Petrologic, tectonic, and metallogenic evolution of the southern segment of the ancestral Cascades magmatic arc, California and Nevada

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ABSTRACT

Ongoing arc magmatism along western North America was preceded by ancestral arc magmatism that began ca. 45 Ma and evolved into modern arc volcanism. The southern ancestral arc segment, active from ca. 30 to 3 Ma, adjoins the northern segment in northern California across a proposed subducted slab tear. The east edge of the Walker Lane approximates the east edge of the southern arc whose products, mostly erupted from stratovolcanoes and lava dome complexes arrayed along the crest of the ancestral arc, extend down the west flank of the Sierra Nevada. Southern arc segment rocks include potassic, calc-alkaline intermediate- to silicic-composition lava flows, lava dome complexes, and associated volcaniclastic deposits.

Northern and southern segment rocks are similar to other convergent-margin magmatic arc rocks but are compositionally distinct from each other. Southern segment rocks have lower TiO₂, FeO*, CaO, and Na₂O contents and higher K₂O contents, and exhibit less compositional-temporal variation. Compositional distinctions between the northern and southern segment rocks reflect the composition and thickness of the crust beneath which the associated magma systems were sourced. Northern segment rock compositions are consistent with generation beneath thin, primitive crust, whereas southern segment rocks represent magmas generated and fractionated beneath thicker, more evolved crust.

Although rocks in the two arc segments have similar metal abundances, they are metallogenically distinct. Small porphyry copper deposits are characteristic of the northern segment whereas significant epithermal precious metal deposits are most commonly associated with the southern segment. These metallogenic differences are also fundamentally linked to the tectonic settings and crustal regimes within which these two arc segments evolved.

INTRODUCTION

Cenozoic subduction along western North America is widely recognized as a major contributor to the geologic evolution of this region. Associated Cascades arc magmatism (McBirney, 1978) is universally accepted as representing subduction of the oceanic Farallon plate beneath North America. Subduction and related arc magmatism were progressively extinguished at the southern end of the arc by northward migration of the Mendocino triple junction and formation of a transform plate margin (Atwater and Stock, 1998). Cenozoic volcanic rocks of the Cascades magmatic arc have been traditionally divided into two components: (1) those derived from Pliocene to Quaternary volcanoes of the active High Cascades arc (McBirney, 1978; Hildreth, 2007), and (2) those associated with deeply dissected Tertiary (mostly Eocene to late Miocene) volcanoes of the ancestral Cascades arc. In Oregon and Washington the ancestral Cascades arc rocks form the Western Cascades (Callaghan, 1933; Thayer, 1937; Peck et al., 1964); together with minor Oligocene and Miocene volcanic rocks exposed in northernmost California (see du Bray and John, 2011, their figure 1), these form the northern segment of the ancestral Cascades magmatic arc (hereafter, northern arc segment). The southern segment of the ancestral Cascades arc (hereafter, southern arc segment), along the California-Nevada border, was first suggested by Noble (1972) and corroborated by Christiansen and Yeats (1992). Cousens et al. (2008) and Cogan et al. (2011) argued convincingly for a north-east-trending tear in the subducting slab between Mount Shasta and Lassen Peak, volcanoes that are part of the modern High Cascades magmatic arc. However, Glazner and Farmer (2008) suggested that the ancestral Cascades arc did not extend south of Lassen Peak. Studies by Putirka and Busby (2007), Busby et al. (2008a, 2008b), Cousens et al. (2008, 2011), Hagan et al. (2009), Busby and Putirka (2009), Putirka et al. (2012), and John et al. (2012) confirm the presence of subduction-related magmatic arc volcanic rocks that extend, astride the California-Nevada border, at least as far south as latitude 38°N. Those studies have considerably enhanced our understanding of the ancestral arc between Lake Tahoe and Mono Lake, California, but much of the remainder of the diffuse southern arc segment remains relatively poorly known.

Despite reasonably abundant geochronological data and the importance of the southern arc segment rocks, these data had not been assembled prior to the compilation of du Bray et al. (2009). The goal of the work described here is to evaluate the time-space-compositional evolution of magmatism associated with the southern arc segment and characterize genetic associations between magmatism and mineral deposits in this region. The southern arc segment extends between about latitudes 42°N and 37°N along the northwest-elongate region that spans the California-Nevada border (Fig. 1), where accumulations of Cenozoic volcanic rocks are reasonably abundant. These volcanic rocks include mafic and intermediate lava flows and interbedded debris-flow deposits, as well as intermediate-composition lava dome complexes and associated pyroclastic deposits. Rhyolite (including high-silica variants) lava domes, although not voluminous, are a significant constituent of the southern arc segment, especially in the Bodie Hills and Tonopah areas (Fig. 1). In contrast to the northern arc segment, phaneritic Tertiary intrusive rocks are essentially absent in the southern arc segment; shallowly emplaced intrusions have been identified but are rare.

Decades of geologic investigations in the southern arc segment, including those by Thompson and White (1964), O’Neil et al.
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The distinction between southern arc segment rocks and those that (1) clearly pre- or post-date the arc, or (2) represent geospatially coincident rocks whose genesis is unrelated to subduction, is not unambiguous. However, Christiansen and Yeats (1992) and Ludington et al. (1996) assigned Tertiary volcanic rocks of this region to one of three assemblages: (1) 43–19 Ma interior andesite-rhyolite, (2) 20–0 Ma bimodal basalt-rhyolite, or (3) 31–3 Ma western andesite. As summarized by John (2001):

(1) The interior andesite-rhyolite assemblage consists of mid-Cenozoic calc-alkaline rocks in central Nevada and western Utah that are dominated by caldera-derived rhyolite to dacite ash flows but also include volumetrically minor...
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andesite to dacite lava flows (Best et al., 2013; Henry and John, 2013). These rocks are related to flat subduction of the Farallon plate beneath western North America and subsequent lithospheric slab delamination that promoted asthenospheric mantle upwelling (Humphreys, 1995).

(2) The mid-Miocene to present bimodal basalt-rhyolite assemblage principally includes potassium-rich, tholeiitic basalt and basaltic andesite and rhyolite lava flows and flow dome complexes in southeast Oregon and central Nevada, largely east of the ancestral arc terrane. These rocks were erupted in an extensional, continental rifting environment and, although coeval with subduction-related rocks of the western andesite assemblage, are unrelated to arc magmatism; associated continental extension may reflect a subjacent mantle plume (Yellowstone hot spot) or collapse of an over-thickened orogenic plateau, which may have triggered magmatic upwelling and Yellowstone hot-spot magmatism (Colgan and Henry, 2009).

(3) Oligocene to Pliocene western andesite assemblage rocks in western Nevada and eastern California consist mostly of potassic, calc-alkaline intermediate-composition lava flows, domes, and breccias. These rocks, genetically associated with subduction of oceanic crust beneath western North America, are broadly equivalent to rocks that constitute the southern arc segment. For the purposes of this compilation and synthesis, we used the following criteria to differentiate plausible constituents of the southern arc segment from other volcanic rocks exposed in the area.

Spatial Constraints

Southern arc segment rocks include Tertiary volcanic rocks exposed between latitudes 42°N and 37°N. We suggest an eastern limit of the southern arc segment that is approximately coincident with the eastern edge of the Walker Lane (Fig. 1; Stewart, 1988; Faulds and Henry, 2008). The Walker Lane is coincident with a fundamental change in style but not composition (Putirka et al., 2012; Putirka and Platt, 2012) of volcanism; Oligocene, Miocene, and Pliocene volcanic rocks erupted west of the eastern edge of the Walker Lane are genetically associated with southern arc segment magmatism. In contrast, to the east, rocks of the interior andesite-rhyolite assemblage (Ludington et al., 1996) represent magmatism associated with orogenic arc subduction hinge line retreat. Accordingly, we infer that the change in interior andesite-rhyolite magmatism to that associated with the southern arc segment is transitional, which is consonant with the inferences of Cousens et al. (2008) and Henry and John (2013), who suggested that the southern arc segment does not have a distinct eastern edge and envisioned that subduction-related volcanism migrated progressively across the Great Basin and stagnated in the Sierra Nevada starting at 28 Ma, at the earliest. After 28 Ma, the migration of the slab hinge slowed considerably and the southern arc segment became established, largely post-20 Ma. The eastern limit of southern arc segment magmatism is admitted arbitrary but largely reflects the change from caldera-related volcanism (Fig. 1) to that associated with composite arc volcanoes (Henry and John, 2013).

The southwestern transition to southern arc segment magmatism is particularly ill defined in several areas. Specifically, the distribution and tectonic affinities of Oligocene and Miocene volcanic rocks in northwest Nevada, east of the Warner Range domain (the term “domain”, as used here, pertains to a geographically coherent component of the southern arc segment that includes a suite of samples from one or several related volcanic fields) (Fig. 1), are not well documented. Consequently, the distribution of southern arc segment rocks and the location of the boundary between those rocks, especially the South Willow Formation (Bonham and Papke, 1969), and rocks of the interior andesite-rhyolite assemblage are poorly constrained. Similarly, the east edge of the southern arc segment is ambiguous in the Pyramid domain (Fig. 1). As suggested by Ressel (1996), Miocene volcanic rocks in this area have transitional compositions. In the west part of the Pyramid domain (Virginia Mountains) these rocks have dominantly calc-alkaline compositions, whereas in the east part of the domain (Lake Range) the rocks are dominantly tholeiitic (Ressel, 1996). Accordingly, along this part of the southern arc segment, we delineate the boundary of the southern arc segment as separating these two ranges and infer that rocks to the east, in the Lake Range, are part of the bimodal assemblage and associated magmatic processes.

To the west, southern arc segment rocks, especially lava and volcaniclastic flows that are presumably products of stratovolcanoes and domes aligned along the crest of the ancestral arc, extend down the gently sloping west flank of the Sierra Nevada. These rocks are generally spatially coincident with the distribution of the western andesite assemblage of Ludington et al. (1996) and, conversely, geographically isolated from bimodal basalt-rhyolite and interior andesite-rhyolite assemblage rocks located east of the Walker Lane.

Age Constraints

Southern arc segment rocks are mostly between 25 and ca. 4 Ma, but may include rocks as young as ca. 3 Ma in the area immediately around Lake Tahoe (Cousens et al., 2008) and as old as 30 Ma in the Warner Range of northeastern California and northwestern Nevada (Duffield and McKee, 1986; Carmichael et al., 2006) and in the Granite Range of northwest Nevada (Bonham and Papke, 1969). Spatially coincident volcanic rocks less than 3 Ma with broadly calc-alkaline compositions and located north of the time-appropriate Mendocino triple junction position (Fig. 1) probably represent products of the active High Cascades arc. Other Pliocene to Holocene volcanic rocks distributed along the east edge of the ancestral arc terrane, including young basalts near Lake Tahoe and Pleistocene to Holocene volcanic rocks in the Long Valley area, have broadly tholeiitic compositions and are assigned to the bimodal basalt-rhyolite assemblage. Time-space characteristics of southern arc segment rocks are generally consistent with equation 1 of Putirka et al. (2012), which predicts the arrival of the Mendocino triple junction and the approximate cessation of arc-related magmatism at any given latitude.

Compositional Constraints

Most southern arc segment rocks have calc-alkaline compositions (Irving and Baragar, 1971), though some, especially from the Warner and Pyramid Ranges and other isolated locales, are tholeiitic. Miocene to Pliocene tholeiitic, high-alumina (low-potassium) olivine basalts in the Modoc Plateau of northern California and southern Oregon are considered to represent magmatism associated with back-arc spreading or continental extension, not ancestral arc magmatism (Hart, 1985; Hildreth, 2007). Likewise, Tertiary potassic and ultra-high-potassium basalts, mostly in the Sierra Nevada (Moore and Dodge, 1980; Farmer et al., 2002), are probably unrelated to arc magmatism. As indicated by equation 1 of Putirka et al. (2012), the time-space characteristics of the Pliocene subset of these rocks are inconsistent with their being related to arc magmatism. In addition, rocks erupted after northward passage of the Mendocino triple junction and cessation of arc magmatism are distinctly more potassic than those associated with arc magmatism (Putirka et al., 2012). Although the time-space characteristics of the Miocene subset are consistent with a subduction relationship, they probably reflect low degrees of mantle partial melting, unrelated to subduction, during post-arc deformation along the edge of the Sierra Nevada (Putirka and Busby, 2007). Similarly, middle Miocene volcanic rocks temporally and chemically equivalent to the voluminous Columbia River Basalt Group, including the Steens and Lovejoy Basalts, are unrelated to southern arc segment magmatism.
Volcanic Rock Form Constraints

The southern arc segment rocks include lava flows, flow domes, and debris-flow deposits; these rock types are consistent with eruption from composite volcanoes and lava dome complexes that predominate in subduction-related magmatic arcs (McBirney, 1978; Hildreth and Moorabth, 1988; Hildreth, 2007). Otherwise age-appropriate ash-flow tuffs exposed within the study area are considered far-traveled, interior andesite-rhyolite assemblage rocks with sources far to the east and unrelated to southern arc segment magmatism (Henry and John, 2013). We have, however, included data for the Eureka Valley Tuff (erupted from the Little Walker caldera; Fig. 1), because Priest (1979) suggested that the tuff is a product of ancestral arc magmatism. However, Busby et al. (2008b) proposed an origin principally related to localization along a major transtensional fault zone related to development of a new plate margin. Compositional data for volcaniclastic sedimentary rocks intercalated within demonstrably arc-related rocks are not included in this analysis. Similarly, rocks from volcanoes that retain primary constructional morphology, unmodified by erosion, probably reflect either Quaternary High Cascades arc magmatism or back-arc magmatism associated with formation of the Modoc Plateau and are unrelated to ancestral arc magmatism; accordingly, compositional data for these rocks are excluded from our analysis.

BASEMENT ROCKS OF THE SOUTHERN ARC SEGMENT

The southern arc segment straddles the boundary, defined by radiogenic isotopic data for Mesozoic plutons (Fig. 2; Kisler, 1990; Tosdal et al., 2000), along the western edge of North American between old basement rocks to the southeast and younger rocks to the northwest. A variety of Paleozoic and Mesozoic accreted terranes form basement rocks northwest of this boundary, whereas Neoproterozoic and Paleozoic sedimentary rocks deposited on the rifted margin of the North American craton form basement rocks to the southeast (Stewart, 1980; Oldow, 1984; Silberling et al., 1992; Tosdal et al., 2000; Wyld, 2002; Provett and Dilles, 2008). Distinguishing between these old basement rocks and rocks of the younger accreted terranes is important because each potentially contributed different geochemical, isotopic, and metallogenic characteristics to magmas with which they interacted. Accreted terranes that form basement to the ancestral arc include: (1) Paleozoic to Mesozoic island arc sequences (East Klamath, Northern Sierra, and Black Rock terranes) that underlie the north and northwestern parts of the ancestral arc; (2) the Upper Triassic–Lower Jurassic Jungo terrane, an extraordinarily thick, back-arc basin sequence composed of fine-grained, continuously derived clastic rocks that lies mostly east of the ancestral arc; (3) the Pine Nut terrane, which is composed of Triassic and Middle to Late Jurassic continental margin arcs separated by Upper Triassic to Middle Jurassic sequences of interbedded volcanoclastic, clastic sedimentary, carbonate, and evaporite rocks that underlie much of the west-central part of the ancestral arc; and (4) the Paradise terrane, which is composed of Upper Paleozoic andesite, overlain by Triassic to Lower Jurassic marine to non-marine carbonate, volcanoclastic, and siliciclastic rocks, and underlies the west-central part of the ancestral arc (Fig. 2).

