been observed in the northeastern Great Basin, it is a fault rather than a surface of deposition (Compton et al., 1977; Todd, 1980; Miller, 1980; McGrew, 1992).

Mesozoic History

Due to a lack of Mesozoic igneous bodies, the exact timing of Mesozoic deformational and metamorphic events in the A-RR-GC core complex is not completely understood. However, a complex sequence of events, including alternating episodes of contraction and extension, has been recognized throughout much of the core complex. Egger et al. (2003) have recently proposed an initial episode of Mesozoic deformation and metamorphism at ~160 Ma based on the presence of ~160-Ma rims overgrowing zircons in the Archean adamellite orthogneiss. Evidence for deformation associated with prograde metamorphism is extensive throughout the A-RR-GC core complex. In the Raft River Mountains, it is manifested by: (1) a subhorizontal foliation and north-northeast- to northeast-trending elongation lineations associated with top-to-the-northeast simple shear and (2) a synchronous component of flattening strain related to thrust-nappe emplacement (Compton et al., 1977; Malavieille, 1987b; Wells and Allmendinger, 1990; Wells, 1997). Mesozoic fabrics in the Albion Mountains also trend northeast and associated folds are southeast vergent (Miller, 1980). In the Grouse Creek Mountains, an initial north–south-trending lineation and west-vergent folds are developed throughout the autochthon (Todd, 1980). Subsequently, Wells et al. (2000) obtained ~105 Ma $^{40}Ar/^{39}Ar$ ages from syndeforma-

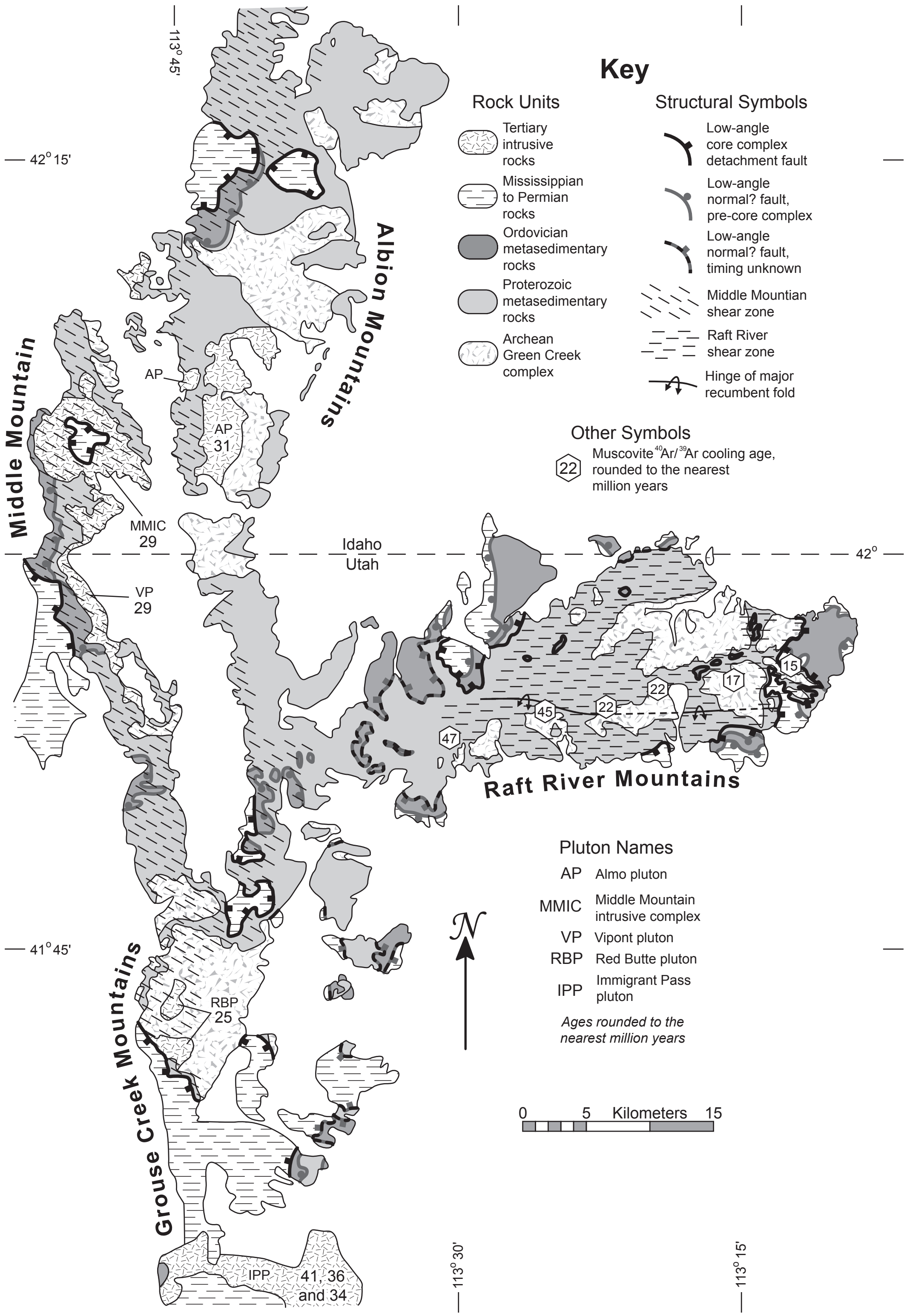

Figure 4. Geologic map of the Albion Mountains-Raft River Mountains-Grouse Creek Mountains core complex showing major structures and intrusive bodies. Adapted and compiled from Compton (1972, 1975), Compton et al. (1977), Miller (1980), and Wells (1997, 2001).

tional muscovite from some of these rocks and reinterpreted the deformation as extensional.

Garnet-rim thermobarometry and Gibbs'-method modeling of garnet growth coupled with in-situ monazite isotopic dating provide evidence for multiple episodes of thrust burial within the autochthon and allochthon of the A-RR-GC core complex (Hanson, 1997; Hoisch et al., 2002a; Harris, 2003; Kelly et al., 2003, 2004). Rapid episodes of garnet growth due to thrust burial beneath the Basin-Elba fault occurred at ~144 Ma and ~120 Ma and generally coincide with pressure increases of up to ~2.7 kb (Hanson, 1997; Hoisch et al., 2002a; Harris and Hoisch, 2003; Kelly et al., 2003, 2004). Strickland et al. (2007) reported similar dates (120–140-Ma) for rims on detrital zircons collected from schist in the southern Albion Mountains and interpret them as direct dates of contractional deformation. Peak temperatures associated with these events are on the order of 575–635°C. Estimates of absolute peak pressures are highly variable, despite the well-constrained relative pressure increases, ranging from 4.5–9.5 kb (Hanson, 1997; Hoisch et al., 2002a; Kelly et al., 2003). Therefore, we follow Hoisch et al. (2002a) and adopt an estimate of ~6.5 kb as the approximate peak pressure obtained during mid-Cretaceous thrust burial in the Albion and Grouse Creek Mountains. Archean mafic metavolcanic rocks and metagabbros exposed in the autochthon of the Raft River Mountains preserve an epidote-amphibolite facies metamorphic assemblage. The absence of garnet in these rocks limits peak metamorphic pressures to ~6 kb or less (W. A. Sullivan, unpublished data). Wells et al. (2000) interpreted $^{40}Ar/^{39}Ar$ spectra from hornblendes collected from the Archean mafic metavolcanic rocks as indicating maximum cooling ages between 54.6–90.5 Ma, placing a Late Cretaceous to early Tertiary upper limit on the age of epidote-amphibolite facies metamorphism in the Raft River Mountains.