Most of the western edge of the southern arc segment is underlain by Mesozoic granitoids of the Sierra Nevada batholith (Fig. 2). These intrusions also extend east and northeast forming a belt of plutons emplaced into rocks of the North American craton (to the south) and accreted terranes (to the north). The proportion of basement rocks that consist of Sierran plutons is variable along the length and width and southern arc segment (e.g., Barton et al., 1988; Van Buer et al., 2009). In addition, recent seismic studies suggest that granitic basement is absent at the northwestern end of the southern arc segment in northeastern California and northwestern Nevada, including the area of Warner Range (Lerch et al., 2007; Van Buer et al., 2009).

TECTONIC SETTING OF THE SOUTHERN ARC SEGMENT

The southern arc segment straddles the boundaries between the Great Basin part of the Basin and Range, the Sierra Nevada, and the southern Cascade Mountains, and the Walker Lane forms a northwest-trending belt along the axis of the arc (Fig. 3). These late Cenozoic physiographic and tectonic features resulted from the complex Cenozoic tectonic processes that affected the region and are also reflected in the character and distribution of eruptive products and mineral deposits in the southern arc segment (e.g., Christiansen and Yeats, 1992; John, 2001; Faulds and Henry, 2008; Colgan and Henry, 2009; Vikre and Henry, 2011; John et al., 2012).

Most of the southern arc segment is in or along the margins of the Walker Lane in the variably extended western Great Basin; the west and northwest edges of the arc are in the relatively unextended Sierra Nevada–southern Cascade Mountains (Fig. 3). The amount of late Cenozoic extension across the Great Basin is strongly heterogeneous, and in the region of the southwestern arc segment varies from ~10% (northeast California–northwest Nevada; Colgan et al., 2006) to >150% (Yerington district–northern Wassuk Range; Provett, 1977; Dilles and Gans, 1995). In areas that underwent large-magnitude extension (i.e., >50%), an early period of rapid large-magnitude extension along closely spaced normal faults was followed by a younger period of low-magnitude extension on more widely spaced normal faults that formed the present basins and ranges (e.g., Provett, 1977; Dilles and Gans, 1995; Surpess et al., 2002; Colgan et al., 2006; Colgan and Henry, 2009).

The Walker Lane, a northwest-trending zone of dextral shear and transtension that connects with the Las Vegas shear zone south of the Garlock fault (Fig. 1; Atwater, 1970; Zoback et al., 1981; Stewart, 1988; Oldow, 1992; Dilles and Gans, 1995; Faulds and Henry, 2008), has been divided into 10 domains based on distinct structural styles (Fig. 3; Stewart, 1988; Faulds and Henry, 2008). Busby (2013) and Busby et al. (2013a) added a domain between the Sierran crest and the west side of the Walker Lane as portrayed by Faulds and Henry (2008) (SF, Fig. 3). Structures in these domains include complex systems of kinematically related and broadly coeval northwest-striking dextral faults and north- to northeast-northeast–striking normal faults (Modoc Plateau, Pyramid Lake, Walker Lake, and Inyo-Mono domains), east-northeast–striking sinistral-normal faults (Carson and Spotted Range–Mine Mountain domains and Mina deflection), and areas that lack major strike-slip faults (Goldfield domain). The Mina deflection is an east-west zone across which right-lateral displacement on northwest-striking faults in the Walker Lake domain is transferred west to similar faults in the Inyo-Mono domain. The Mina deflection also approximately corresponds to the edge of the Neoproterozoic continental margin (Fig. 2).

Recent studies across much of the northern and western parts of the southern arc segment suggest that modern Basin and Range extension began between ca. 16 and 10 Ma; earlier, this area was part of the little-deformed Sierra Nevada block (e.g., Dilles and Gans, 1995; Henry and Perkins, 2001; Stockli et al., 2002; Surpess et al., 2002; Colgan et al., 2006, 2011; Faulds and Henry, 2008; Colgan and Henry, 2009; Lee et al., 2009; Busby et al., 2013a). Dextral shear in the central Walker Lane related to formation of the transform plate margin also began ca. 10 Ma (Faulds and Henry, 2008). However, the late-Miocene tectonic history of much of the central part of southern arc segment is incompletely understood and contro-
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Figure 2. Map showing simplified basement terranes, Mesozoic plutons, and mineral deposits of the southern arc segment. Basement terranes modified from Silberling (1991) and Silberling et al. (1992): BR—Black Rock terrane; Cz—Cenozoic cover deposits overlying indeterminate basement rocks; EK—East Klamath terrane; GC—Golconda allochthon; JO—Jungo terrane; NAm—North American mio-gocline; NS—Northern Sierra terrane; PD—Paradise terrane; PN—Pine Nut terrane; RM—Roberts Mountains allochthon; SN—Sierra Nevada batholith; TR—Trinity terrane; WK—terranes of western and central Klamath Mountains; WS—terranes of the Western Sierra (includes Bucks Lake, Don Pedro, Foothills, and Merced River terranes); YR—Yreka terrane. Northwestern extent of Mesozoic granitic basement from Lerch et al. (2007) and Van Buer et al. (2009). Red dashed line is the initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ isopleth for Mesozoic plutonic rocks in California (Kistler, 1990) and Nevada (Tosdal et al., 2000). Blue dashed line is the $^{208}\text{Pb}/^{204}\text{Pb} = 38.8$ isopleth (Tosdal et al., 2000). Mineral deposits: 1—High Grade; 2—Hayden Hill; 3—Leadville; 4—Pyramid; 5—Guanomi; 6—Golden Dome; 7—Peavine; 8—Wedekind; 9—Olinghouse; 10—Gooseberry; 11—Ramsey-Comstock; 12—Talapoosa; 13—Comstock Lode; 14—Flowery (Golden Eagle); 15—Como; 16—Dan Tucker–Summit King; 17—Rawhide; 18—Monitor/Leviathan; 19—Monitor/Zaca; 20—Patterson-Silverado; 21—Masonic; 22—Borealis; 23—Bodie; 24—Aurora; 25—Cinnabar Canyon/Calmono; 26—Paradise Peak; 27—Santa Fe–Isabella–Pearl; 28—Tonopah; 29—Divide/Tonopah Divide; 30—Divide/Hasbrouck; 31—Goldfield.
Figure 3. Map showing Cenozoic tectonic features and mineral deposits (summarized in Table 3) of the southern arc segment. Domains of the Walker Lane from Faulds and Henry (2008), Pluhar et al. (2009), Busby (2013): C—Carson; G—Goldfield; IM—Inyo-Mono; MD—Mina deflection; MP—Modoc Plateau; PL—Pyramid Lake; SR—Spotted Range–Mine Mountain; WL—Walker Lake; SF—Sierra Front. Areas of steep (>40°) tilting of Oligocene and early Miocene volcanic rocks modified from John et al. (1989) and Dilles and Gans (1995). Mineral deposits as in Figure 2.
versial; some studies suggest earlier periods of “pre–Basin and Range” extension and/or strike-slip faulting along ancestral Walker Lane faults (e.g., Proffett, 1977; Eken et al., 1980; John et al., 1989; Seedorff, 1991; Hardyman and Oldow, 1991; Dilles and Gans, 1995).

Early Miocene and older (222 Ma) volcanic rocks in numerous areas in the central and southeastern parts of the southern arc segment are steeply tilted (240°), which is uncharacteristic of modern Basin and Range extension (Fig. 3). Several studies suggested that earlier period(s) of pre–Basin and Range extension, possibly related to southwestward migration of extension that accompanied or slightly post-dated silicic ignimbrite magmatism in areas northeast of the southern arc segment, affected much of the east-central and southeastern parts of the southern arc segment (Figs. 1, 3; Proffett, 1977; Seedorff, 1981, 1991; Shaver and McWilliams, 1987; John et al., 1989; Hardyman and Oldow, 1991; Dilles and Gans, 1995; John, 1995; Hudson et al., 2000). More recent studies of several of these areas indicate that either extension is significantly younger than previously estimated and broadly synchronous with the initiation of regional Basin and Range extension (e.g., Yerington district–northern Wassuk Range: Dilles and Gans, 1995; Surpless et al., 2002; southwest Paradise Range: Sillitoe and Lorson, 1994) or these areas are paleovalleys, not extensional basins (e.g., Candelaria trough; Henry and John, 2013). Faulds and Henry (2008) concluded that dextral shear in the central and southern Walker Lane probably started ca. 10 Ma and has propagated northwest to the Modoc Plateau (Fig. 3). In contrast, several previous studies concluded that strike-slip faulting began in the central Walker Lane (i.e., northern Wassuk, Gabbs Valley, and Gillis Valley Ranges) at ca. 25 Ma (Eken et al., 1980; Hardyman and Oldow, 1991; Oldow, 1992; Dilles and Gans, 1995).

The effects of the complex and variable late Cenozoic tectonism on southern arc segment development are unclear. In general, during its earliest stages, the arc developed in a neutral to a mildly extensional or transtensional stress field with the onset of Basin and Range extension and Walker Lane strike-slip faulting at ca. 16−10 Ma. A relatively uniform horizontal stress field is suggested by volcanic landforms dominated by approximately equidimensional strato-volcanoes and composite dome fields, broadly circular volcanic fields, and the scarcity of dikes (Nakamura, 1977; Takada, 1994; John, 2001), as exemplified by middle to late Miocene volcanic fields in northeastern California (Grose, 2000), the Virginia City area (Hudson et al., 2009), and the Bodie Hills (John et al., 2012). Stress fields perturbations that may have influenced arc magmatism, including the strongly extensional stress field inferred during eruption of the late Miocene K-rich Stanislaus Group near Sonora Pass in the eastern Sierra Nevada, are evident in some places (Putirka and Busby, 2007; Busby et al., 2008b). Rapid, large-magnitude extension in the Yerington district–Buckskin Range at ca. 14 Ma was accompanied by eruption of voluminous hornblende andesite (Proffett, 1977; Dilles and Gans, 1995). The long-active (ca. 15−6 Ma) Bodie Hills volcanic field may have been localized by its complex tectonic setting, between the Walker Lane and the little-deformed Sierra Nevada and at the northwest end of the Mina deflection, in which it is situated. The Bodie Hills volcanic field also may be coincident with the margin of the Neoproterozoic craton (John et al., 2012).

DATA COMPILATION METHODS

Geochemical data for more than 2000 samples were compiled from a variety of sources (du Bray et al., 2009). The compilation is representative of the southern arc segment rocks, but appropriate geochemical data are not available for all parts of the southern arc segment. In some parts of the southern arc segment, only analyses of altered rocks, inappropriate to petrogenetic studies, are available. Other parts of the southern arc segment are inadequately sampled or completely unsampled (Fig. 1). Nevertheless, available data probably adequately represent the southern arc segment; additional geochemical data likely will not dramatically alter findings presented herein.

Subsequent to publication of the compilation (du Bray et al., 2009), (1) numerous new analyses, especially for rocks of the Bodie Hills volcanic field (John et al., 2012), were added to the interpreted data set, and (2) some samples were removed because subsequent re-evaluation of geologic relations or compositional features suggest that these represent modern arc, bimodal, or interior andesite-rhyolite magmatism. In addition, regional ash-flow tuff samples (unrelated to arc magmatism), scarce intrusive rocks (less likely than volcanic rocks to preserve magmatic liquid compositions), and poorly located samples or those with poorly constrained geologic context, including age, were removed from the interpreted data set (see the Supplemental File1).

Samples with any of the following characteristics are considered to be altered and were also removed from the interpreted southern arc segment data set: SiO₂ abundances greater than 78%; total volatile content greater than 4%; Al₂O₃ abundances greater than 22% or less than 10%; total iron abundances (as FeO) greater than 15%; MnO abundances greater than 0.6%; CaO abundances greater than 6% or less than 0.15%; values of Na₂O/K₂O less than 0.5; and samples with initial total analytic totals greater than 102% or less than 98%. These thresholds were established by considering typical igneous rock compositions and by reference to the tails of frequency distributions presented by du Bray et al. (2006). Final filtering involved visual inspection of major oxide variation diagrams; rare samples with unusual abundances (well beyond data arrays formed by the majority of samples and probably indicative of otherwise undetected alteration) were identified and removed from the interpreted data set, which includes data for more than 1600 samples.

Major oxide data were recalculated to 100%, volatile free, and total iron is reported as FeO; all geochemical data were processed to replace censored data (greater or less than analytical limits, or not detected, etc.) with null values. Using stratigraphic relations and radiometric and geologic age data (du Bray et al., 2009), a best age estimate was assigned to each sample. Best ages for samples with specified age ranges were defined as the midpoint of the range. The data set was then sorted by age and each sample assigned to one of the time intervals defined below.

Despite decades spent studying the southern arc segment, radiogenic isotopic data for the associated rocks are remarkably sparse and pertain to just a few of its domains. Specifically, Cousens et al. (2008) and Clarke (2012) presented isotopic data for southern arc segment rocks in the Lake Tahoe and Virginia City domains, the study of the Warner Range domain by Colgan et al. (2011) includes a small amount of Sr and Nd isotopic data, John (1992) presented limited Sr isotope data for western andesite rocks in the Paradise Range, and some radiogenic isotopic data have been produced for some of the rocks in the Bodie Hills domain (B.L. Cousins, 2013, personal data). The scarcity of radiogenic isotope data precludes their meaningful inclusion in our petrogenetic study of the southern arc segment.

To facilitate comparison of ancestral and modern Cascade arc geochemistry, a representative set of more than 1000 analyses (Table DR2 in the Supplemental File [see footnote 1]) was extracted from the GEOROC (2010) database. Selected analyses represent the major High Cascades volcanic edifices between Mount Baker...
in the north and Mount Shasta in the south. All analyses for samples of these volcanoes that include major oxide analyses with analytical totals between 98% and 102% and total volatile contents <3% are included in the modern High Cascades arc database developed for comparative purposes; analyses of high-alumina olivine tholeiites and samples from rear-arc volcanic fields identified by Hildreth (2007) were not included in this database.

**GOELOGIC BACKGROUND**

**Temporal Evolution of the Ancestral Cascades Arc**

As previously described, the ancestral Cascades arc appears to be segmented in northern California across a subducting-slab tear between the Mount Shasta and Lassen Peak volcanic centers of the modern arc (Cousens et al., 2008; Colgan et al., 2011). Research summarized by du Bray and John (2011), indicates that arc magmatism began in the northern part of the northern arc segment as early as 45 Ma and became voluminous shortly thereafter. In the southern arc segment, subduction-related magmatism seems to have initiated significantly later. Colgan et al. (2011) described volumetrically insignificant volcanic rocks in the Warner Range of northeastern California that erupted 41 Ma (Axelrod, 1966). Mafic lava flows erupted 28–26 Ma in the Warner Range are the oldest, volumetrically significant, well-documented (Colgan et al., 2011) subduction-related rocks in the southern arc segment. Significantly less well-known intermediate to mafic lava flows and associated debris-flow deposits, the ca. 32 Ma South Willow Formation in the Granite Range of northwest Nevada (Bonham and Papke, 1969), similarly depict the earliest phases of southern segment ancestral arc magmatism. Busby et al. (2008b) concluded that arc magmatism was well established in the central Sierra Nevada region by 15 Ma, and Cousins et al. (2008) documented subduction-related magmatism in the Lake Tahoe area as young as 3–2 Ma. Consequently, significant magmatism in the southern segment of the ancestral arc appears to extend from 28 to ca. 2 Ma (Vikre and Henry, 2011; Henry and John, 2013).

As described by Coney and Reynolds (1977), Best and Christiansen (1991), Christiansen and Yeats (1992), Humphreys (1995), Dickinson (2006), Henry et al. (2009), Best et al. (2009), Colgan et al. (2011), and Henry and John (2013), a significant component of Cenozoic Great Basin magmatism is related to subduction-zone hinge-line retreat and the associated subducted slab rollback that accompanied foundering of the Farallon slab. Between ca. 90 and 50 Ma, the Farallon slab dipped shallowly beneath western North America and subduction-related magmatism was deflected far to the east of the continental margin (Coney and Reynolds, 1977; Christiansen and Yeats, 1992). Flat-slab subduction constrained the downgoing slab to follow the base of the lithosphere thereby eliminating an asthenospheric wedge between the subducted slab and superjacent mantle lithosphere. The prevailing geometry precluded development of a typical convergent-margin magmatic arc until steeper subduction was re-established following slab rollback. The relatively regular southwestward progression of renewed magmatism across the Great Basin during the Eocene, Oligocene, and Miocene is a direct manifestation of slab rollback processes. Slab rollback fostered continuous southwest to westward migration of the magmatic front, resulting in establishment of magmatism associated with the ancestral Cascades arc in western Nevada and eastern California by the middle of the Cenozoic Era. As suggested by Henry and John (2013), the predominance of middle Cenozoic, primarily rhyolitic, caldera-related magmatism in central Nevada versus intermediate-composition magmatism associated with composite volcano and dome complex development in western Nevada and eastern California may reflect contrasting tectonic environments that prevailed in these two areas (Dickinson, 2002). Specifically, magmatism associated with slab rollback and that associated with stalled slab rollback may manifest quite differently (Henry and John, 2013).

In recognition of the discontinuous nature of ancestral arc magmatism (summarized by du Bray and John, 2011) in the northern arc segment, Smith (1993) and Sherrod and Smith (2000) defined geologic-compilation map units that correlate particular time intervals with geologic discontinuities related to magmatic output variations. Accordingly, their map units “...are based on a mixture of traditional chronostratigraphic units and the more or less instantaneous geologic events” (Sherrod and Smith, 2000, p. 5). Similarly, Busby et al. (2008b) recognized three major pulses of ancestral arc volcanism in the central Sierra Nevada, 15–14, 10–9, and 7–6 Ma, which demonstrate the discontinuous nature of volcanism in the southern segment of the ancestral arc as well. Given that the geologic compilation of volcanic rocks in northern California (J.G. Smith, 2011, written commun.) uses these same time intervals, and in order to maintain comparability with northern arc segment time-volume relations, we have also applied the northern arc segment time intervals to our temporal evaluation of the southern arc segment. The time intervals identified by Smith (1993) and Sherrod and Smith (2000) relative to the northern arc segment are: (1) 45–36 Ma: 45 Ma approximates the onset of arc-related volcanism. (2) 35–26 Ma: 35 Ma corresponds to the time of well-established ancestral arc volcanism. (3) 25–18 Ma: Several significant ancestral arc pyroclastic flow sequences were erupted between 25 and 23 Ma, which approximates the Oligocene-Miocene boundary. (4) 17–8 Ma: Between 17 and 15 Ma extensive mafic magma was erupted in northern and central Oregon. (5) 7–2 Ma: 7 Ma is the age of renewed widespread mafic volcanism following an interval of limited magmatism; this period was in turn followed by the inception of modern High Cascades magmatism ca. 2 Ma, except at Lassen, where the products of modern arc magmatism were erupted starting 4 Ma onto surfaces not underlain by ancestral arc rocks.

Geochronologic data suggest that the volume of southern arc segment magmatism varied through time (Fig. 4). As one measure of time-volume relations, we propose that numbers of geochronologic determinations correlate with erupted magma volumes, i.e., time periods with the greatest number of age determinations correspond to proportionately more abundant coeval rocks. The resulting age-frequency histogram (Fig. 4) is therefore one proxy for relative time-volume relations. Ancestral arc volcanic rock ages suggest relatively low-volume magmatism at the onset of arc volcanism. Subsequently, magma output volume increased slightly during 25–18 Ma and then increased dramatically in the 17–8 Ma time slice. The frequency of geochronology determinations in the 17–8 Ma time slice may reflect over-representation by multiple age determinations for specific stratigraphic units in the well-studied Bodie Hills and Virginia City domains. Specifically, taking the extreme position of allowing only a single age determination per stratigraphic unit in these two domains would reduce the frequency of geochronologic determinations for the 17–8 Ma time slice from 160 to ~100. Consequently, the associated over-representation of 17–8 Ma ages for these rocks is minor and only slightly alters observed age distribution relations. Finally, during 7–2 Ma, southern segment arc magmatic output decreased significantly, but remained greater than that for the 25–18 and 35–26 Ma time slices.

**Spatial Distribution of Ancestral Cascades Arc Magmatism Through Time**

The frequency distribution of numbers of southern arc segment geochemical samples as a function of age is indistinguishable from that
of the geochronology frequency distribution (Fig. 4). Moreover, the spatial distribution of known-age samples indicates that the locus of arc magmatism migrated systematically during ancestral arc magmatism (Fig. 5). The small number and spatial distribution of samples representative of the 35–26 Ma interval suggest that southern arc segment magmatism was volumetrically minor and principally focused at its northern limit, at the east edge of the arc segment, especially in the Warner Range of northeast California. However, Cousens et al. (2008) and C.D. Henry (2006, written commun.) identified several small-volume lava flows in the Lake Tahoe area that may be as old as 28 Ma. Evaluation of the relative proportions of samples of various compositions (lithology entries in Table DR1 in the Supplemental File [see footnote 1]) indicate that volcanic rocks in the Warner Range erupted during this period include approximately equal volumes of mafic (basalt and basaltic andesite) and intermediate (andesite and dacite) compositions. Other, volumetrically minor volcanic rocks possibly erupted in the 35–26 Ma interval include andesite and dacite.

Magmatism became somewhat more voluminous during the 25–18 Ma interval (Fig. 4); the distribution of 25–18 Ma volcanic rock samples indicates that magmatic activity remained strongly concentrated along the east edge of the ancestral arc terrane (Fig. 5). During this period, magmatism was also largely restricted to the southern two-thirds of the ancestral arc, between the Pyramid and Goldfield domains; the northern third of the southern arc segment seems to have been inactive or any products have been concealed beneath voluminous mafic lava flows, associated with either late Cenozoic bimodal basalt-rhyolite assemblage (Ludington et al., 1996) or active High Cascades arc magmatism (Hildreth, 2007), that form the Modoc Plateau. Magma erupted in this interval includes approximately equal amounts of basaltic andesite, andesite, dacite, and rhyolite.

The large quantity of samples in the 17–8 Ma age group indicates dramatically more voluminous magmatism during this interval and defines the period of maximum magma productivity in the southern arc segment. To preclude the nearly 400 available analyses of Bodie Hills samples causing over-representation of 17–8 Ma age group sample frequency, only a representative subset of ~40 of these analyses were utilized in the frequency analysis. During this interval, magmatism was strongly concentrated throughout the northern two-thirds of the arc (Fig. 5), consistent with northerly Mendocino triple junction migration, and shifted dramatically westward, to near the midline of the ancestral arc terrane. Magma erupted in this interval ranges continuously from basalt to rhyolite.

During the final, 7–2 Ma interval of southern arc segment magmatism, erupted volumes appear to have decreased once again but remained greater than those that prevailed prior to 18 Ma. Magmatism was strongly focused in the central third of the southern arc segment (Fig. 5), particularly from the Bodie–Aurora domain through the Lake Tahoe domain. In addition, the Lassen domain, east of Lassen Peak, was the locus of relatively low-volume, dispersed volcanism. All of these magmas were, once again, dominantly composed of basaltic andesite and andesite but also included minor basalt, dacite and rhyolite. During this interval, arc magmatism migrated farther west, to its westernmost position prior to being extinguished by northward migration of the Mendocino triple junction.

Volcanologic Characteristics of Ancestral Cascades Arc Eruptive Centers

Volcanic rocks in the southern arc segment depict a broad array of effusive and explosive eruptive styles (Table 1). Regionally extensive platforms of coalesced monogenetic mafic cones and less voluminous, dispersed shield volcanoes (Grose, 2000; Colgan et al., 2011), significant parts of the active High Cascades arc, are non-
Figure 5. Map of the southern ancestral arc segment (modified from Colgan et al., 2011; John et al., 2012) showing the distribution of samples from each age group as indicated by geochronologic age determinations. Age determinations are from the database of du Bray et al. (2009) and Table DR1 in the Supplemental File (see footnote 1). SNB—Sierra Nevada batholith. Symbol colors and shapes correspond to age group symbols used in subsequent figures.

RESULTS

Major Oxide Data

Major oxide characteristics of southern arc segment rocks are consistent with their genesis in a convergent-margin magmatic arc setting. Abundances of SiO₂ in southern arc segment rocks range continuously from ~50 to 77 wt%, although samples with more than ~65 wt% SiO₂ are distinctly less abundant than those with lower silica contents (Figs. 6, 7). Concentrations...
### TABLE 1. GENERALIZED CHARACTERISTICS OF VOLCANIC DOMAINS INCLUDED IN THE SOUTHERN ARC SEGMENT, ANCESTRAL CASCADES ARC

<table>
<thead>
<tr>
<th>Domain (Fig. 1 abbreviation)</th>
<th>Location in arc segment</th>
<th>Dominant age group(s)</th>
<th>Dominant volcanic compositions</th>
<th>Volcanic products</th>
<th>Volcanic edifice type</th>
<th>Mineral deposits type</th>
<th>Mineral deposit references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warner Range (WR)</td>
<td>Extreme northeaster</td>
<td>35–26 and 17–8 Ma</td>
<td>Basalt, basaltic andesite and dacite</td>
<td>Lava flows, associated block-and-ash flows</td>
<td>Composite and shield volcanoes; minor, likely monogenetic vents</td>
<td>High Grade Low-sulfidation Au-Ag</td>
<td>Carmichael et al., 2006; Colgan et al., 2011</td>
</tr>
<tr>
<td>Lassen (L)</td>
<td>North</td>
<td>17–8 and 7–2 Ma</td>
<td>Andesite and basaltic and dacite</td>
<td>Lava flows and associated pyroclastic deposits</td>
<td>Dispersed shield volcanoes and dissected composite volcanoes, lava domes, cones, and plugs</td>
<td>Hayden Hill Low-sulfidation Au-Ag</td>
<td>Detra and Burnett, 1994; Grose, 2000</td>
</tr>
<tr>
<td>Sierra Valley (SV)</td>
<td>North central</td>
<td>17–8 and 7–2 Ma</td>
<td>Andesite, basaltic and dacite and rhyolite</td>
<td>Lava flows and associated pyroclastic deposits</td>
<td>Dispersed shield volcanoes and dissected composite volcanoes, lava domes, cones, and plugs</td>
<td>Golden Dome, Zule High-sulfidation Au-Ag</td>
<td>Canby, 1992; Young and Cuer, 1992; Grose, 2000; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>Pyramid (P)</td>
<td>East central</td>
<td>25–18 and 17–8 Ma</td>
<td>Basaltic andesite and dacite</td>
<td>Lava flows</td>
<td>Large volcanic complex in the north-central Virginia Mountains.</td>
<td>Composite and shield volcanoes; minor, likely monogenetic vents</td>
<td>Wallace, 1975; Henry et al., 2004; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>Wadsworth (W)</td>
<td>Central</td>
<td>17–8 Ma</td>
<td>Andesite and dacite</td>
<td>Lava flows</td>
<td>Pyramid district Polymetallic vein and/or high-sulfidation Au-Ag</td>
<td>Large volcanic complex in the north-central Virginia Mountains.</td>
<td>Wilson et al., 1999; Garside and Bonham, 2006</td>
</tr>
<tr>
<td>Lake Tahoe (LT)</td>
<td>Central</td>
<td>17–8 and 7–2 Ma</td>
<td>Andesite and basaltic and dacite and rhyolite</td>
<td>Lava flows and associated debris-flow deposits</td>
<td>Large volume composite volcanoes; minor domes and plugs</td>
<td>None</td>
<td>Coursens et al., 2008; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>Virginia City (VC)</td>
<td>Central</td>
<td>17–8 and 7–2 Ma</td>
<td>Andesite, basaltic and dacite and rhyolite</td>
<td>Lava flows, intrusions, and minor associated debris-flow deposits</td>
<td>Composite volcanoes and lava domes</td>
<td>Low- and high-sulfidation Au-Ag</td>
<td>Hudson, 1977; Vikre, 1989; Van Neuwenhuyse, 1991; Hudson, 2003; Hudson et al., 2009</td>
</tr>
<tr>
<td>Stillwater (ST)</td>
<td>East central</td>
<td>17–8 Ma</td>
<td>Trachydacite and dacite</td>
<td>Lava flows and minor intrusions</td>
<td>Shield or composite volcanoes and lava domes</td>
<td>Peavine and Wedekind districts; Comstock Lode, Ramsey-Comstock, Talapoosa</td>
<td>Page, 1965; Wiliden and Speed, 1974; John and Silberling, 1994</td>
</tr>
<tr>
<td>Barnett Hills (BH)</td>
<td>East central</td>
<td>25–18 and 17–8 Ma</td>
<td>Andesite, basaltic and dacite and rhyolite</td>
<td>Lava flows and breccias</td>
<td>Lava domes</td>
<td>Rawhide, Golden Pen</td>
<td>Ekre et al., 1980; Black et al., 1991; Peters et al., 1994</td>
</tr>
<tr>
<td>Carson Pass (CP)</td>
<td>West central</td>
<td>17–8 and 7–2 Ma</td>
<td>Andesite and dacite and rhyolite</td>
<td>Lava flows and associated block-and-ash flows</td>
<td>Lava domes, composite volcano</td>
<td>Low- and high-sulfidation Au-Ag</td>
<td>Busby et al., 2008b; Hagan et al., 2009; Hagan, 2010</td>
</tr>
<tr>
<td>Paradise Range (PR)</td>
<td>Southeast</td>
<td>25–18 and 17–8 Ma</td>
<td>Andesite, basaltic and dacite and rhyolite</td>
<td>Lava flows, debris-flow deposits, plugs</td>
<td>Lava domes, composite volcano</td>
<td>Lava domes, composite volcano and lava domes; minor plugs</td>
<td>Vikre et al., 2008; John et al., 2009; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>Sonora Pass (SP)</td>
<td>West central</td>
<td>17–8 and 7–2 Ma</td>
<td>Basalt, basaltic andesite, and dacite and rhyolite</td>
<td>Lava flows and associated block-and-ash flows, plugs; minor lava flows</td>
<td>Lava domes and small shallow intrusions</td>
<td>None</td>
<td>Hagan, 2010; Busby et al., 2013b</td>
</tr>
<tr>
<td>Little Walker (LW)</td>
<td>West central</td>
<td>17–8 Ma</td>
<td>Trachydacite and dacite and rhyolite</td>
<td>Ash-flow tuff, lava flows; minor associated volcaniclastic deposits</td>
<td>Caldera</td>
<td>Abundant altered rock</td>
<td>Brem, 1977; Priest, 1979</td>
</tr>
<tr>
<td>Sweetwater (S)</td>
<td>Southwest</td>
<td>17–8 and 7–2 Ma</td>
<td>Rhyolite and trachydacite</td>
<td>Lava flows, debris-flow deposits</td>
<td>Lava domes</td>
<td>Kentuck, Silverado Low-sulfidation Au-Ag</td>
<td>Osborne, 1991; Chesterman et al., 1986; Eng, 1991; John et al., 2012</td>
</tr>
<tr>
<td>Bodie-Aurora (BA)</td>
<td>Southwest</td>
<td>17–8 and 7–2 Ma</td>
<td>Trachydacite, dacite, and rhyolite; minor basaltic trachydacite</td>
<td>Lava flows, and associated block-and-ash and debris-flow deposits</td>
<td>Composite volcanoes and lava domes; minor plugs</td>
<td>Bode, Aurora, Masonic, Paramount, Calmon, Borealis None</td>
<td>Spurr, 1905; Nolan, 1935; Bonham and Garside, 1979; Graney, 1987</td>
</tr>
<tr>
<td>Benton (B)</td>
<td>Southwest</td>
<td>17–8 and 7–2 Ma</td>
<td>Trachydacite</td>
<td>Lava flows and associated volcaniclastic deposits</td>
<td>Unknown</td>
<td>None</td>
<td>Crowder et al., 1972</td>
</tr>
<tr>
<td>Tonopah (T)</td>
<td>Southeast</td>
<td>25–18 and 17–8 Ma</td>
<td>Basaltic trachydacite, dacite, and rhyolite</td>
<td>Lava flows, plugs, lava domes, and associated block-and-ash and debris-flow deposits</td>
<td>Lava domes, composite volcanoes(?), and monogenetic cones</td>
<td>Tonopah, Divide, Hasbrouck Mountain Low-sulfidation Au-Ag</td>
<td>Spurr, 1905; Nolan, 1935; Bonham and Garside, 1979; Graney, 1987</td>
</tr>
<tr>
<td>Goldfield (G)</td>
<td>Southeast</td>
<td>25–18 Ma</td>
<td>Trachydacite, dacite, and rhyolite</td>
<td>Lava flows, shallow intrusions, lava domes</td>
<td>Lava domes and shallow intrusions</td>
<td>Goldfield, Gemfield High-sulfidation Au-Ag</td>
<td>Ransome, 1909; Ekre et al., 1971; Cornwall, 1972; Ashley, 1974, 1990a; Vikre and Henry, 2011</td>
</tr>
</tbody>
</table>
Figure 6 (on this and following page). Variation diagrams showing abundances of major oxides (in weight percent) in southern arc segment rocks. Field boundaries (dotted green lines) on K₂O versus SiO₂ diagram from Le Maitre (1989); high-K–shoshonitic dividing line (dotted green line) from Ewart (1982). Black and red dashed lines delineate the composition fields of modern High Cascades arc rocks (MC) (data from GEOROC, 2010) and northern arc segment rocks (NS), respectively.
of TiO₂ and P₂O₅ vary considerably at lower SiO₂ abundances but scatter less and decrease to lower values at higher SiO₂ contents. Concentrations of FeO* and CaO (Fig. 6), as well as MnO (Table DR1 in the Supplemental File [see footnote 1]), decrease in a linear fashion with increasing SiO₂; like TiO₂ and P₂O₅, Al₂O₃ abundances increase in samples with 50 to ~55 wt% SiO₂ and then decrease with increasing SiO₂; like TiO₂ and P₂O₅, Al₂O₃ abundances vary considerably at lower SiO₂ abundances but scatter less at higher SiO₂ contents. Abundances of MgO decrease in a systematic though curvilinear fashion with increasing SiO₂ to produce a concave-up data array. Na₂O abundances vary widely and seem to increase with increasing SiO₂ among samples with less than 65 wt% SiO₂ and then decrease somewhat in the samples with higher SiO₂ contents. Abundances of K₂O increase broadly with increasing SiO₂ content, forming a data array that is transitional from medium- to high-K (Gill, 1981) at low SiO₂ abundances and from high-K to shoshonitic compositions in samples (dominantly from the Little Walker and Lake Tahoe domains) with more than ~57 wt% SiO₂. Relative to standard metrics (in cited sources), the vast majority of the southern arc segment rocks are subalkaline (Fig. 8) (Irvine and Baragar, 1971), metaluminous (Fig. DR1 in the Supplemental File [see footnote 1]) (Shand, 1951), magnesian (Fig. 9) (Frost et al., 2001), and calc-alkaline to calcic (Fig. 10) (Frost et al., 2001).