Numerous studies indicate an episode of Late Cretaceous or early Tertiary extension in the A-RR-GC core complex that followed peak metamorphism and thrust-nappe emplacement (Wells et al., 1990; Wells, 1997; Wolff, 1997; Wells et al., 1998). Wells et al. (1990) recognized ~82–90-Ma $^{40}Ar/^{39}Ar$ muscovite cooling ages in the lower structural levels of the allochthon in the Raft River Mountains and interpreted them to represent cooling during the final stages of layer-parallel extension postdating peak metamorphism. Wells (1997), Wolff (1997), and Wells et al. (1998) have since shown that this extension was accommodated along a series of low-angle, top-to-the-west attenuation faults in the allochthon, and Wells et al. (2000) interpreted fabrics as old as ~105 Ma as extensional in origin. Additionally, Hodges and Walker (1992) have interpreted northwest-trending lineations in the northern Albion Mountains (Miller, 1980) associated with top-to-the-west displacement (Malavieille, 1987b) and Late Cretaceous cooling ages (Armstrong, 1976) as evidence for Late Cretaceous extensional tectonics. Renewed contraction followed Late Cretaceous extension throughout the A-RR-GC core complex. In the Raft River Mountains, this deformation is manifested by km-scale tight to isoclinal recumbent folds that deform the attenuation faults in the allochthon (Wells, 1997; Wells et al., 1998). Using Gibbs'-method modeling of garnet growth and in-situ monazite Th-Pb dating, Wells and Hoisch (2002) and Hoisch et al. (2002b) have documented a Late Cretaceous or early Tertiary pressure increase of ~0.9 kb in the Albion Mountains, and Harris (2003) related this episode of thrust loading to movement along the Basin-Elba fault. Hoisch and Wells (2004) have also proposed an episode of Late Cretaceous to early Tertiary prograde metamorphism in the Grouse Creek Mountains.

Tertiary History

A protracted history of Tertiary crustal-scale extension centered about two major normal-sense mylonitic shear zones and associated frictional/brittle detachment faults that range in age from Eocene to late Miocene is recorded in the A-RR-GC core complex (Fig. 4) (Sabisky, 1985; Malavieille, 1987a, 1987b; Saltzer and Hodges, 1988; Wells, 1997, 2001; Wells et al., 2000). A 25–31-Ma suite of granitic plutons was emplaced in the Grouse Creek and Albion Mountains during Tertiary extension (Fig. 4). Forrest and Miller (1994) dated the Almo pluton and Middle Mountain intrusive complex at ~29 Ma (U-Pb monazite), and Strickland et al. (2007) obtained an age of 30.5±1 Ma from the Almo pluton (U-Pb, zircon). The Vipont pluton has been dated at 27±2 Ma (U-Pb, Monazite) by Wells et al. (1997b), and Strickland et al. (2007) obtained a 29±0.3 Ma age (U-Pb, zircon) from part of the pluton cut by the Middle Mountain shear zone. Compton et al. (1977) dated the Red Butte pluton in the northern Grouse

Creek Mountains at 24.9±0.6 Ma and Immigrant Pass pluton in the southern Grouse Creek Mountains at 38.2±2 Ma (Rb-Sr whole-rock minimum ages). Egger et al. (2003) have subsequently shown that the Immigrant Pass pluton was emplaced in three pulses (41.3±0.3 Ma, 36.1±0.2 Ma, and 34.3±0.3 Ma), and they provided an age of 25.3±0.5 Ma for the Red Butte pluton (U-Pb zircon) (Fig. 4). The oldest phase of the Immigrant Pass plutonic complex cuts apparent normal faults in the allochthon, requiring a pre-41-Ma age for the earliest extension in the Grouse Creek Mountains (Egger et al., 2003).

Armstrong (1968b) proposed an episode of Tertiary metamorphism in the A-RR-GC core complex restricted to the southern Albion Mountains in the vicinity of the Almo pluton, and Saltzer and Hodges (1988) reported cooling ages of 38.2±0.8 Ma for hornblende that grew in amphibolite bodies within the autochthon during this episode of metamorphism. In the southern Grouse Creek Mountains, pelitic schists within the autochthon record an episode of Tertiary amphibolite-facies metamorphism synchronous with emplacement of the Red Butte pluton (Todd, 1973; Compton et al., 1977; Egger et al., 2003). A north–south-trending elongation lineation developed during this metamorphic event. At high structural levels, this lineation is overprinted by east–west-trending lineations associated with the extensional Middle Mountain shear zone (Todd, 1973; Egger et al., 2003).

The A-RR-GC core complex is unusual among Cordilleran metamorphic core complexes in that it has been exhumed along two oppositely rooted, Tertiary, normal-sense shear zones and associated normal-sense detachment faults (Figs. 3B, 4). The west-rooted Middle Mountain shear zone and associated detachment fault lie along the west side of the complex in the Albion and Grouse Creek Mountains (Saltzer and Hodges, 1988; Wells et al., 1997a; Wells, 2001) and the east-rooted Raft River shear zone and associated detachment fault lie along the east side of the complex in the Raft River Mountains (Fig. 4) (Sabisky, 1985; Malavieille, 1987a; Wells, 2001). Shear-sense indicators from these two shear zones yield top-to-the-west-northwest, normal-sense displacement for the Middle Mountain shear zone and top-to-the-east, normal-sense displacement for the Raft River shear zone (Compton, 1980; Sabisky, 1985; Malavieille, 1987a, 1987b; Saltzer and Hodges, 1988; Wells, 2001).