In contrast to the northern arc segment, the major oxide compositions of southern segment rocks vary insignificantly in a temporal context (Fig. 6). Abundances of FeO*, CaO, Na₂O, and K₂O are indistinguishable among samples of all four age groups, except that a subset of 17–8 Ma age group rocks, almost exclusively rocks of the Stanislaus Group, have K₂O abundances that extend to unusually high values (Putirka and Busby, 2007). TiO₂ and MgO abundances are low and those for Al₂O₃ are high in 35–26 Ma age group rocks relative to those for other southern arc segment rocks. With several exceptions, major oxide compositions of the 25–18, 17–8, and 7–2 Ma age groups are essentially indistinguishable; some 17–8 and 7–2 Ma age group samples with less than ~65 wt% SiO₂ (dominantly rocks of the Stanislaus Group) have abundances of TiO₂ and P₂O₅ that extend to higher values than those for other southern arc segment rocks (Fig. 6).

Most of the southern arc segment rocks are subalkaline and span continuously the basalt to rhyolite composition range (Fig. 8); however, many rocks of the Stanislaus Group are distinctly more-alkaline trachydacites. A significant majority of the southern arc segment rocks have compositions that range from basaltic trachyandesite–basaltic andesite to trachyandesite–andesite; samples of trachydacite-dacite or rhyolite are reasonably common, whereas samples of basalt are uncommon. Total alkali–silica relations also suggest relatively minor compositional differences among southern arc segment rocks with time. Samples of the 35–26 Ma age group are restricted to relatively total alkali–poor basaltic andesite and andesite, whereas samples of the other three age groups are indistinguishable and range fairly continuously from basaltic trachyandesite–trachyandesite to rhyolite.

The southern arc segment includes both calc-alkaline and tholeiitic rocks although only ~20% of the analyzed samples are tholeiitic (Fig. 9) relative to the metric of Miyashiro (1974). About 10% of the southern arc segment rocks are ferroan as defined by Frost et al. (2001), but the remainder are magnesian. Low-silica samples of the 35–26 Ma age group exhibit a subtle
tendency toward tholeiitic compositions (Fig. 9) but otherwise, relative abundances of FeO* and MgO in all other southern arc segment rocks are indistinguishable. These relations are confirmed by relative abundances of (K₂O + Na₂O), FeO*, and MgO (Fig. DR2 in the Supplemental File [see footnote 1]): essentially all southern arc segment rocks plot in the calc-alkaline field (Irvine and Baragar, 1971), but about half of the 35–26 Ma age group samples, all from the Warner Range, have compositions that approach the tholeiitic–calc-alkaline boundary.

Through most of their silica abundance range, southern arc segment rocks define a compositional array that is calc-alkalic and transitional to calcic, as defined by Frost et al. (2001) (Fig. 10). However, samples of the 35–26 Ma age group are systematically more calcic than the other southern arc segment rocks. In addition, the Stanislaus Group subset of the 17–8 Ma age group rocks have compositions that are distinctly more alkaline (alkali-calcic and alkali) than all other ancestral arc samples.

All but ~10% of the southern arc segment rocks are metaluminous [molar Al₂O₃/(Na₂O + K₂O + CaO) ≤ 1.0]; some are weakly peraluminous and none are peralkaline [molar (Na₂O + K₂O)/Al₂O₃ ≥ 1.0] (Fig. DR1 in the Supplemental File [see footnote 1]). Alumina and alkali saturation indices for southern arc segment rocks display essentially no systematic, time-dependent variation. Only ~2.5% of the southern segment rocks have alumina saturation indices greater than 1.10. A disproportionate majority of the strongly peraluminous samples represent high-silica rhyolite lavas in the Bodie-Aurora domain; however, small clusters of high-silica samples in the Paradise and Sweetwater domains are similarly peraluminous. Given the common association of Sn, W, and Mo deposits with high-silica, moderately to strongly peraluminous rocks (Tischendorf, 1977; du Bray et al., 1988; Cerny et al., 2005), the dearth of southern arc rocks with these characteristics indicates a generally low probability for associated rare metal deposits. However, the presence of strongly peraluminous rocks in the Sweetwater Range is consistent with the findings of Brem et al. (1983) who suggested moderate potential for Climax-type porphyry molybdenum mineralization associated with southern arc segment rhyolites. Otherwise, rare samples with strongly peraluminous compositions are not concentrated in particular southern arc segment volcanic centers.

Major oxide compositions of the southern arc segment and modern High Cascades arc rocks are almost indistinguishable (Fig. 6). However, some southern arc segment rocks with 50–65 wt% SiO₂ have somewhat lower MgO contents at any given silica content and, most distinctively, almost half of the southern arc segment rocks contain dramatically higher K₂O contents at
any particular silica content. Accordingly, these southern segment rocks with high K₂O contents are more alkaline than their modern arc counterparts (Fig. 10). Similarly, the relative proportions of FeO* and MgO in the majority of southern arc segment and modern arc rocks are comparable (Fig. 9); consequently both arcs are dominated by magnesian, calc-alkaline compositions. Samples of the 35–26 and 25–18 Ma age groups have somewhat more restricted SiO₂ contents than those of the modern arc (Fig. 7). Specifically, neither of these age groups includes many samples with more than ~65 wt% SiO₂ and the 25–18 Ma age group contains relatively few samples with 45–55 wt% SiO₂.

The geochemistry of the southern arc segment rocks is subtly distinct relative to that of its ancestral northern arc segment analog. Silica contents of the southern arc segment rocks are distinct from those of the northern arc segment in the same ways as was noted above relative to the modern arc rocks. In addition, at any given silica content, the southern arc segment rocks have TiO₂, FeO*, CaO, and Na₂O abundances clustered in the lower-concentration parts of ranges characteristic of the northern arc segment and elevated K₂O contents relative to those of northern arc segment rocks (Fig. 6). Distinctly elevated K₂O abundances cause the southern arc segment rocks to be significantly more alkaline than the northern arc segment rocks (Figs. 8, 10). A significantly greater proportion of the northern arc segment rocks are ferroan and tholeiitic (~44% of analyzed samples) than is the case for the southern arc segment rocks (Fig. 9).

**Trace Element Data**

Southern arc segment rocks have high large-ion lithophile element (LILE) abundances and low high-field-strength element (HFSE) abundances similar (Table DR1 in the Supplemental File [see footnote 1]) to those of other convergent-margin, broadly calc-alkaline igneous rocks, such as those in the Andean, Kamchatka, and Central American arcs (GEOROC, 2010). Abundances of Rb increase with increasing silica content (Fig. DR3 in the Supplemental File [see footnote 1]), whereas those of Sr and Ba increase as silica increases in samples with up to ~59 and 65 wt% SiO₂, respectively, and then decrease with increasing silica (Figs. DR4–DR5 in the Supplemental File [see footnote 1]). Yttrium and Yb abundances decrease, somewhat nonsystematically, with increasing silica (Figs. DR6–DR7 in the Supplemental File [see footnote 1]), whereas La/Yb, and Nb, Th, U, Ta, and La abundances increase (Figs. DR8–DR13 in the Supplemental File [see footnote 1]). Abundances of Zr increase as silica contents increase from 50 to ~65 wt% SiO₂ and decrease subsequently (Fig. DR14 in the Sup-
At any given silica content, samples of the 25–18, 17–8, and 7–2 Ma age groups have essentially indistinguishable Rb, Sr, Ba, Zr, Nb, Y, La, Yb, Th, and total rare earth element (REE) abundances (Figs. DR3–DR7, DR9–DR10, DR13–DR14, DR15 in the Supplemental File [see footnote 1]). Uranium and Ta abundances are indistinguishable in samples of all four age groups (Figs. DR11–DR12 in the Supplemental File [see footnote 1]). The 35–26 Ma age group samples contain distinctly lower abundances of Rb, Sr, Ba, Zr, Nb, Th, U, Ta, La, Zr, and Hf, as is consistent with their more alkaline compositions (Figs. DR3, DR5, DR9–DR14, DR16 in the Supplemental File [see footnote 1]). Niobium abundances >20 ppm (Fig. DR9 in the Supplemental File [see footnote 1]) for a small group of 7–2 Ma age group samples are probably too large. These analyses are from a single literature source (Latham, 1985) and were conducted more than thirty years ago, and more recent analyses (Cousens et al., 2011) of the same rock units did not replicate these abundances.

Transition metal abundances, including those of Co, Ni, Sc, and V, in southern arc segment rocks display remarkably coherent geochemical behavior and decrease systematically with increasing silica content (Figs. DR17–DR20 in the Supplemental File [see footnote 1]); Cr exhibits similar but less systematic behavior (Fig. DR21 in the Supplemental File [see footnote 1]). Abundance variations for Co, Sc, and V in these rocks form linear arrays, whereas the abundances for Cr and Ni define curvilinear, concave-up arrays. At any given silica content, abundances of Cr, Co, Ni, Sc, and V in the 25–18, 17–8, and 7–2 Ma age group samples are indistinguishable; Sc and V abundances in the 35–26 Ma age group rocks are also indistinguishable from those of all other southern segment arc rocks (Figs. DR17–DR21 in the Supplemental File [see footnote 1]). Abundances of Cr and Ni are low and those of Co are high, at any given silica content, in the 35–26 Ma age group rocks relative to all other southern segment rocks. Linear declines in V and Ti abundances (principally concentrated in magnetite) with increasing SiO₂ content (Fig. 6; Fig. DR20 in the Supplemental File [see footnote 1]) among all southern arc segment rocks suggest that the host magmas

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Figure 10. Na₂O + K₂O – CaO versus SiO₂ variation diagram showing the composition of southern arc segment rocks relative to boundaries between alkalic, alkali-calcic, calc-alkalic, and calcic rock series. Boundaries between various rock series from Frost et al. (2001). Black and red dashed lines delineate the composition fields of modern High Cascades arc rocks (MC) (data from GEOROC, 2010) and northern arc segment rocks (NS), respectively.
achieved early magnetite saturation and were therefore relatively oxidized (Christiansen and McCurry, 2008). John (2001) noted a dearth of ilmenite in southern arc segment rocks from the Bodie-Aurora, Virginia City, and Paradise Range domains, which emphasizes the oxidized character of these magmas. Cobalt abundances >150 ppm (Fig. DR17 in the Supplemental File [see footnote 1]) for a small group of 17–8 Ma age group samples are implausibly elevated and probably represent contamination during sample grinding. These analyses are from a single literature source (Putirka and Busby, 2007) and other analyses (du Bray et al., 2009) of the same rock units did not replicate these abundances.

Ore metal abundances also exhibit fairly regular variations with respect to silica content. Abundances of Cu and Zn decrease with increasing silica content (Figs. DR22–DR23 in the Supplemental File [see footnote 1], whereas those of Pb and perhaps Mo increase (Figs. DR24–DR25 in the Supplemental File [see footnote 1]). At any given silica content, abundances of Cu, Mo, and Zn are indistinguishable among all four age groups; abundances of Pb in the 35–26 Ma age group samples are distinctly lower than those in all other southern segment rocks (Figs. DR22–DR25 in the Supplemental File [see footnote 1]). The ore metal abundances, including those of Cu, Mo, Pb, and Zn, in unmineralized southern segment rocks are comparable to their global average abundances in basalt and granite (Turekian and Wedepohl, 1961). A significant subset of the 17–8 Ma age group samples, in particular, appear to have subtly elevated abundances of Mo, Pb, and Zn, however (Figs. DR23–DR25 in the Supplemental File [see footnote 1]).

Samples with noticeably elevated Mo (≥66 ppm) and Pb (≥30 ppm) are dominated by those from the Wadsworth, Bodie-Aurora, and Little Walker (Stanislaus Group) domains, whereas those with elevated Zn abundances (≥110 ppm) are dominated by pre–Stanislaus Group rocks from the Sonora Pass domain and by samples from the Little Walker domain (Stanislaus Group). Other geochemical parameters for the Wadsworth samples are inconsistent with their reported (elevated) Mo abundances; accordingly, these high Mo abundances, determined by notably inaccurate X-ray fluorescence spectrometry, are considered spurious. Ore metal abundances among northern and southern arc segment rocks are similar except that some southern segment rocks of the 17–8 Ma age group, and to a lesser extent those of the 7–2 Ma age group, have Pb contents greater than those of any northern arc segment samples.

Less than 5% of the southern arc segment rocks with REE data are composed of basalt and only ~10% are composed of rhyolite. The vast majority of the southern segment arc rocks for which REE data are available have intermediate compositions and constitute a population with relatively uniform REE characteristics. The dearth of basalt samples precludes interpretation of REE compositions in primary (mantle-derived) magmas. Interpretation of REE data for the southern arc segment rocks including, and alternately excluding, data for basalt, dacite, and rhyolite samples does not significantly alter the analysis of REE abundances for the southern segment rocks, and the observations enumerated below apply regardless (Table 2; Fig. DR26 in the Supplemental File [see footnote 1]). REE data for each of the four southern arc segment age groups are subtly distinct and typical of intermediate-composition, calc-alkaline convergent-margin magmatic arc igneous rocks (e.g., Gill, 1981; Cameron and Cameron, 1985; Wark, 1991; Feeley and Davidson, 1994). REE patterns for each of the southern arc segment age groups have negative slopes and most have only weakly developed negative Eu anomalies (Fig. 11; Fig. DR27 in the Supplemental File [see footnote 1]); light REE (LREE) pattern segments are more steeply sloping than heavy REE (HREE) segments; middle REE (MREE) to HREE pattern segments are distinctly U-shaped for some samples (Fig. DR28 in the Supplemental File [see footnote 1]). Within-age-group REE patterns are essentially parallel. However, at any given SiO₂ content, La/Yb increases systematically from the 35–26 Ma age group through the 17–8 Ma age group and then decreases slightly in the 7–2 Ma age group (Fig. DR8 in the Supplemental File [see footnote 1]); average and median La/Yb values vary similarly as a function of age group (Table 2). Consequently, chondrite-normalized REE patterns for the 25–18 and 17–8 Ma age groups exhibit subtle clockwise rotation relative to patterns for the 35–26 Ma age group; patterns for 7–2 Ma age group rocks are then very slightly counterclockwise rotated relative to those for the 17–8 Ma age group but are still more steeply negatively sloping than those for two oldest southern arc segment age groups. Total REE as well as La abundances also vary in a fashion identical to that depicted by La/Yb for the four age groups (Table 2). The 17–8 Ma (and to a lesser extent the 7–2 Ma) age group rocks are further distinguished by a significant group of rhyolite samples with well-developed negative Eu anomalies and U-shaped patterns in their MREE to HREE segments.

Northern arc segment and modern High Cascades arc rocks have quite similar REE characteristics (du Bray and John, 2011). Patterns for the two groups of rocks are essentially parallel. Although 35–26 Ma rocks of the northern segment are distinctly REE enriched relative to the modern arc rocks, the northern segment rocks become progressively REE depleted with time and their compositions merge with those of the modern arc (Fig. 11). In contrast, southern arc segment rocks have several features that distinguish them from northern arc segment rocks as well as the modern arc rocks. Most conspicuously, abundances of Eu are distinctly lower in the northern arc samples, whereas those of the modern arc sample.

<table>
<thead>
<tr>
<th>Age group (Ma)</th>
<th>n</th>
<th>(La/Yb)</th>
<th>Eu/Eu⁺</th>
<th>La (ppm)</th>
<th>∑REE (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7–2, intermediate</td>
<td>54</td>
<td>9.7</td>
<td>0.88</td>
<td>24.8</td>
<td>115</td>
</tr>
<tr>
<td>7–2, all</td>
<td>66</td>
<td>10.5</td>
<td>0.88</td>
<td>24.9</td>
<td>113</td>
</tr>
<tr>
<td>Median:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7–2, intermediate</td>
<td>54</td>
<td>8.2</td>
<td>0.89</td>
<td>22.5</td>
<td>102</td>
</tr>
<tr>
<td>7–2, all</td>
<td>66</td>
<td>8.2</td>
<td>0.89</td>
<td>22.8</td>
<td>101</td>
</tr>
<tr>
<td>Mean:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>12.9</td>
<td>0.86</td>
<td>31.7</td>
<td>151</td>
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<tr>
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<td>14.6</td>
<td>0.81</td>
<td>33.8</td>
<td>151</td>
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<tr>
<td>Median:</td>
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<tr>
<td>17–8, intermediate</td>
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<td>11.5</td>
<td>0.87</td>
<td>32.1</td>
<td>149</td>
</tr>
<tr>
<td>17–8, all</td>
<td>91</td>
<td>14.6</td>
<td>0.85</td>
<td>32.6</td>
<td>141</td>
</tr>
</tbody>
</table>
| Note: “Intermediate” samples are those composed of basaltic andesite, andesite, dacite, and each of their alkaline counterparts, whereas “all” samples include those with any of those compositions or basalt or rhyolite.
Figure 11. Chondrite-normalized rare earth element (REE) diagrams for samples of the southern arc segment (left column) versus northern arc segment (right column), by age group. Only representative data are presented for the 17–8 and 7–2 Ma age groups in order to preclude abundant data available for samples of those age groups from several domains (in particular, the Bodie-Aurora domain) from overwhelming the remainder of the population. Chondrite abundances from Anders and Ebihara (1982). Shaded field depicts the REE abundances in ~400 modern High Cascades arc samples (data from GEOROC, 2010).
ously, the southern segment rocks are significantly LREE enriched, resulting in patterns that are noticeably clockwise rotated relative to those of the northern arc segment and the modern arc. Secondly, development of distinctively U-shaped MREE to HREE pattern segments is a diagnostic characteristic of the southern arc segment rocks and is absent among the northern arc segment and modern arc rocks. Furthermore, a significant group of rhyolitic rocks with well-developed negative Eu anomalies and MREE depletion is restricted to the southern arc segment rocks. Finally, the trend among southern segment rocks toward progressively greater total REE contents, particularly LREE, with decreasing age is opposite the temporal sequence depicted by the northern arc segment rocks.

In the context of primitive mantle–normalized patterns, trace element abundances in both the northern and southern arc segment rocks as well as those for the modern arc are (1) essentially indistinguishable (Fig. 12; Fig. DR29 in the Supplemental File [see footnote 1]) and (2) similar to those characteristic of other convergent-margin, subduction-related magmatic arc rocks. The southern arc segment rocks have well-developed negative Nb-Ta anomalies considered characteristic of arc magmas (Wood et al., 1979; Gill, 1981; Pearce et al., 1984). These anomalies are generally better developed in the southern arc segment rocks than in their northern segment analogs. These patterns also emphasize that LILE, Th, Pb, and Zr abundances of the 17–8 and 7–2 Ma age group rocks of the southern arc segment are slightly greater than in the corresponding northern arc segment rocks. Finally, negative P and Ti anomalies in southern arc segment rocks are larger than those characteristic of the northern arc segment rocks and may reflect the greater abundance of more evolved rocks in the southern arc segment than in the northern arc segment.

**DISCUSSION**

Petrogenetic Implications of Major Oxide Data

Broadly calc-alkaline, magnesian, metaluminous, and transitional subalkaline to weakly alkaline major oxide compositions of southern arc segment rocks are fully consistent with genesis of these rocks in a convergent-margin, magmatic arc setting. In particular, the majority of these rocks have subalkaline, basaltic andesite to andesite compositions equivalent to archetypal Cascades calc-alkaline compositions (Fig. DR2 in the Supplemental File [see footnote 1]). However, the lack of significant compositional variation of southern arc segment major oxide compositions through time as well as their compositional distinctions relative to the northern arc segment rocks suggest that the two arc segments did not develop under completely analogous conditions. The northern arc segment developed in a terrane dominated by thin, young, primitive crust with an oceanic affinity that thickened through time (du Bray and John, 2011), whereas the western edge of the North American margin that hosted most of the southern arc segment is relatively thick, continental, and dominated by Mesozoic intrusive rocks of the Sierra Nevada batholith (Fig. 1). At the onset of arc magmatism in the northern arc segment, the prevailing crustal regime fostered relatively rapid ascent of subduction-related magmas that experienced minimal fractional crystallization and contamination during their crustal transit. As the northern arc segment evolved, thickened, and matured, it served as a progressively more effective density filter, and arc magmas ascending through this regime slowed and fractionated, and compositions transitioned from dominantly tholeiitic to dominantly calc-alkaline (Evarts and Swanson, 1994; du Bray and John, 2011). Similarly, ascent of subduction-related magmas associated with the southern arc segment through relatively thick continental crust along the western edge of North America was slowed, allowing melting, assimilation, storage, and homogenization (MASH) processes (Hildreth and Mooibath, 1988; Ammen et al., 2006) to yield a greater proportion of felsic magmas than is typical of the northern arc segment. Distinctive relative compositional differences between the two arc segments (Fig. 13), especially relative to abundance of silicic samples (33% of southern segment rocks have >62 wt% SiO₂ versus only 13% of northern segment rocks), is likely a direct consequence of magmatism associated with subduction beneath relatively thick continental crust. Putirka and Busby (2007), Cousins et al. (2008), John et al. (2012), Putirka and Platt (2012), and Putirka et al. (2012) also argued convincingly that continental mantle lithosphere thickens along the north-south transect beneath the Sierra Nevada batholith between the Lassen Peak region and the Southern Sierra Nevada, and that this tectonic framework exerts significant influence on Cenozoic volcanic rock compositions.

Essentially indistinguishable major oxide compositions among the 25–18, 17–8, and 7–2 Ma age groups implies a marked consistency among the large-scale tectonic and magmatic processes that contributed to volcanism in the southern arc segment. In contrast, rocks of the 35–26 Ma age group, essentially restricted to the Warner Range at the north end of the southern arc segment, have major oxide compositions that are more universally mafic and tholeiitic than all other southern arc segment rocks; their petrogenesis may reflect development in a distinct magmatic/tectonic setting.

Abundance variations of several major oxides partly constrain the crystallization history of southern arc segment magmas. In particular, the decrease in Al₂O₃ and Na₂O abundances (Fig. 6) in rocks with more than ~60 wt% SiO₂ is consistent with the onset of sodic plagioclase crystallization and fractionation. The significant increase in K₂O abundances with increasing silica probably reflects its concentration in residual magma that became more evolved by fractionation. Southern arc segment rocks with low MgO contents at a given SiO₂ content (especially 50–55 wt% SiO₂) may reflect early crystallization of pyroxene, which retarded the increase of SiO₂ abundances (K. Putirka, 2013, personal commun.). The somewhat irregular decrease in P₂O₅ abundances in samples with more than ~65 wt% SiO₂ probably reflectsapatite saturation and fractionation, in accord with the findings of Putirka et al. (2012).

Some southern arc segment domains contain subalkaline rocks composed of basaltic andesite, andesite, and dacite (Fig. 14) but other domains include rocks with those compositions as well as those with their alkaline analogs. The alkalinity of these rocks is entirely a function of elevated K₂O contents. Rocks with an alkaline affinity are essentially unknown in the northern arc segment, which underscores the differences between magmas associated with the two arc segments. The tendency toward alkaline compositions is best developed among rocks in the Little Walker domain, whose eruptive products are almost ubiquitously alkaline. Feldstein and Lange (1999) and Farmer et al. (2002) suggested that Piocone lavas erupted nearby in the southern Sierra Nevada owe their potassic character to lithospheric delamination and subsequent partial melting of a K₂O-enriched lower-crust or upper-mantle source. However, Putirka and Busby (2007) and Putirka et al. (2012) suggested convincingly that southern arc segment rocks with elevated K₂O abundances can be generated by low degrees of mantle partial melting and subsequent fractional crystallization, which obviates the need to involve geochemically distinct mantle in the petrogenesis of these rocks. Regardless, rocks in various domains within the southern arc segment seem to be characterized by various levels of alkalinity (Fig. 14). Alkalinity variations that appear unrelated to either temporal or geospatial context suggest that these differences most likely indicate extents of partial melting and subsequent fractionation (Putirka and Busby, 2007; Putirka et al., 2012) that vary locally within each of the southern arc segment domains.
Figure 12. Primitive mantle-normalized (Sun and McDonough, 1989) trace element diagrams for samples of southern arc segment (left column) versus northern arc segment (right column), by age group. Shaded field depicts the trace element abundances in ~400 modern High Cascades arc samples (data from GEOROC, 2010).
Petrogenetic Implications of Trace Element Data

As demonstrated by Hildreth and Mooibath (1988) and Annen et al. (2006), MASH zone processes impart important petrogenetic controls on the geochemical variation of magmatic arc rocks. Aside from subtly distinct trace element abundances characteristic of the 35–26 Ma age group rocks, LILE and HFSE abundances of the southern arc segment rocks are similar, regardless of age. Low Zr abundances among the 35–26 Ma age group rocks, relative to all other southern arc segment rocks, suggest a distinct source for the associated magmas. Abundances of Zr increase with increasing silica in southern arc segment rocks with 50 to ~65 wt% SiO2; as silica abundances increase further, Zr abundances decrease, probably indicative of zircon saturation and fractionation (Fig. DR14 in the Supplemental File [see footnote 1]). The distinctive set of samples with ~65 wt% SiO2 and more than ~300 ppm Zr (Table DR1 in the Supplemental File [see footnote 1]) represent the Eureka Valley Tuff, erupted from the Little Walker caldera. Unusually elevated Zr contents for these samples are consistent with elevated alkalinity of the tuff and experimental findings of Watson (1979), which demonstrate increased Zr solubility in alkaline magmas. Distinctive, previously described trace element characteristics of Stanislaus Group magmas associated with the Little Walker domain probably reflect petrogenetic processes, including small degrees of partial melting in a transtensional regime, similar to those enumerated by Putirka and Busby (2007); these features probably do not require a source or magmatic processes different from those that contributed to the petrogenesis of the remaining southern segment rocks. The extent of magma evolution involving feldspar fractionation, as indicated by relative abundances of K, Rb, and Sr, is minor. Plagioclase fractionation causes abundances of K to increase relative to those of Sr, and Rb enrichment relative to K (Hanson, 1980); however, these systematic trends are also influenced by mantle source compositions as well as by subducted-slab contributions. Relative abundances of K, Rb, and Sr in southern arc segment rocks are, with the exception of a subset of 17–8 Ma age group samples, essentially indistinguishable; abundance variations are dominated by Sr and K to a lesser extent (Fig. 15). As corroborated by the lack of negative Eu and Sr anomalies (Figs. 11, 12), these relatively Sr-enriched compositions suggest that plagioclase, which preferentially incorporates Eu and Sr, was not significantly fractionated from most of these rocks. In contrast, the 17–8 Ma age group rocks includes a subset, dominated by high-silica Bodie-Aurora domain rocks but also including numerous samples from the Sweetwater and Virginia City domains, that extends to significantly Sr-depleted compositions; accordingly, plagioclase fractionation was more important in the petrogenesis of these rocks than is typical of most southern arc segment rocks. Sr/K for most 35–26 Ma age group rocks is generally restricted to high values, whereas Sr/K values extend over a broad range, to significantly lower values, for rocks of the other southern arc segment age groups; these relations further define the geochemical distinctiveness of the 35–26 Ma age group rocks.