Saltzer and Hodges (1988) recognized that upper greenschist- to amphibolite-facies deformation associated with west-northwest-trending lineations within the Middle Mountain shear zone was in part synchronous with Tertiary metamorphism in the area and that the 29-Ma Middle Mountain intrusive complex was deformed by shear zone fabrics. Miller and Bedford (1999) documented stope-blocks of Middle Mountain shear zone mylonites within the 29-Ma Almo pluton. Subsequently, a number of workers have shown that the Red Butte pluton is deformed by the Middle Mountain shear zone (Sheely, 2001; Egger et al., 2003; Wells et al., 2004). Wells et al. (2000) reported cooling ages from the Middle Mountain shear zone of 37 and 42 Ma ($^{40}Ar/^{39}Ar$, muscovite). These data point to an early episode of high-temperature, west-northwest-directed, normal-sense displacement along the Middle Mountain shear zone. The resulting exhumation and cooling took place in the late Eocene to early Oligocene, prior to emplacement of the 25–31-Ma plutonic suite in the Albion and Grouse Creek Mountains. A second pulse of deformation along the Middle Mountain shear zone produced east–west-trending greenschist-facies fabrics which deform plutons of the 25–31-Ma suite. These younger, lower-grade fabrics were recognized by Sheely (2001), Egger et al. (2003), and Wells et al. (2004). Cooling ages of rocks that contain these fabrics are ~20 Ma ($^{40}Ar/^{39}Ar$ muscovite and biotite) (Sheely et al., 2001). Muscovite from the Raft River Mountains yields $^{40}Ar/^{39}Ar$ cooling ages that range from ~47 Ma in the westernmost part of the range to ~15 Ma in the easternmost part (Fig. 4) (Wells et al., 2000). This pattern indicates that exhumation associated with Eocene displacement along the Middle Mountain shear zone allowed cooling of the western part of the Raft River Mountains to below the closure temperature of muscovite, whereas the eastern end of the range remained buried until middle Miocene time (Wells et al., 2000). These assertions are supported by microstructural studies of strain and deformation mechanisms in the Raft River shear zone (Wells et al., 2000; Wells, 2001). Apatite fission-track ages from the west side of the A-RR-GC core complex record final unroofing accomplished by frictional/brittle range-bounding faults at ~13.5 Ma (Egger et al., 2003), whereas apatite fission-track ages from the Raft River Mountains record protracted, progressive west-to-east unroofing along the Raft River detachment fault between 13.5–7.4 Ma (Wells et al., 2000). The thermochronologic and microstructural data presented by Wells et al. (2000) and Wells (2001) argue for a rolling hinge (Wernicke and Axen, 1988) geometry for the Raft River shear zone.

In summary, the A-RR-GC metamorphic core complex was partially exhumed during the late Eocene along the west-rooted, normal-sense Middle Mountain shear zone (Saltzer and Hodges, 1988; Wells et al., 2000; Wells, 2001; Egger et al., 2003). After a brief hiatus, exhumation resumed in the late Oligocene or early Miocene and was accommodated along the Middle Mountain shear zone, the east-rooted, normal-sense Raft River shear zone, and their associated detachment faults.

SNAKE RANGE, NEVADA AND UTAH

Introduction

The SR metamorphic core complex encompasses the northern and southern parts of the Snake Range in east-central Nevada and can be extended to include the Kern Mountains and Deep Creek Range to the north (Figs. 1, 5) (Miller et al., 1999a). It includes rocks that range in age from Neoproterozoic to Tertiary (Gans et al., 1999a, 1999b; Lee et al., 1999a, 1999b, 1999c; Miller et al., 1994, 1999b; Miller and Gans, 1999; McGrew and Miller, 1995; Miller and Grier, 1995). Two basic structural elements are typically recognized in the SR core complex: (1) an upper tier of sedimentary and volcanic rocks, and (2) a lower tier of metamorphic and plutonic rocks (Figs. 3C, 5; Table 1) (Miller et al., 1983, 1999a; McGrew, 1993). The upper tier consists of brittlely attenuated nonmetamorphosed Cambrian through Permian sedimentary rocks and Tertiary volcanic and sedimentary rocks. It is separated from the lower tier by an east-rooted, frictional/brittle, normal-sense detachment fault (Misch, 1960; Miller et al., 1983; McGrew, 1993). Within the northern Snake Range and locally in the Kern Mountains and southern Snake Range, the frictional/brittle detachment fault is underlain by an east-rooted mylonite zone (Figs. 3C, 5) (Miller et al., 1983, 1999a; Bartley and Wernicke, 1984; McGrew, 1986, 1993; Gans, 1987; Lee et al., 1987). Elsewhere, the detachment fault is underlain by variably deformed plutonic and metasedimentary rocks that have experienced little or no post-Cretaceous penetrative deformation or metamorphism (Figs. 3C, 5) (Gans, 1987; Rodgers, 1987; Miller et al., 1988, 1999a). The mylonitic, metamorphic and plutonic rocks beneath the detachment fault collectively comprise the lower tier of this core complex. This basic structural outline serves as the framework for the structural, metamorphic, and magmatic events described in geochronological order below.

Mesozoic History

The complex Mesozoic deformational, metamorphic and magmatic history imposed upon Neoproterozoic through Ordovician metasedimentary rocks exposed in the lower tier of the SR metamorphic core complex includes two distinct episodes of metamorphism, numerous Jurassic and Cretaceous intrusions, and the development of at least two penetrative deformational fabrics. During the Jurassic, a suite of plutons all dated at ~160 Ma (U-Pb zircon) intruded the southern Snake Range and southernmost portion of the northern Snake Range (Fig. 5) (Miller et al., 1988). A highly variable subgreenschist- to amphibolite-facies metamorphic event that increases in grade both structurally downwards and nearer to pluton margins is associated with these plutons (Misch and Hazzard, 1962; McGrew, 1986, 1993; Miller et al., 1988). The presence of andalusite in metapelitic rocks in the amphibolite-facies contact aureoles of these plutons indicates emplacement at relatively shallow depths (Miller et al., 1988). Jurassic penetrative deformation has been widely recognized in the southern Snake Range and to the west in the Schell Creek Range. This deformation is manifested by a north–south-striking, east-dipping cleavage that forms an intersection lineation with bedding (Miller et al., 1988). This episode of cleavage development overlaps temporally with metamorphism associated with the Jurassic plutons in the southern Snake Range and has been interpreted by Miller et al. (1988) to have developed in response to top-to-the-west, layer-parallel simple shear. Cross-section reconstructions of the upper tier of the southern Snake Range indicate pre-Tertiary development of a west-vergent ramp anticline in the frictional/brittle upper crust of this area, although such a structure does not appear on published sections (McGrew, 1993). However, throughout most of east-central Nevada, there is little angular discordance across the Paleozoic-Tertiary unconformity, suggesting little Mesozoic deformation of the upper crust (Armstrong, 1968a, 1972; Gans and Miller, 1983).