At any given silica content, Sr abundances of southern arc segment rocks are similar to those of the modern High Cascades arc but are considerably elevated relative to those of most northern arc segment rocks (Fig. 16). In southern arc segment rocks with 50–60 wt% SiO2, Sr abundances broadly increase with increasing silica content, whereas in rocks with >60 wt% SiO2, Sr abundances decrease somewhat more systematically (except among the 7–2 Ma rocks), probably as a consequence of plagioclase crystallization and fractionation. In addition, northern and southern arc segment rocks, as well as modern High Cascades arc rocks, have Sr abundances considerably greater (Table DR1 in the Supplemental File [see footnote 1]) than those of the Andean arc. Cousins et al. (2008) suggested that LILE enrichment (including Sr) of some southern arc segment rocks reflects a significant lithospheric mantle (metasomatized by subduction-related fluids) contribution, whereas Putirka and Busby (2007) suggested that elevated Sr abundances reflect small-degree melting of lithospheric mantle. Sr-enriched Andean arc magmas are known to be associated with magma genesis beneath thick continental crust at elevated pressures (Hildreth and Moorbath, 1988). Importantly, plagioclase is unstable at pressures greater than ~20 kb (Green, 1982). Consequently, any components, including Sr, normally incorporated into plagioclase are preferentially partitioned into partial melts during magma genesis at these pressures. Therefore, elevated Sr abundances in the most primitive southern arc segment rocks are in accord with their genesis at depths ~70 km beneath relativley thick continental crust.

Partial melting at plagioclase-unstable, garnet-stable pressures also yields magmas with characteristically elevated Sr/Y. Consequently, adakitic compositions, with Sr/Y > 20 and Y < 18 ppm (Richards, 2011), also indicate partial melt generation beneath thick crust; importantly, a large subset of southern arc segment rocks have Sr/Y > 40 (Fig. DR30 in the Supplemental File [see footnote 1]). High Sr/Y andesites from Mount Shasta (Fig. 1), a modern High Cascades analog for composite volcanoes of the southern
Figure 14. Total alkali–silica variation diagrams showing compositions of southern arc segment rocks in each of their domains. Field boundaries from Le Bas et al. (1986).
arc segment, reflect open-system behavior and crustal contamination of arc magmas (Streck et al., 2007). The relative distribution coefficients for Sr and Y in hornblende (Sisson, 1994) also contribute to elevated Sr/Y, as a function of hornblende fractionation. In contrast, Borg et al. (2002) suggested that Lassen region (Fig. 1) magmas with (Sr/P)N > 5.5 are slab-fluid enriched. The southern arc segment rocks have intermediate values of (Sr/P)N in the 1–4 range, which suggests minimal slab fluid involvement. Therefore, Sr abundance relations (as a proxy for the LILE) suggest that LILE abundances in southern arc segment rocks primarily reflect partial melt generation at depths >70 km, but may also reflect crustal contamination, hornblende fractionation, and low-degree partial melting; in contrast, southern arc segment LILE compositions reflect small contributions from slab-derived fluids.

Relative abundances of Rb, Y, and Nb in most southern arc segment rocks are consistent with their genesis in a volcanic arc setting, as defined by the tectonic setting discriminant diagram (Fig. 17) of Pearce et al. (1984). Samples of the southern arc segment age groups have relative abundances of Y + Nb that are essentially indistinguishable. Samples of the 35–26 Ma age group have Rb abundances that are generally coincident with only the very low Rb abundance part of the data array for most other southern arc segment rocks. Southern arc segment rocks—particularly a subset of the 17–8 Ma age group, dominantly intermediate-composition Stanislaus Group rocks but also including high-silica rhyolite rocks of the Bodie-Aurora domain—have higher Rb abundances than those for the modern High Cascades arc. Low Rb abundances characteristic of some northern arc segment rocks (du Bray and John, 2011) are essentially absent among the southern arc segment rocks. Relatively elevated Rb abundances among southern arc segment rocks are also consistent with the petrogenesis of these rocks involving a significant lithospheric mantle contribution (Cousens et al., 2008), as well as small and variable degrees of partial melting (Putirka and Busby, 2007; Putirka et al., 2012).

Scarcely samples that have within-plate compositions (elevated Y + Nb) are the above-identified samples with elevated but likely inaccurate Nb abundances; these data therefore have no tectonic or petrogenetic significance. Gill (1981) determined that magmatic arc rocks have Ba/Nb < 15. Consequently, these rocks have a mid-ocean ridge basalt (MORB)–like affinity that is probably related to slab window magmatism (du Bray and John, 2011). Unlike the northern arc segment rocks, all southern arc segment rocks have Ba/Nb > 15 (Fig. 18), which corroborates their convergent-margin magmatic arc affinity. Hawkesworth et al. (1995), Pearce and Peate (1995), Cousens et al. (2008), and Schmidt et al. (2008) associated elevated Ba/Nb with the addition of subducted slab components to magmas generated during slab dehydration and fluid flux–induced partial melting of the mantle wedge. Distinctly elevated Ba/Nb ratios (>100 for many southern arc segment samples), very well-developed negative Nb-Ta anomalies, and significant LILE enrichments indicate the contributions of a slab-derived fluid component in magmas represented by rocks of the southern arc segment. High Th and LREE abundances are also consistent with subducted sediment and/or continental crust assimilation signatures. Ba/Nb values for all but the 35–26 Ma age group are essentially indistinguishable; 35–26 Ma age group samples with 50–60 wt% SiO2 have elevated Ba/Nb values that are similar to only those southern arc segment rocks with the highest Ba/Nb values.
Negative primitive mantle–normalized Nb-Ta anomalies are also consistent with a convergent-margin magmatic arc setting for the southern arc segment rocks (Fig. 12). These anomalies are larger among the southern arc segment rocks than is typical of their northern segment analogs. Negative Nb-Ta anomalies on primitive mantle–normalized plots reflect significant enrichment of the adjacent incompatible elements, including Rb, Ba, Th, K, Sr, and Pb, as the source region for the southern arc segment magmas became depleted in incompatible elements during magma genesis. Large negative P and Ti anomalies and smaller Zr anomalies (Fig. 12) among southern arc segment rocks probably reflect fractionation of apatite, Fe-Ti oxides, and zircon during differentiation in crustal reservoirs.

Chondrite-normalized REE patterns for southern arc segment rocks further constrain their petrogenesis. The first-order characteristic of these rocks is their moderately steep negative slope, best exemplified by the intermediate-composition (52–63 wt% SiO₂) subset (Fig. DR26 in the Supplemental File [see footnote 1]). Modern Andean magmatic arc rocks are also preferentially LREE enriched, which Hildreth and Moorbath (1988) ascribed to garnet stability in a high-pressure partial melting source region beneath relatively thick continental crust. Magmas so generated inherit a HREE-depleted signature, because garnet is HREE enriched and its high-pressure stability precludes HREE partitioning to derived partial melts. Consequently, negatively sloping, HREE-depleted chondrite-normalized patterns characteristic of the southern arc segment rocks are consistent with magma genesis in a high-pressure, garnet-stable regime. Negatively sloping LREE-enriched patterns may also reflect a subducted sediment component in subduction-related arc magmas. However, Putirka and Busby (2007) and Cousens et al. (2008) emphasized the importance of garnet-bearing residues to REE budgets of the southern arc segment rocks. Also, most obvious among the intermediate-composition subset of southern arc segment rocks (Fig. DR26 in the Supplemental File [see footnote 1]), the MREE to HREE segments of chondrite-normalized patterns are somewhat U-shaped. Mineral/melt partition coefficients for amphibole are greatest for the MREE (especially Dy), progressively and slightly lower for the HREE, and dramatically lower for the LREE (Sisson, 1994; Davidson et al., 2007). Consequently, source-region retention or fractionation of amphibole yields magmas that are MREE depleted. Accordingly, subtly U-shaped MREE patterns characteristic of the southern arc segment may be a consequence of hornblende source-region retention and/or fractionation in a shallow magma reservoir; apatite fractionation may also have contributed to MREE depletion. Putirka et al. (2012), who modeled the effects of hornblende fractionation on MREE abundances in Cenozoic volcanic rocks of the Sierra Nevada and Walker Lane, also concluded that U-shaped MREE patterns, such as those characteristic of some southern arc segment rocks, are attributable to hornblende fractionation. The lack of U-shaped MREE patterns among northern arc segment rocks (du Bray and John, 2011) may indicate that hornblende crystallization did not contribute to the petrogenesis of these rocks, which may in turn indicate that the associated magmas were not sufficiently hydrous to stabilize hornblende (Rutherford and Hill, 1993). Finally, southern arc segment rocks have insig-

Figure 16. Variation diagram showing Sr versus SiO₂ in southern arc segment rocks. Black and red dashed lines delineate the composition fields of modern High Cascades arc rocks (MC) (data from GEOROC, 2010) and northern arc segment rocks (NS), respectively.
significant negative Eu anomalies (also best exemplified by the intermediate-composition subset), which implies that source-region plagioclase instability and limited plagioclase fractionation combined to suppress negative Eu anomaly development (Fig. DR26 in the Supplemental File [see footnote 1]; Table 2). MREE depletion controlled by amphibole may have further suppressed negative Eu anomaly development associated with limited plagioclase fractionation. However, very high Sr/K values among most southern arc segment rocks also seem to indicate a minor role for plagioclase fractionation in the petrogenesis of these rocks. The dacitic and rhyolitic subset of the 17–8 and 7–2 Ma age group rocks have distinctive REE patterns (Fig. 11) that imply more complex petrogenetic histories. Specifically, with increasing silica content these rocks have significantly better developed negative Eu anomalies (smallest Eu/Eu* = 0.31), HREE depletion is more pronounced, and U-shaped MREE anomalies are better developed. These features suggest that fractionation of plagioclase, amphibole, and perhapsapatite was significantly more important among rocks with more evolved compositions than in those with intermediate compositions.

TECTONIC AND GEOCHEMICAL EVOLUTION OF THE SOUTHERN ANCESTRAL CASCADES ARC SEGMENT

Relatively rapid convergence of the Farallon plate along western North America fostered shallow subduction during the Eocene (Coney and Reynolds, 1977). At latitudes coincident with the southern arc segment, shallow subduction deflected associated magmatism well to the east into central Nevada. Subsequently, the subduction-related magmatic front swept progressively southwestward (Christiansen and Yeats, 1992) in a process Humphreys (1995) attributed to asymmetric foundering of the Farallon slab beneath the Great Basin. Rocks of the interior andesite-rhyolite assemblage (Ludington et al., 1996; John, 2001), products of the ignimbrite flareup described by Best and Christiansen (1991) and Best et al. (2009, 2013), were erupted in the wake of slab rollback, and renewed asthenospheric mantle upwelling accompanied receding subduction. Steepening subduction and continued southwest-directed slab rollback promoted localization of the magmatic front (Dickinson, 2006) progressively further to the southwest in western Nevada. By ca. 30 Ma subduction-related magmatism (the western andesite assemblage of Ludington et al. [1996] and John [2001]) established the southern arc segment, a north-northwest–trending array of magmatic centers that extended from northeast California southeastward and just east of the present California-Nevada border. Magmatism associated with the southern arc segment persisted in this region but continued to migrate slowly westward (Fig. 1) and was progressively terminated on the south by northward migration of the Mendocino triple junction.

Major oxide and trace element compositions of northern and southern arc segment rocks strongly suggest that the northern and southern arc segments evolved in significantly different tectonic settings. Whereas compositions of northern arc segment rocks vary (du Bray and John, 2011) systematically through time (Figs. 11, 12), southern arc segment rocks (considered in their entirety), with the exception of geographically isolated and incompletely sampled 35–26 Ma age group rocks, exhibit no systematic compositional variation through time or space; consequently, subduction-related processes responsible for southern arc segment magmatism were probably also relatively uniform through time.

The northern arc segment developed adjacent to a North American continental border dominated by thin, immature crust (du Bray and John, 2011). In contrast, most of the southern arc segment developed beneath relatively thick continental crust previously affected by voluminous magmatism represented by the Triassic–Cretaceous Sierra Nevada batholith and associated subduction-modified lithospheric mantle. Evarts and Swanson (1994, p. 2H-6) observed that “the base of the crust acts as a density filter that controls the depth at which basalt derived from the mantle wedge stagnates and fractionates,” which is consonant with development of compositional differences between the northern and southern arc segment rocks as a function of prevailing crustal thickness. Specifically, thin, dense (mafic) crust like that which hosted the northern arc segment fostered the transit and eruption of unfractonated, high-density mafic magmas (Fig. 13) that are volumetrically dominant in the northern arc segment. In contrast,
thicker, lower-density crust, such as that which prevailed in most of the southern arc segment region, inhibited the ascent of dense, mafic melts. With buoyancy-driven magma ascent obstructed in the southern arc segment, magma reservoirs formed and fractionated to relatively less-dense compositions enriched in SiO$_2$ (Fig. 13), K$_2$O (Fig. 6), and H$_2$O (as indicated by hornblende and biotite phenocrysts that are abundant in southern segment rocks but scarce in northern segment rocks). In accord with the findings of Putirka and Busby (2007), Putirka and Platt (2012), and Putirka et al. (2012), these processes controlled the composition of magmas delivered to shallow crustal reservoirs and the processes that ensued therein. Southern arc segment magmas were also subject to contamination by assimilation of Sierra Nevada batholith components (Cousens et al., 2008) just as some Andean magma compositions reflect variable contamination by crustal assimilation (Feeley and Davidson, 1994).

The character of REE abundance variations through time also contrasts the respective petrogenetic histories of the northern and southern arc segment rocks. Progressively younger northern arc segment rocks have systematically lower REE abundances that are consistent with progressive depletion of incompatible elements from a relatively homogeneous mantle source (White and McBirney, 1978). In contrast, LREE abundances progressively increase with decreasing age through the first three southern arc segment age groups; REE abundances then decrease slightly among samples of the youngest age group (Table 2; Fig. 11; Fig. DR31 in the Supplemental File [see footnote 1]). Southern arc segment rock REE characteristics are consistent with the associated magmas having been increasingly contaminated by a relatively REE-enriched assimilant. Given that relatively thick continental crust, principally rocks of the Sierra Nevada batholith, hosts the southern arc segment, systematically greater contamination (Cousens et al., 2008) of the associated arc magmas during their ascent through thick, batholith-dominated crust is consistent with the elevated REE content of the southern arc segment rocks. Basalts from the Lake Tahoe area have Sr, Nd, and Pb isotopic compositions that span the entire range characteristic of southern arc segment rocks (Cousens et al., 2008; Clarke, 2012). Some of the associated primary magmas have isotopic compositions solely consistent with a lithospheric mantle source ($^{87}$Sr/$^{86}$Sr > 0.705) and data for some of the intermediate to evolved lavas are consistent with a combination of lithospheric mantle, mantle wedge, and crustal components that is indistinguishable from a lithospheric mantle source alone. Progressive crustal warming due to subduction-related mantle partial melting and crustal underplating by derived mafic magmas may have fostered progressively greater incorporation of crustally derived contaminants. In particular, temporally correlated clockwise REE pattern rotation (Fig. 11) and increased LREE contents (Table 2) characteristic of southern arc segment rocks may reflect progressively greater involvement of subducted-slab devolatilization-derived fluids (Cousens et al., 2008) and/or assimilation of Sierra Nevada batholith rocks that are...
LREE enriched relative to southern arc segment magmas as a consequence of accessory mineral assemblages that include LREE-enriched (Sawka, 1988; Barbarin et al., 1989) titanite, allanite, and apatite. Major oxide data are similarly consistent with assimilation of crustal contaminants. In particular, among southern arc segment rocks, P2O5/K2O systematically decreases with increasing SiO2 and increases with MgO (Fig. DR32 in the Supplemental File [see footnote 1]), which, as demonstrated by Farner et al. (2002), is a key manifestation of contamination of mantle-derived partial melts by crustal assimilants. Furthermore, among southern arc segment rocks, CaO/Al2O3 decreases, and La/Sm, Zr/Sm, and incompatible trace element abundances all increase with increasing SiO2, which Coussens et al. (2008) also observed among southern arc segment rocks in the Lake Tahoe region and ascribed to increased levels of crustal contamination. The impacts of assimilated LREE-enriched rock on southern arc segment rocks may ultimately have waned among magmas represented by the rocks of the youngest southern arc segment age group due to incompatible element depletion processes similar to those described by White and McBirney (1978) for northern arc segment rocks. Using REE ratios, Putirka et al. (2012) developed quantitative models that constrain the partial melting processes, and, to a more limited extent, subsequent fractionation processes, responsible for REE compositional systematic characteristics of Cenozoic volcanic rocks in the Sierra Nevada–Walker Lane region; these relations indicate that compositional variation within the southern arc segment rocks is dominated by the effects of fractional crystallization.

Relative abundances of K and Rb also suggest that the northern and southern arc segments evolved in distinctly different tectonic environments. Magma source composition, extent of partial melting, and crustal contamination principally control K/Rb. K/Rb values at any given Rb abundance reflect only varying amounts of contamination because (1) Rb is geochemically incompatible (Hanson, 1980) and (2) its abundance is fixed by source composition and extent of partial melting. Accordingly, rocks with the highest K/Rb, at any given Rb abundance, represent the greatest amount of crustal contamination. At 10–20 ppm Rb, the oldest northern arc segment rocks have the lowest K/Rb. Progressively younger northern arc segment rocks have higher K/Rb, which is consistent with progressive crustal thickening and increased crustal contamination (du Bray and John, 2011). In contrast, at any given Rb abundance, K/Rb values for the southern arc segment rock age groups are indistinguishable (Fig. DR33 in the Supplemental File [see footnote 1]), which supports the hypothesis that all of the associated magmas evolved in a relatively similar regime in which crustal thickness was uniform and extent of crustal contamination was relatively consistent.

The southern arc segment and modern High Cascades arc rocks have similar major oxide and trace element compositions. These observations are consistent with fundamentally identical tectonic and geochemical processes prevailing during the generation of both sets of rocks. Consequently, in the area of the southern arc segment, subduction-related magmatic processes seem to have transitioned from those associated with the ancestral arc to those associated with the modern High Cascades arc. Furthermore, geochemical characteristics of the southern arc segment rocks are consistent with the processes responsible for subduction-related magmatism being relatively static through time. Rocks of the southern arc age groups have La/Nb, Th/Nb, and Ba/Zr whose variations are uncorrelated with either latitude or longitude and are indistinguishable from one another (Figs. DR34–DR36 in the Supplemental File [see footnote 1]), which further substantiates the uniformity of the petrogenetic processes responsible for the genesis of these rocks. Compositions of the northern arc segment rocks exhibit well-defined spatial and temporal variation, whereas those of the southern arc segment are relatively constant through time and space. Consequently, with the exception of the rocks in the Warner Range, discussed below, southern arc segment rocks appear to reflect a stable convergence rate and uniform subduction-zone geometry that fostered a petrogenetic regime capable of producing magmas, during a nearly 30 m.y. interval, with indistinguishable compositional features.

Available evidence indicates that magmatism associated with the southern arc segment migrated westward from ca. 30 Ma onward; younger, post–ancestral arc volcanoes (for instance, Mount Shasta and Lassen Peak) of the modern High Cascades arc are located still further to the west (Figs. 1, 5). In contrast, du Bray and John (2011) concluded that the locus of subduction-related magmatism associated with the northern arc segment migrated systematically eastward with time, largely as a result of increased convergence rate and shallow subduction. The distributions of southern arc segment and contiguous modern High Cascades arc rocks suggest that slowing convergence, slab rollback, and steepening slab dip are responsible for the westward migration of subduction-related magmatism across western Nevada and eastern California. In the context of apparent differences between the northern and southern arc segments and associated convergence rates, subduction zone steepness, and arc-perpendicular migration of subduction-related magmatism, the subducted-slab tear proposed by Cousens et al. (2008) and Colgan et al. (2011) appears to be a required element of the regional tectonic framework. Just such a feature is necessary to decouple different slab geometries and trajectories at the interface of the northern and southern arc segments.

Furthermore, mafic, tholeiitic rocks in the Warner Range may reflect a slab tear, just north of the Warner Range (Colgan et al., 2011), that separates the northern and southern arc segments. Ascending asthenospheric mantle wedge flow around the edge of the slab tear (Humphreys, 1995; Trua et al., 2011) may have provided access to source materials appropriate to genesis of magmas like those erupted in the Warner Range, but found nowhere else along the length of the southern arc segment. Similarly, Cousens et al. (2011) suggested that post–ancestral arc volcanism in the Lake Tahoe region was related to asthenospheric mantle flow around the edge of the subducted Farallon plate after northward passage of the Mendocino triple junction through this area. The Warner Range rocks have 87Sr/86Sr < 0.7039 (Colgan et al., 2011), which is also consistent with an asthenospheric mantle source. The age of the oldest tholeiitic rocks in the Warner Range, ca. 30 Ma (Carmichael al., 2006), constitutes a minimum age for development of the proposed slab tear and constrains the temporal genesis of this tectonic feature. As such, Warner Range rocks may reflect tectonic and associated magmatic regimes—specifically a slab tear that focused upwelling asthenospheric mantle (essentially leaky transform magmatism) through relatively thin, primitive crust—unique to this part of the southern arc segment. However, Lerch et al. (2007) concluded that this is the only part of the southern arc segment not underlain by Mesozoic granitic rocks. Consequently, distinct geochemical and isotopic characteristics of the Warner Range rocks may reflect magma contamination by crustal components different than those involved in the petrogenesis of all other southern arc segment magmas.

METALLOGENY OF THE SOUTHERN SEGMENT OF THE ANCESTRAL CASCADES ARC

Epithermal gold-silver deposits and large areas of hydrothermally altered rock are abundant in late Oligocene to early Pliocene rocks of the southern arc segment, especially in the western Great Basin south of latitude 40°N.
Rich gold-silver vein deposits of the Comstock Lode at Virginia City were discovered in 1859 and in the following year at Aurora, leading to a major gold rush in western Nevada (Tingley et al., 1993). A second gold rush, touched off by discovery of rich gold-silver deposits at Tonopah (in 1900) and Goldfield (in 1902), lasted through ca. 1920. In the 1970s, rise of gold and silver prices due to deregulation and changes in mining techniques used to exploit low-grade ores produced from open pit mines led to renewed exploration for epithermal gold-silver deposits and discovery and development of large, but relatively low-grade, deposits at Borealis, Santa Fe, Paradise Peak, and Rawhide in the 1980s to early 2000s (Fig. 3). Widespread exploration activity for epithermal deposits in the southern part of the ancestral arc continues, as exemplified by the recent announcement of gold resources in the Goldfield district (International Minerals, 2012).

Numerous, widespread epithermal gold-silver deposits, many with <1 Moz gold production, are characteristic of the southern arc segment (e.g., John, 2001; Vikre and Henry, 2011), whereas known epithermal deposits in the northern arc segment are sparse and small (du Bray and John, 2011). In contrast, plutonic rocks and genetically related porphyry copper and related deposits are abundant in the northern arc segment, whereas plutonic rocks are rarely exposed and porphyry copper and skarn deposits are unknown in the southern arc segment.

Characteristics of Hydrothermal Alteration and Mineral Deposits in the Southern Arc Segment: Types, Distribution, Age, and Relationship to Magmatism

Hydrothermally altered rock and epithermal gold-silver deposits are especially abundant (1) in the Walker Lane in the western Great Basin south of latitude 40°N and (2) in adjacent areas in the eastern Sierra Nevada south of Portola (Fig. 2). Some parts of the ancestral arc, notably around the Comstock Lode in the Virginia Range in western Nevada and in the Markleeville area (Monitor district) in eastern California, include areas of propylitically altered rock in excess of 100 km² (Coats, 1940; Wilshire, 1957; Whitebread, 1976; Vikre, 1989; John, 2001; Hudson et al., 2009; John et al., 2012). Other types of hydrothermal alteration commonly are superimposed on more regionally developed propylitic alteration. Alteration of this sort includes more than 40 “quartz-alunite alteration cells,” which are areas of intense hydrolytic alteration that range in size from <0.1 km² to >100 km² and result from convective circulation of low-pH magmatic-hydrothermal fluids, destruction of primary igneous minerals, and formation of quartz + alunite + pyrite and other mineral assemblages stable at low pH (Vikre and Henry, 2011).

Numerous epithermal gold-silver deposits and prospects and several larges stratiform elemental sulfur deposits are within areas of hydrothermally altered rock in the southern arc segment. Both high-sulfidation (quartz-alunite) and low- and intermediate-sulfidation (adularia-sericite) types of epithermal deposits (Heald et al., 1987; Hedenquist et al., 2000; Simmons et al., 2005) are well represented in the southern arc segment (Fig. 3; Table 3). The Comstock Lode, Tonopah, Bodie, Aurora, and Rawhide are low- or intermediate-sulfidation deposits that had large production (>1 Moz Au); Goldfield and Paradise Peak are high-sulfidation deposits that produced >1 Moz Au.

Elemental sulfur deposits are the only other significant type of deposit presently known in the southern arc segment (Table 3). Two large stratiform sulfur deposits, the Leviathan (Monitor) and Calmono deposits, replace volcanlastic deposits related to andesitic stratovolcanoes in the western part of the ancestral arc (Vikre and Henry, 2011; John et al., 2012). Sulfur isotope data indicate that both formed from magmatic-hydrothermal fluids (Vikre, 2000; Vikre and Henry, 2011).

Most of the southern arc segment is not deeply eroded and plutonic rocks are rarely exposed. Consequently, most exposed deposits are shallowly formed (0–1500 m) epithermal gold-silver, mercury, and sulfur deposits. Small polymetallic (Ag-Pb-Zn-Cu-Au) veins deposits, possibly formed at somewhat greater depths, are present in early arc-related volcanic rocks in the Pyramid district and at Leadville (Fig. 3). Near the Guanomi mine on the southwest side of Pyramid Lake, distally sourced Oligocene ash-flow tuffs are intruded by a small quartz monzonite porphyry stock and contain low-grade Cu-Mo mineralization in ca. 24 Ma stockwork quartz-pyrite-molybdenite veins and associated sericitically altered rock (Bonham and Papke, 1969; Prochnau, 1973). However, drilling these altered rocks did not result in identification of porphyry Cu-Mo deposits (Prochnau, 1973).

Although no known porphyry copper or genetically related skarn, polymetallic vein, or polymetallic replacement deposits are exposed in the southern arc segment, some have suggested that porphyry copper deposits may underlie areas of advanced argillic alteration and/or epithermal gold-silver deposits, notably in the Pyramid district west of Pyramid Lake (Wallace, 1979), in the Peavine and Wedekind districts near Reno (Wallace, 1979; Hudson, 1977, 1983), and at the south end of the Bodie district (Hollister and Silberman, 1995). Others have suggested that porphyry molybdenum systems may underlie altered late Miocene rhyolite dome complexes at Washington Hill just east of Reno (Margolis, 1991; Albino, 1992) and along the crest of the Sweetwater Range (Brem et al., 1983). Limited drilling in these areas has not proven the existence of porphyry-style mineralization.

Most of the known large epithermal deposits formed in eruptive centers or volcanic fields that were episodically active for extended periods, commonly several million years (Table 3; John, 2001). For example, (1) the Comstock Lode formed at ca. 14 Ma, following discontinuous magmatism that began ca. 18 Ma and persisted until ca. 14.2 Ma (Hudson et al., 2009), and (2) deposits in the Aurora and Bodie districts formed at ca. 10.5–10.2 and 8.5–8.1 Ma, respectively, in the Bodie Hills volcanic field, which was episodically active between ca. 15 and 6 Ma (John et al., 2012).

Most of the significant mineral deposits are temporally related to intermediate-to silicic-composition lava dome complexes and are not related to more mafic shield and stratovolcanoes. Some of the arc-related stratovolcanoes host significant mineral deposits (e.g., the Comstock Lode, Aurora), but these stratovolcanoes are notably older than the contained hydrothermal alteration and associated mineral deposits (Table 3; Hudson et al., 2009; Vikre and Henry, 2011; John et al., 2012).

Volcaniclastic rocks, including debris-flow and pyroclastic deposits related to stratovolcanoes and lava domes, are strongly hydrothermally altered in many places but generally are poor host rocks for economic mineral deposits. These rocks have high primary permeability, which, although conducive to convective circulation of hydrothermal fluids, produced large areas of intensely altered, but unmineralized or weakly mineralized rock (e.g., the 20–30 km² Red Wash and Paramount–Bald Peak alteration zones in the Bodie Hills; Vikre and Henry, 2011; John et al., 2012). Notable exceptions include the large Leviathan and Calmono stratiform sulfur deposits, which are hosted in volcaniclastic rocks related to stratovolcanoes.

Ages of mineral deposits in the southern arc segment range from ca. 22 to 5 Ma (Table 3). Although ages progressively decrease from southeast to northwest and from east to west (Fig. DR37 in the Supplemental File [see footnote 1]), which mimics the age of nearby magmatic activity, the oldest deposits are small polymetallic veins in the Pyramid district (ca. 22 Ma) and in the Leadville district (undated, probably ≥30 Ma) in the northern half of the
<table>
<thead>
<tr>
<th>Number</th>
<th>District/Deposit Name</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Deposit type</th>
<th>Production/ resources</th>
<th>Age (Ma)</th>
<th>Host rocks</th>
<th>Volcanic setting</th>
<th>Basement rocks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High Grade</td>
<td>41.950</td>
<td>−120.210</td>
<td>Low-sulfidation Au-Ag</td>
<td>ca. 4400 oz Au</td>
<td>14.5</td>
<td>Rhyolite domes and andesite lava flows</td>
<td>Rhyolite domes intruding mafic lava flows</td>
<td>Unknown</td>
<td>Keats, 1985; this study</td>
</tr>
<tr>
<td>2</td>
<td>Hayden Hill</td>
<td>40.995</td>
<td>−120.875</td>
<td>Low-sulfidation Au-Ag</td>
<td>421,171 oz Au; 909,403 oz Ag</td>
<td>ca. 8</td>
<td>Late Miocene dacite breccias and tuffs and fluviatilisacustrine sedimentary rocks</td>
<td>Dacite domes separated by shallow basins</td>
<td>Unknown</td>
<td>Detra and Burnett, 1994</td>
</tr>
<tr>
<td>3</td>
<td>Leadville</td>
<td>41.099</td>
<td>−119.404</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>small production Ag-Pb-Zn minor Au, Ag</td>
<td>Undated</td>
<td>Eocene andesite</td>
<td>Unknown</td>
<td>Mesozoic granitic and metavolcanic rocks</td>
<td>Bonham and Papke, 1969; this study</td>
</tr>
<tr>
<td>4</td>
<td>Pyramid</td>
<td>39.860</td>
<td>−119.610</td>
<td>High-sulfidation/ polymetallic veins</td>
<td>23.2 Ma dacite ignimbrite, andesite dikes</td>
<td>22.6</td>
<td>Andesite dikes intruding tuff filling small caldera(?)</td>
<td>Andesite dikes separated by shallow basins</td>
<td>Unknown</td>
<td>Garside et al., 2003; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>6</td>
<td>Golden Dome</td>
<td>39.643</td>
<td>−120.293</td>
<td>High-sulfidation Au-Ag</td>
<td>1.5 Mt @ 0.1 oz Au; 1.2 oz Ag/t</td>
<td>7.0 to 7.2</td>
<td>Mesozoic granitic rocks, ca. 9 Ma dacite</td>
<td>Dacite dome field</td>
<td>Mesozoic granitic rocks</td>
<td>Young and Cleur, 1992; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>7</td>
<td>Peavine</td>
<td>39.600</td>
<td>−119.900</td>
<td>High-sulfidation Au-Ag</td>
<td>1747 oz Au; 199,750 oz Ag</td>
<td>ca. 16 to 15</td>
<td>Miocene andesite lava flows and plugs, Jurassic metavolcanic rocks</td>
<td>Subvolcanic intermediate-composition intrusions</td>
<td>Mesozoic granitic and metavolcanic rocks</td>
<td>Hudson, 1977</td>
</tr>
<tr>
<td>8</td>
<td>Wedekind</td>
<td>39.570</td>
<td>−119.750</td>
<td>High-sulfidation Au-Ag</td>
<td>Included in Peavine</td>
<td>ca. 16 to 15</td>
<td>Miocene andesite lava flows and plugs, Jurassic metavolcanic rocks</td>
<td>Subvolcanic intermediate-composition intrusions</td>
<td>Mesozoic granitic and metavolcanic rocks</td>
<td>Hudson, 1977</td>
</tr>
<tr>
<td>9</td>
<td>Olinghouse</td>
<td>39.670</td>
<td>−119.408</td>
<td>Low-sulfidation Au-Ag</td>
<td>74,272 oz Au; 48,632 oz Ag</td>
<td>10.5</td>
<td>Miocene basalt lava flow and dikes, dacite dikes</td>
<td>Dacite dike swarm</td>
<td>Mesozoic granitic and metavolcanic rocks</td>
<td>Wilson et al., 1999; John et al., 1999; Garside and Bonham, 2006</td>
</tr>
<tr>
<td>10</td>
<td>Gooseberry</td>
<td>39.480</td>
<td>−119.460</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>84,866 oz Au; 3.57 Moz Ag</td>
<td>10.3</td>
<td>Miocene andesite dacite lava flows, breccias, and domes</td>
<td>Flow dome complex</td>
<td>Mesozoic granitic and metavolcanic rocks</td>
<td>Sprecher, 1985</td>
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<td>11</td>
<td>Ramsey-Comstock</td>
<td>39.470</td>
<td>−119.380</td>
<td>High-sulfidation Au-Ag</td>
<td>18,650 oz Au</td>
<td>ca. 9.3</td>
<td>Miocene andesite lava flows and interbedded epiclastic rocks</td>
<td>Flow dome complex</td>
<td>Mesozoic granitic and metavolcanic rocks</td>
<td>Vikre and Henry, 2011; Clark, 1992</td>
</tr>
</tbody>
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(continued)
### TABLE 3. CHARACTERISTICS OF SIGNIFICANT MINERAL DEPOSITS ASSOCIATED WITH SOUTHERN ARC SEGMENT ROCKS, ANCESTRAL CASCADES ARC (continued)