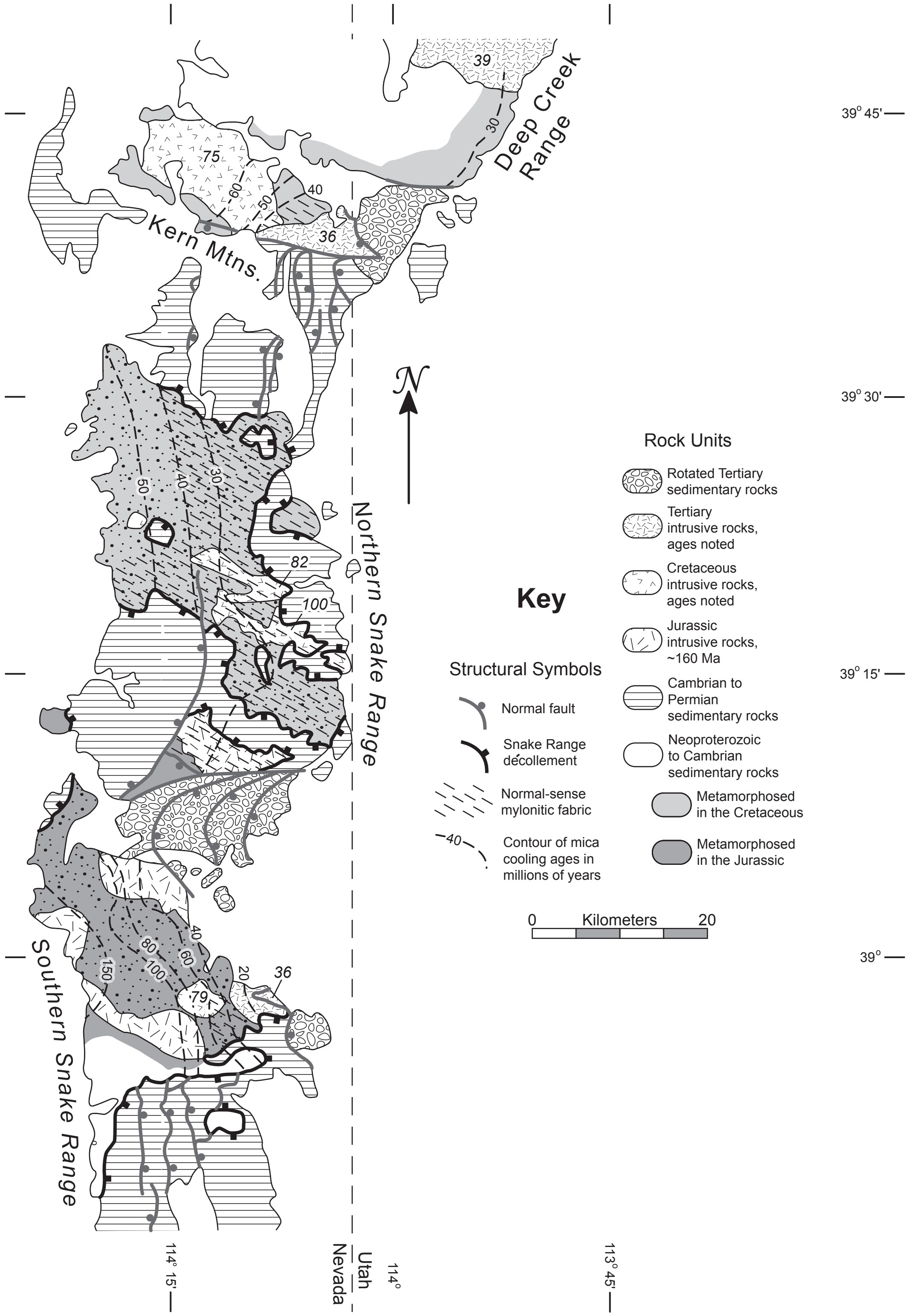

Figure 5. Geologic map of the Snake Range core complex showing major structures, intrusive bodies, and contours of mica-cooling ages. Adapted and compiled from Lee (1995), McGrew and Miller (1995), Miller and Grier (1995), Gans et al. (1999a, 1999b), Lee et al. (1999a, 1999b, 1999c), Miller and Gans (1999), and Miller et al. (1994, 1999a, 1999b).

Because of the wide variety of structural levels exposed in the lower tier of the SR metamorphic core complex, the record of Cretaceous deformation, metamorphism, and magmatism is highly variable. In the southern Snake Range, a weak cleavage that dips west relative to bedding and crenulates the older Jurassic cleavage is locally developed (Miller et al., 1988). Miller et al. (1988) correlated this cleavage with a similar one in the Schell Creek Range to the west and inferred a Cretaceous age for both. They interpreted this younger cleavage to have developed in response to top-to-the-east simple shear. Cretaceous metamorphism in the southern Snake Range is restricted to the contact aureoles of a few small Late Cretaceous two-mica granitic plutons (Lee et al., 1986; Miller et al., 1988). Available K-Ar muscovite data for these plutons indicate that they cooled below ~300°C within a few million years of their emplacement (Lee et al., 1970, 1981, 1986). This, coupled with their narrow contact aureoles, indicates emplacement at relatively shallow depths. A similar history of shallow Late Cretaceous plutonism and localized metamorphism, largely centered about the 75±9 Ma (U-Pb zircon) Tungstonia granite, is recorded in the Kern Mountains (Fig. 5) (Lee et al., 1986; Gans, 1987; Miller et al., 1988).

Most of the lower tier of the northern Snake Range experienced pervasive Barrovian metamorphism and penetrative deformation during the Late Cretaceous (Lee and Fischer, 1985; Geving and Holdaway, 1986; Geving, 1987; Miller et al., 1988; Miller and Gans, 1989; Huggins and Wright, 1989; Huggins, 1989; Gans et al., 1993; Lewis et al., 1999; Conrad and Colberg, 2005). Tertiary penetrative deformation has largely overprinted earlier deformation fabrics in the northern Snake Range, and Cretaceous deformation fabrics are now preserved only in the northwest part of the range and as inclusion trails within porphyroblasts (Huggins, 1989; Lewis et al., 1999). A 100±8-Ma (U-Pb, zircon) granitic to tonalitic plutonic complex affected by Late Cretaceous metamorphism is exposed in the lowest structural levels throughout the central part of the northern Snake Range (Fig. 5) (Miller et al., 1988). A swarm of ~82-Ma (U-Pb monazite) granitic pegmatite dikes intrudes both the plutonic rocks and surrounding metamorphic rocks (Fig. 5) (Miller et al., 1988; Miller and Gans, 1989; Huggins and Wright, 1989; Huggins, 1989). Igneous zircons and metamorphic monazite from the northern Snake Range give direct U-Pb dates of metamorphism that all cluster around 78 Ma (Lee and Fischer, 1985; Huggins and Wright, 1989; Huggins, 1989). Thermobarometric studies have been carried out in several locations in the lower tier in the southern part of the northern Snake Range (Geving and Holdaway, 1986; Geving, 1987; Huggins and Wright, 1989; Huggins, 1989; Lewis et al., 1999; Conrad and Colberg, 2005). Estimates of peak metamorphic temperatures are fairly consistent and range from 500–560°C in the south, increasing to 600°C or higher closer to the Cretaceous plutons exposed in the center of the range. Estimates of peak metamorphic pressures are highly variable, however, ranging from ~3.8 to 8.0–9.5 kb. By integrating data from three independent thermobarometers coupled with detailed petrographic studies, Lewis et al. (1999) estimated that a peak pressure of 8.1±0.7 kb was reached during Late Cretaceous metamorphism.

The depth and mechanism(s) of burial of the lower tier of the northern Snake Range have been a subject of much debate (Miller et al., 1983; Bartley and Wernicke, 1984; Gans et al., 1985; Gans and Miller, 1985; Wernicke and Bartley, 1985; Lewis et al., 1999). Miller et al. (1983) originally proposed that the rocks of the lower tier of the SR metamorphic core complex never reached depths greater than the stratigraphic depth of the lowest exposed units or 9–12 km. However, a growing body of petrologic and thermobarometric data indicates that the lowest structural levels of the northern Snake Range reached depths of ~30 km or more during the Cretaceous (Huggins, 1989; Lewis et al., 1999; Conrad and Colberg, 2005). This is in stark contrast to the southern Snake Range and Kern Mountains that indeed appear to have never reached depths much greater than the depth of stratigraphic burial (9–12 km) (McGrew, 1986; 1993; Miller et al., 1988). In the northwestern part of the northern Snake Range Lee et al. (1999a, 1999b) have documented a km-scale, east-vergent, recumbent, tight-to-isoclinal synform and some small east-vergent thrust faults and associated folds that they assign a Late Cretaceous age. Lewis et al. (1999) proposed a loosely constrained model that involves tectonic burial via a thick-skinned, west-vergent thrust system. Beyond this, however, little is known or understood about the mechanisms accommodating the apparent deep burial of the lowermost tier of the northern Snake Range. Finally, there is limited evidence for an episode of Late Cretaceous tectonic exhumation in the area of the SR core complex (Gans et al., 1993).

Tertiary History

A protracted history of Tertiary crustal-scale extension is recorded in the lower tier and frictional/brittle upper tier of the SR core complex. As with the extent of Mesozoic tectonic burial, the nature of this extensional deformation and the amount of tectonic exhumation have been a subject of much debate. Miller et al. (1983) and Gans and Miller (1985) originally interpreted the mylonitic shear zone and frictional/brittle detachment fault in the northern Snake Range as an exhumed, "fossil" plastic-to-frictional/brittle transition zone wherein the mylonite zone records pure-shear stretching of the plastic middle and lower crust. Subsequently, Bartley and Wernicke (1984) and Wernicke and Bartley (1985) interpreted these structures as large-displacement, low-angle normal faults. Microstructural and quartz *c*-axis fabric analyses from the footwall shear zones of the SR core complex indicate that the eastern two-thirds of these structures are characterized by large components of noncoaxial deformation accommodating top-to-the-east, normal-sense displacement. Mylonites in the westernmost part of the northern Snake Range experienced a more coaxial deformation history (McGrew, 1986; 1993; Lee et al., 1987). Within the northern Snake Range, a retrograde metamorphic event accompanied Tertiary penetrative deformation, growing new chlorite at structurally high levels and new biotite and local staurolite at structurally low levels (Geving, 1987; Huggins, 1989; McGrew, 1993; Lewis et al., 1999; Conrad and Colberg, 2005). Elsewhere in the SR core complex, Tertiary metamorphism is largely restricted to the narrow contact aureoles of ~39–36-Ma plutons that intrude the southern Snake Range and Kern Mountains (Fig. 5) (Miller et al., 1988). Tertiary intrusive bodies are notably absent from the northern Snake Range. The ~39–36-Ma plutonic episode also overlaps temporally with an extensive episode of intermediate to felsic volcanism dated at 36–35 Ma (Gans et al., 1989). A second less voluminous period of episodic volcanism with no known plutonic equivalent occurred between 29–23 Ma (Gans et al., 1989).

A progressive west-to-east decrease in K-Ar and $^{40}Ar/^{39}Ar$ mica cooling ages has long been recognized in the lower tier of the SR metamorphic core complex (Fig. 5) (Lee et al., 1970, 1980, 1986; Miller et al., 1988, 1999a; Lee and Sutter, 1991). The far western side of the northern Snake range cooled below ~300°C by 50 million years ago, whereas the western edge of the southern Snake Range cooled below ~300°C soon after the emplacement of the Jurassic plutons (Fig. 5). Modeling of $^{40}Ar/^{39}Ar$ spectra obtained from K-feldspars collected across the northern Snake Range indicates that the SR core complex experienced three episodes of rapid cooling during the Tertiary (Lee, 1995). The first of these took place in the middle Eocene (48–41 Ma) and is recognized only in the western part of the northern Snake Range (Lee, 1995). This cooling phase is probably related to initial formation of the low-angle, frictional/brittle Snake Range décollement and the apparent coaxial deformation recognized in the underlying mylonite zone in this part of the northern Snake Range (Lee et al., 1987; Lee, 1995). The second rapid cooling phase took place during the Oligocene (30–26 Ma) (Lee, 1995). This cooling phase corresponds to a well-documented episode of extension in the upper tier of the SR core complex, with high-angle normal faults cutting ~36-Ma volcanic rocks (Rowles, 1982; Miller et al., 1983; Miller et al., 1988; Gans et al., 1989). Final tectonic exhumation of the SR core complex along the Snake Range décollement occurred during the Miocene (~17 Ma) (Lee, 1995; Miller et al., 1999a). This phase of tectonic exhumation apparently took place very rapidly, as apatite fission-track cooling ages are indistinguishable (within error) across strike within most of the lower tier of the southern Snake Range and all of the northern Snake Range (Miller et al., 1999a). Noncoaxial deformation in the mylonite zones beneath the Snake Range décollement in the eastern half of the SR core complex may have taken place during both the Oligocene and, in the far eastern part of the range, Miocene episodes of extensional deformation and tectonic exhumation (Lee, 1995; Miller et al., 1999a). The mica and K-feldspar cooling data from the SR core complex argue strongly in favor of a rolling-hinge geometry for the Snake Range décollement (Wernicke and Axen, 1988; Lee, 1995); however, the last stage of tectonic exhumation apparently took place synchronously across most of the core complex (Miller et al., 1999a).

SYNTHESIS AND DISCUSSION

Introduction

The data and interpretations outlined in the previous sections show that the rocks exposed in the R-EH, A-RR-GC, and SR metamorphic core complexes record similar tectonic histories. A widely recognized three-part, first-order subdivision of the tectonic events recorded in the core complexes includes: (1) a Precambrian history involving Late Archean magmatism, development of a Paleoproterozoic passive margin, and Neoproterozoic rifting along the western margin of North America that resulted in a second passive margin; (2) initiation of contractional deformation, magmatism, and metamorphism in the Late Jurassic leading to significant crustal thickening during Cretaceous time and possibly an episode of Late Cretaceous to early Tertiary tectonic exhumation; and (3) a protracted and episodic history of mid-Tertiary crustal-scale tectonic denudation and variable magmatism. These events are summarized graphically in Figure 6. Below this first-order synthesis, however, several important differences exist among the three core complexes. These differences allow for significant conclusions to be drawn concerning the nature of tectonic events in the region and the processes operating in the hinterland of the Sevier orogenic wedge. Hence, what follows is an analysis and discussion of the structural, magmatic, and metamorphic histories of the R-EH, A-RR-GC, and SR core complexes as they relate to the Mesozoic and Tertiary tectonic history of the region and the processes that operated during the collapse of the Sevier orogenic wedge and the initial development of the Basin and Range extensional province.

Timing and Style of Mesozoic Crustal Thickening

The timing of the Mesozoic deformational, magmatic, and metamorphic events is fairly well constrained in both the R-EH and SR metamorphic core complexes. Moreover, information from recent geochronologic studies of metamorphic rocks in the A-RR-GC core complex coupled with thermochronologic data allow for a broad reconstruction of Mesozoic events in this region. In all three areas, the initiation of Mesozoic plastic contractional deformation and magmatism is loosely constrained to the Late Jurassic (Fig. 6). After the initial pulse of Late Jurassic magmatism and deformation, both the R-EH and SR core complexes underwent protracted contractional deformation throughout the Cretaceous (Fig. 6). Peak metamorphic conditions in these two areas were reached at ~84 Ma, and this metamorphism appears to be intimately related to an extensive pulse of peraluminous granitic magmatism. The A-RR-GC core complex also records protracted episodic deformation, thrust burial, and metamorphic mineral growth throughout much of the Cretaceous. However, contractional deformation stalled by ~105 Ma and the A-RR-GC core complex underwent multiple periods of significant extensional exhumation punctuated by renewed contraction and thrust burial, while the other two areas were experiencing crustal thickening, extensive magmatism, and high-grade metamorphism (Fig. 6). The cause of this regional variation in the style and timing of Late Cretaceous deformation remains unclear, but it is interesting to note that this upper-crustal extension was not associated with magmatic activity. This observation illustrates that extension and magmatism need not always be linked. There also appears to be spatial variation in the style of Mesozoic contractional deformation and related metamorphism and magmatism. The SR and A-RR-GC core complexes lie along strike within the hinterland of the Sevier orogenic belt (Fig. 1); not surprisingly, they record similar peak metamorphic temperatures at similar depths of burial. The style of Mesozoic contractional deformation in these areas is also similar, consisting of penetrative fabric development, localized folding, low-angle faulting, and evidence for top-to-the-east movement. In contrast, the R-EH core complex records much higher peak metamorphic temperatures and is characterized by extensive migmatization and large-scale fold-nappe emplacement within the lower tier. These observations record a fundamental change in the style of contractional deformation in the hinterland of the Sevier orogenic belt where higher metamorphic temperatures and associated partial melting have facilitated greater plastic flow of the lower crust.

We attribute the apparent lack of syncontractional magmatism in the A-RR-GC core complex to the composition of the lower crust in this area. Most of the core complex is underlain by relatively dry adamellite, metatrondhjemite, and metagabbro with only local domains of metapelitic rocks. Compared to

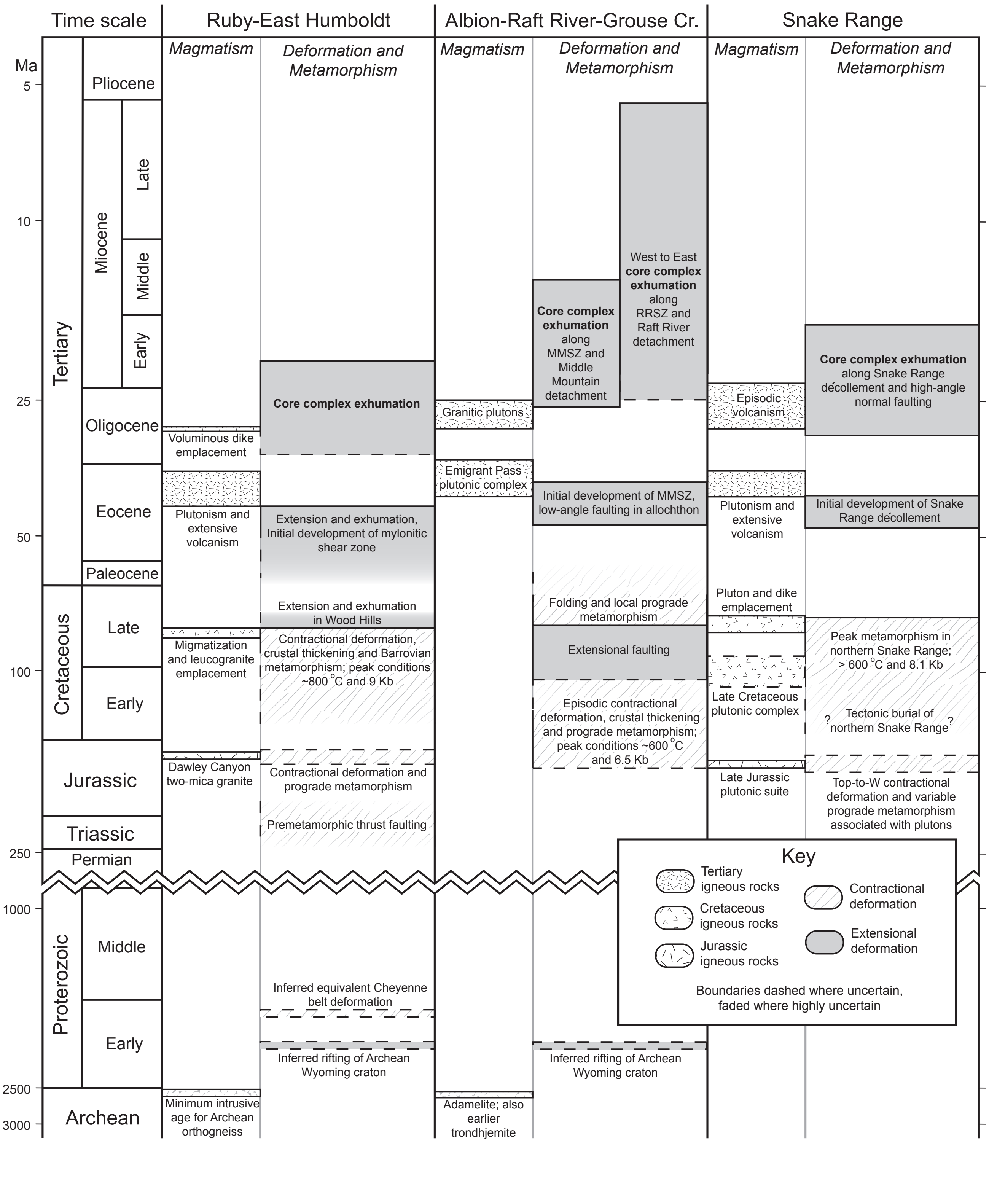

Figure 6. Diagram illustrating the major deformational, magmatic, and metamorphic events recorded in the Ruby Mountains-East Humboldt Range, Albion Mountains-Raft River Mountains-Grouse Creek Mountains, and Snake Range core complexes as discussed in the text. Logarithmic time scale in Ma.

the Neoproterozoic passive-margin pelites that must structurally underlie much of the R-EH and SR metamorphic core complexes, these Archean rocks provided a relatively infertile source for melt generation. These observations serve to illustrate the importance of the composition of the lower crust in controlling the distribution of magmatism within orogenic systems.

Timing and Style of Tertiary Extension

In all three areas, significant crustal-scale extension began in the middle to late Eocene and was closely followed by a ~42–36-Ma episode of magmatism (Fig. 6). Late Eocene extensional deformation fabrics yield: (1) a top-to-the-west-northwest sense of displacement along the Middle Mountain shear zone in the A-RR-GC metamorphic core complex; (2) an east-southeast–west-northwest pure-shear-dominated elongation direction in the SR metamorphic core complex; and (3) an inferred top-to-the-west-northwest sense of motion in the Wood Hills and R-EH core complex. These observations indicate a regionally homogeneous stress field throughout the northeastern Great Basin at this time. In all three areas, the initial phase of extensional deformation seems to have stalled in the late Eocene (Fig. 6). Crustal-scale, west-northwest-directed extension and magmatism resumed in the mid-Oligocene in the R-EH and SR core complexes, leading to final exhumation of the northern and central parts of the R-EH core complex by the late Oligocene and final exhumation of the SR core complex by late early Miocene time (Fig. 6). The A-RR-GC core complex also experienced a mid-Oligocene episode of magmatism. However, extension leading to core-complex exhumation in the A-RR-GC core complex did not resume until the end of the Oligocene and continued throughout most of the Miocene (Fig. 6). This later pulse of extension was east–west-directed and largely accommodated along the top-to-the-east Raft River shear zone. Contemporaneous extension in the SR metamorphic core complex is west-northwest–east-southeast directed. These data indicate that the regional stress field was somewhat inhomogeneous during the Miocene, in contrast to the regionally homogenous stress field present during the Eocene pulse of extensional deformation. To summarize, both pulses of extension occurred slightly earlier in the R-EH core complex than in the SR and A-RR-GC core complexes to the east. The final stages of extension in the A-RR-GC core complex were east–west-directed, indicating a change in the regional stress field. The timing of magmatism remains relatively constant throughout the region. However, the timing of extensional deformation varies between the three core complexes, indicating that late Oligocene magmatism and extension may not be entirely temporally linked in the northern Basin and Range province. Finally, the last stages of exhumation in the R-EH and SR core complexes and the western half of the A-RR-GC metamorphic core complex took place nearly synchronously across the north–south-trending ranges. The Raft River Mountains, on the other hand, record progressive west-to-east unroofing along the frictional/brittle Raft River detachment fault.

The data presented above show that the metamorphic rocks exposed in the R-EH, A-RR-GC, and SR core complexes record a wide variety of peak metamorphic pressures. Since all of these rocks currently lie at the same structural level (plus or minus a km of current topography), the observed variations in peak-metamorphic pressures must represent different amounts of exhumation during Late Cretaceous(?) and Tertiary extension. In the R-EH core complex, peak metamorphic pressures developed during Cretaceous tectonic burial range from 4–4.5 kb in the central Ruby Mountains to ~9 kb in the northern East Humboldt Range. This indicates a ~15-km difference in the amount of tectonic exhumation over a horizontal distance of ~80 km. Thermochronologic and petrologic data from the East Humboldt Range show that this area had decompressed to 3–4 kb by the Oligocene. Therefore, the along-strike variation in the amount of tectonic exhumation within the R-EH core complex may be due to localized pre-Oligocene extension in the northern part of the core complex (see Snoke and Mueller, 1993).

Three possibilities arise from this along-strike variation in the amount of exhumation: (1) the crust beneath the northern East Humboldt Range is now significantly thinner than that beneath the central Ruby Mountains; (2) the crust in the northern East Humboldt Range was significantly thicker than the crust in the central Ruby Mountains during the Late Cretaceous (Howard, 2003); and (3) some form of deep-crustal flow has allowed for significantly more mid-crustal exhumation in the northern part of the R-EH core complex. Seismic data indicate that the current thickness of the crust beneath the northeastern Great Basin is relatively uniform, and that the R-EH metamorphic core complex is underlain by the thickest crust in the region (Allenby and Schnetzler, 1983; Das and Nolet, 1998). Consequently, a large variation in the present-day crustal thickness resulting from differential exhumation seems unlikely. Evidence presented by MacCready et al. (1997) supports the notion of northward flow of the lower crust synchronous with extension along the mylonitic shear zone of the R-EH core complex. This is consistent with the hypothesis that some form of deep-crustal flow allowed for variations in the amount of tectonic exhumation during the Tertiary by redistributing the lower crust to areas of large-magnitude crustal extension. Comparisons of the fill in adjacent Tertiary basins with the amount of exhumation in the core complex also supports this hypothesis (Satarugsa and Johnson, 2000). A similar model proposed by Gans (1987) for the eastern Great Basin at the latitude of the SR core complex utilized east–west-directed lower-crustal flow and mantle-derived magmatic additions to explain extreme transport-parallel variations in the amount of middle- and upper-crustal extension and the flat Moho in the region. Alternatively, the evidence for decompression predating exhumation associated with the Tertiary mylonite zone in the northern East Humboldt Range and Wood Hills may indicate significantly thicker crust in that immediate area during the Late Cretaceous. In all likelihood, the exposure of deeper crustal levels in the northern part of the R-EH core complex is a result of both variations in Mesozoic crustal thickening and subsequent variations in Tertiary extension that appear to be partially accommodated by plastic redistribution of the lower crust.

A similar variation in Late Cretaceous metamorphic conditions is also recorded in the SR core complex with peak pressures ranging from 3–4 kb in the southern Snake Range and Kern Mountains to >8 kb in the northern Snake Range in the center of the core complex. However, unlike the gradational variations recorded in the R-EH metamorphic core complex, this 12–15-km difference in the amount of tectonic exhumation is abrupt, taking place over a horizontal distance of 20–25 km across complexly faulted and poorly exposed rocks in topographically low areas separating different parts of the core complex (Fig. 5). As with the R-EH core complex, variations in the amount of tectonic exhumation recorded in the SR core complex could also be explained if the initial mid-Eocene phase of tectonic exhumation was restricted to the northern Snake Range. However, this hypothesis is not supported by structural studies of the upper tier. These studies indicate that all of the extensional faults in the region are intimately tied to the Snake Range décollement, which is exposed in the northern and southern Snake Range (Miller et al., 1983, 1999a). Therefore, we feel that the abrupt variations in the amount of tectonic exhumation in the SR core complex require some form of lateral ramp or transverse fault system in the Snake Range décollement to localize an additional 12 km or more of exhumation in the vicinity of the northern Snake Range. These structures may now lie in the poorly exposed regions separating different parts of the SR metamorphic core complex. As with the R-EH core complex, some form of north–south-directed, syn-extensional lower-crustal redistribution of material and/or magmatic additions to the crust are needed to maintain a relatively constant crustal thickness. Gans (1987) pointed out that extension-parallel (east–west-directed) redistribution of the lower crust is needed in order to maintain a relatively flat Moho in the northeastern Great Basin. The evidence for abrupt, large-magnitude, extension-perpendicular (north–south) variations in the amount of exhumation outlined above emphasizes the additional need for north–south-directed lower-crustal flow into highly extended domains in order to maintain a constant crustal thickness in this region. These combined observations require a complex, three-dimensional pattern of lower crustal flow and magmatic additions throughout the northeastern Great Basin, a conclusion which should be applicable to many other extensional provinces as well. The very localized (variations over 10s of kms) and complex nature of lower crustal redistribution and magmatic additions required by these observations should be taken into consideration in the processing and interpretation of land-based seismic-reflection lines that commonly incorporate off-line receivers and therefore sample a three-dimensional volume of crust.

From examination of the data presented above, it is also apparent that the R-EH and SR core complexes expose deeper structural levels than the A-RR-GC core complex, which records peak metamorphic pressures of ~6.5 kb in the Grouse Creek Mountains.

Three possibilities arise to explain the variation in the amount of exhumation recorded in the three terranes: (1) the crust beneath the R-EH and SR core complexes is now thinner than the crust beneath the A-RR-GC core complex; (2) crustal thickening during the Late Cretaceous in the R-EH and SR areas was greater than that in A-RR-GC area; and (3) the syncontractional episodes of extension recorded in the A-RR-GC core complex maintained a thinner crust during Mesozoic contraction. As previously noted, large-scale variations in present-day crustal thickness seem unlikely, and the R-EH core complex is underlain by the thickest crust in the region (Allenby and Schnetzler, 1983; Das and Nolet, 1998). The voluminous Mesozoic plutonism recorded in the R-EH and SR core complexes and the complete lack of Mesozoic magmatism exposed in the A-RR-GC metamorphic core complex indicate greater crustal thickening in the first two areas. However, it may be that significant Mesozoic intrusions were emplaced beneath the A-RR-GC core complex and are simply not exposed at the current level of erosion. Additionally, the dry Archean intrusive rocks that make up much of the basement of the A-RR-GC core complex would be relatively difficult to melt during orogenesis. In such a case, the earlier syncontractional extensional deformation would have to account for the variations in Tertiary exhumation. Structural and metamorphic data indicate as much as 2 kb of tectonic decompression between thrust-loading episodes during contractional deformation in the A-RR-GC core complex (Wells et al., 1990, 1998; Hoisch et al., 2002a). This would account for the difference in Tertiary exhumation among the three core complexes while maintaining a similar level of total Mesozoic thrust loading. Consequently, it would appear that the lower amount of Tertiary exhumation in the A-RR-GC core complex is likely a result of syncontractional extension that maintained the overall crustal thickness in the region at a lower level than what was achieved in the R-EH and SR areas.

The development of oppositely vergent, diachronous shear zones within Cordilleran metamorphic core complexes is unique to the A-RR-GC metamorphic core complex. This geometry may have arisen in response to the apparent late Oligocene/Early Miocene change in the regional stress field outlined above. Alternatively, the opposing diachronous extensional shear zones in the A-RR-GC core complex may have developed because continued strain accumulation along the older Middle Mountain shear zone became unfavorable due to an inability to transport lower-crustal material (by either magmatic additions or solid-state flow) into domains of localized intense mid-crustal extensional strain. This would result in the extensional strain being redistributed into adjacent domains of thick crust. The latter of these hypotheses is supported by a lack of evidence for Tertiary mobilization of the autochthon of the A-RR-GC core complex and by the absence of a regional metamorphic event accompanying Tertiary extension.

The preceding synthesis illustrates how far our understanding of the R-EH, A-RR-GC, and SR core complexes and surrounding areas has progressed. However, many important questions remain unanswered. For instance, the SR core complex has been the center of much debate concerning the nature of metamorphic core complex detachment faults and their associated footwall shear zones (Miller et al., 1983; Bartley and Wernicke, 1984; Gans et al., 1985; Gans and Miller, 1985; Wernicke and Bartley, 1985; Lee, 1995; Lewis et al., 1999). Advances in the analysis of flow in plastically deformed rocks present opportunities to test each of the end-member models (pure-shear thinning vs. large-magnitude simple-shear translation) for the footwall shear zone in the northern Snake Range. Recent advances in geochronology have also helped to develop a first-order understanding of the timing of Mesozoic deformation and metamorphism in the A-RR-GC core complex, but the exact nature and extent of these processes within this area are still poorly understood. A better understanding of their nature and distribution will also help to unravel the cryptic Archean history in this area. Five distinct episodes of peraluminous granite magmatism during both extensional and contractional deformation have been recognized in the R-EH core complex, but the source of this voluminous granite melt has not yet been determined. Finally, as our understanding of the timing and significance of the large-scale features in each of these core complexes is refined, we can begin to unravel their fine-scale heterogeneities. A more precise understanding of the timing and nature of deformation, magmatism, and metamorphism in these terranes will help us to better understand the apparently episodic patterns of contraction and exhumation recorded in the hinterland of the Sevier orogenic belt and orogenic wedges in general.

CONCLUSIONS

The data and interpretations summarized in this paper demonstrate that rocks exposed in the R-EH, A-RR-GC, and SR metamorphic core complexes record similar tectonic histories (Fig. 6). Widely recognized tectonic events recorded in these rocks include: (1) Late Archean magmatism and the development of two passive margins; (2) significant protracted Mesozoic crustal thickening beginning in the Late Jurassic and culminating in the Late Cretaceous; and (3) significant protracted but episodic Tertiary extension and magmatism. Furthermore, an examination of variations in the style, timing, and distribution of deformation, metamorphism, and magmatism in the three core complexes leads to several important conclusions concerning the tectonic history of the region and nature of accommodation of crustal thickening and subsequent tectonic denudation in the Sevier orogenic wedge.

Mesozoic tectonism began in the Late Jurassic in all three areas. Protracted episodic contractional deformation and crustal thickening continued throughout much of the Cretaceous, culminating in extensive magmatism and peak metamorphism at ~84 Ma in the R-EH and SR core complexes. The A-RR-GC core complex, on the other hand, experienced an episode of extensional deformation at this time. This serves as an example of the importance of extensional denudation in making syncontractional adjustments to orogenic wedges but also indicates that these adjustments need not occur throughout the entire hinterland of an orogen. Additionally, the apparent effect of these syncontractional adjustments on the amount of later Tertiary crustal extension and exhumation that developed in the A-RR-GC area as compared to the R-EH and SR areas indicates that syncontractional processes may help to control the extent and distribution of subsequent crustal-scale extension. A paucity of Mesozoic magmatic activity in the A-RR-GC core complex is likely caused by the relatively dry, infertile Archean basement beneath this area compared to the thick Neoproterozoic passive-margin pelites that we believe must structurally underlie much of the R-EH and SR core complexes.

Each of the three core complexes experienced an initial middle Eocene pulse of extensional deformation closely followed by a late Eocene episode of magmatism. A second magmatic episode occurred during mid-Oligocene time in all three areas. However, extensional deformation leading to core-complex development is diachronous throughout the region, ranging from mid-Oligocene to middle to late Miocene. This indicates that Oligocene extension and magmatism may not be totally linked in the northern Basin and Range province. The amount of Late Cretaceous(?) and Tertiary tectonic denudation experienced within the R-EH and SR core complexes is highly variable. In the R-EH area, this variation likely resulted from restriction of Late Cretaceous(?) and middle Eocene pulses of extension to the northern part of the core complex. Variations in tectonic exhumation within the SR core complex likely resulted from a lateral ramp in the Snake Range décollement. These intra-core, complex variations in extensional exhumation appear to be partly accommodated by solid-state flow of the lower crust into regions of high mid- to upper-crustal extension. This lower-crustal redistribution must include both extension-parallel and subordinate extension-perpendicular components in addition to heterogeneous magmatic additions to the lower crust. These observations require the lower crust in this region to be heterogeneous, and the potential for abrupt extension-perpendicular compositional variations should be considered in processing and interpreting geophysical data. Moreover, one plausible explanation for the development of the Raft River shear zone in the A-RR-GC metamorphic core complex is that slip on the Middle Mountain shear zone was impeded by the inability of the more rigid Archean lower crust to flow into an area of large-magnitude mid-crustal extension. These interpretations concerning the lower crust call attention to the potential importance of lower-crustal flow in localizing extreme extensional strains in the mid-crust by helping to maintain a constant crustal thickness throughout an extending region.

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