<table>
<thead>
<tr>
<th>Number</th>
<th>District/Deposit Name</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Deposit type</th>
<th>Production/resources</th>
<th>Age (Ma)</th>
<th>Host rocks</th>
<th>Volcanic setting</th>
<th>Basement rocks</th>
<th>References</th>
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<tr>
<td>13</td>
<td>Comstock Lode</td>
<td>39.300</td>
<td>-119.650</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>8.4 Moz Au; 193 Moz Ag; minor Cu and Pb</td>
<td>14.2 to 14.0</td>
<td>18.3 to 17.4 Ma, 15.8 to 15.2 Ma, and 14.9 to 14.2 andesite</td>
<td>Andesite dome field built on earlier andesite stratovolcano</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Hudson, 2003; Hudson et al., 2009; Vikre, 1989; Becker, 1862</td>
</tr>
<tr>
<td>14</td>
<td>Flowery (Golden Eagle)</td>
<td>39.320</td>
<td>-119.590</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>130,072 oz Au; &gt;305,055 oz Ag</td>
<td>13.4</td>
<td>Late Miocene andesite lavas and intrusions</td>
<td>Andesite dome field built on earlier andesite stratovolcano</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Castor et al., 2005</td>
</tr>
<tr>
<td>15</td>
<td>Como</td>
<td>39.170</td>
<td>-119.480</td>
<td>Low-sulfidation Au-Ag</td>
<td>small Au-Ag production</td>
<td>7.0 to 6.6</td>
<td>Middle Miocene andesite lavas and intrusions</td>
<td>Andesite stratovolcano(?)</td>
<td>Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Vikre and McKee, 1994</td>
</tr>
<tr>
<td>16</td>
<td>Dan Tucker–Summit King</td>
<td>39.274</td>
<td>-118.353</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>20,895 oz Au; 1.28 Moz Ag</td>
<td>ca. 19</td>
<td>Miocene rhyolite dikes and andesite lava flows, Oligocene rhyolite ignimbrites, Mesozoic metavolcanic rocks</td>
<td>Rhyolite dikes</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Wilden and Speed, 1974; Garside et al., 1981</td>
</tr>
<tr>
<td>17</td>
<td>Rawhide</td>
<td>39.030</td>
<td>-118.420</td>
<td>Low-sulfidation Au-Ag</td>
<td>1.56 Moz Au; 12.7 Moz Ag</td>
<td>ca. 15.5</td>
<td>Middle Miocene rhyolites, andesite, and volcaniclastic and lacustrine sedimentary rocks</td>
<td>Rhyolite dome field on edge of small basin</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Black et al., 1991; Gray, 1996</td>
</tr>
<tr>
<td>18</td>
<td>Monitor/Leviathan</td>
<td>38.712</td>
<td>-119.658</td>
<td>Stratiform sulfur</td>
<td>0.466 Mt S°</td>
<td>ca. 9</td>
<td>Miocene volcaniclastic sedimentary rocks</td>
<td>Edge of andesite stratovolcano</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Clark and Evans, 1977; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>19</td>
<td>Monitor/Zaca</td>
<td>38.666</td>
<td>-119.706</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>79,000 oz Au; 1.82 Moz Ag</td>
<td>4.9</td>
<td>ca. 5 Ma rhyolite dome</td>
<td>Rhyolite dome field in older trachyandesite stratovolcano</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Clark and Evans, 1977; Prenn and Merriick, 1991; John and Armin, 1984</td>
</tr>
<tr>
<td>20</td>
<td>Patterson-Silverado</td>
<td>38.451</td>
<td>-119.240</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>3000 oz Au; 3 Moz Ag; 35,000 lb Cu</td>
<td>ca. 5.57</td>
<td>Late Miocene rhyolite</td>
<td>Rhyolite dome complex</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Brem et al., 1983; this study</td>
</tr>
<tr>
<td>21</td>
<td>Masonic</td>
<td>38.367</td>
<td>-119.117</td>
<td>High-sulfidation Au-Ag</td>
<td>55,791 oz Au; 38,749 oz Ag; minor Cu</td>
<td>13.4 and 13.0</td>
<td>15 to 14 Ma trachyandesite lava flows and volcaniclastic rocks</td>
<td>Andesite domes emplaced into older trachyandesite stratovolcano</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Vikre and Henry, 2011; P. Vikre, 2013, written commun</td>
</tr>
<tr>
<td>Number</td>
<td>District/Deposit Name</td>
<td>Latitude (°N)</td>
<td>Longitude (°W)</td>
<td>Deposit type</td>
<td>Production/resources</td>
<td>Age (Ma)</td>
<td>Host rocks</td>
<td>Volcanic setting</td>
<td>Basement rocks</td>
<td>References</td>
</tr>
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</tr>
<tr>
<td>22</td>
<td>Borealis</td>
<td>38.380</td>
<td>-118.760</td>
<td>High-sulfidation Au-Ag</td>
<td>653,000 oz Au; &gt;114,000 oz Ag</td>
<td>ca. 16?</td>
<td>Miocene andesite and volcaniclastic rocks</td>
<td>Uncertain</td>
<td>Mesozoic granite and metavolcanic rocks</td>
<td>Eng, 1991; Steininger and Ranta, 2005; Vikre and Henry, 2011; Chesterman et al., 1986; John et al., 2012; P. Vikre, 2013, written commun</td>
</tr>
<tr>
<td>23</td>
<td>Bodie</td>
<td>38.223</td>
<td>-118.982</td>
<td>Low- and intermediate-sulfidation Au-Ag</td>
<td>1.456 Moz Au; 7.28 Moz Ag</td>
<td>8.5 to 8.1</td>
<td>9.1 to 8.9 Ma dacite domes and breccias</td>
<td>Dacite dome field</td>
<td>Uncertain, possibly Paleozoic siliciclastic metasedimentary rocks</td>
<td>Chesterman et al., 1986; John et al., 2012; P. Vikre, 2013, written commun</td>
</tr>
<tr>
<td>24</td>
<td>Aurora</td>
<td>38.290</td>
<td>-118.890</td>
<td>Low-sulfidation Au-Ag</td>
<td>1.817 Moz Au; 20.6 Moz Ag</td>
<td>10.5 to 10.2</td>
<td>13 to 12.5 Ma trachyandesite; 11.2 Ma rhyolite</td>
<td>Rhyolite dome field on edge of trachyandesite stratovolcano</td>
<td>Mesozoic granite and metavolcanic rocks</td>
<td>John et al., 2012; P. Vikre, 2013, written commun; Osborne, 1991; Twain, 1873</td>
</tr>
<tr>
<td>25</td>
<td>Cinnabar Canyon/Calmono</td>
<td>38.190</td>
<td>-119.160</td>
<td>Stratiform sulfur</td>
<td>16.1 Mt @ 17.9% S°</td>
<td>8.8 to 8.7</td>
<td>Volcaniclastic sedimentary rocks</td>
<td>Trachyandesite dome field</td>
<td>Cretaceous granite, Mesozoic metavolcanic rocks, Paleozoic metasedimentary rocks</td>
<td>Ward, 1992; Vikre and Henry, 2011; John et al., 2012; P. Vikre, 2013, written commun</td>
</tr>
<tr>
<td>26</td>
<td>Paradise Peak</td>
<td>38.750</td>
<td>-117.970</td>
<td>High-sulfidation Au-Ag</td>
<td>1.626 Moz Au; ≥24 Moz Ag</td>
<td>19 to 18</td>
<td>22 to 18 Ma andesite-dacite lava flows and breccias and ca. 25 Ma rhyolite ignimbrites</td>
<td>Probably andesite-dacite dome field</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>John et al., 1991; Stillitoe and Lorson, 1994</td>
</tr>
<tr>
<td>27</td>
<td>Santa Fe–Isabella–Pearl</td>
<td>38.590</td>
<td>-118.117</td>
<td>High-sulfidation Au-Ag</td>
<td>356,700 oz Au; 721,523 oz Ag</td>
<td>ca. 19</td>
<td>Mesozoic carbonates, Cretaceous granite, Oligocene ignimbrites</td>
<td>Uncertain; sparse rhyolite dikes</td>
<td>Cretaceous granite, Mesozoic metasedimentary and metavolcanic rocks</td>
<td>Fiannaca, 1987; Albino and Boyer, 1992; Vikre and Henry, 2011</td>
</tr>
<tr>
<td>28</td>
<td>Tonopah</td>
<td>38.070</td>
<td>-117.230</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>1.86 Moz Ag; 174 Moz Ag</td>
<td>ca. 19.5</td>
<td>Early Miocene andesite and rhyolite lavas, breccias, intrusions, and ignimbrites</td>
<td>Uncertain; probably near andesite dome complex</td>
<td>Mesozoic granite rocks, Paleozoic metasedimentary rocks</td>
<td>Spurr, 1905; Nolan, 1935; Bonham and Garside, 1979; Ashley, 1990a</td>
</tr>
<tr>
<td>29</td>
<td>Divide/Tonopah Divide</td>
<td>37.990</td>
<td>-117.240</td>
<td>Intermediate-sulfidation Au-Ag</td>
<td>39,759 oz Au; 4.135 Moz Ag</td>
<td>ca. 16</td>
<td>ca. 19 Ma rhyolite tuff; 17 to 16 Ma rhyolite domes, mid-Miocene volcaniclastic sediments</td>
<td>Rhyolite dome field along edge of sedimentary basin</td>
<td>Paleozoic sedimentary rocks</td>
<td>Erdman and Barabas, 1996</td>
</tr>
<tr>
<td>30</td>
<td>Divide/Hasbrouck</td>
<td>37.990</td>
<td>-117.270</td>
<td>Low-sulfidation Au-Ag</td>
<td>small Ag production</td>
<td>ca. 16</td>
<td>Mid-Miocene volcaniclastic sediments</td>
<td>Rhyolite dome field along edge of sedimentary basin</td>
<td>Paleozoic sedimentary rocks</td>
<td>Graney, 1987</td>
</tr>
<tr>
<td>31</td>
<td>Goldfield</td>
<td>37.710</td>
<td>-117.210</td>
<td>High-sulfidation Au-Ag</td>
<td>4.19 Moz Au; 1.45 Moz Ag; 3835 l Cu</td>
<td>20 to 19</td>
<td>22 to 21 Ma andesite and rhyolite</td>
<td>Andesite dome field</td>
<td>Jurassic granite, Paleozoic argillite</td>
<td>Vikre and Henry, 2011; Ashley, 1974, 1990b; Ransome, 1909</td>
</tr>
</tbody>
</table>
Host rocks for well-dated epithermal deposits generally are hundreds of thousands to several million years older than the contained mineralization. Large age differences between mineralization and associated host rocks are especially notable among low- and intermediate-sulfidation deposits (Table 3). For example, rocks of the 18.3–17.4 Ma Silver City and 15.8–15.3 Ma Virginia City magmatic suites host much of the 14.2–14.0 Ma Comstock Lode veins (Hudson et al., 2009), and the 13.1–12.6 Ma trachyandesite of Aurora hosts most of the 10.5–10.2 Ma veins in the Aurora district (John et al., 2012; this study). In contrast, ages of high-sulfidation deposits and related quartz-aluminate alteration cells are often similar to those of their host rocks. For example, in the Masonic district, two episodes of alunite alteration and associated Au-Ag-Cu mineralization, 13.4 and 13.0 Ma, are approximately the same age as nearby trachyandesite domes (John et al., 2012; P. Vikre, written commun.).

Epithermal Au-Ag deposits associated with the southern arc segment formed both north and south of the Neoproterozoic continental margin, but nearly all deposits north of the continental margin are underlain by basement rocks with continental affinities, mostly in the Pine Nut and Paradise terranes (Fig. 2). Numerous quartz-aluminate alteration zones, both mineralized and unmineralized, also are exposed in this part of the ancestral arc (Vikre and Henry, 2011). However, epithermal Au-Ag deposits and quartz-aluminate alteration zones are scarce to absent in the northern part of the southern arc segment, both in the western Great Basin part of the arc, which is underlain by an accreted island arc (Black Rock terrane), and in the southern Cascade Mountains (Modoc Plateau), for which basement rock characteristics are unknown (Fig. 3). Epithermal deposits at Hayden Hill and in the High Grade district are the only significant known mineralization in this part of the southern arc segment (Fig. 2). Both deposits formed in silicic domes, which are uncommon elsewhere in the northern part of the southern arc segment, in parts of the arc that are north of the inferred edge of the Sierra Nevada batholith (Figs. 2, 3).

Most known mineral deposits in the southern arc segment are in a northwest-trending belt approximately coincident with the Walker Lane (Fig. 3). Most quartz-aluminate alteration cells (Vikre and Henry, 2011) are within this belt, but many of the deposits and alteration zones in the central Walker Lane formed millions of years prior to initiation of dextral shear characteristic of the central Walker Lane at ca. 10 Ma (Faust and Henry, 2008). These relations suggest that Walker Lane tectonics minimally influenced the overall distribution of epithermal mineral deposits in the southern arc segment; however, the transitional regime characteristic of the Walker Lane (Puhar et al., 2009; Busby et al., 2013a) may have provided structural conduits that helped focus mineralizing fluids responsible for genesis of some of these systems.

Ages of epithermal Au-Ag deposits in the southern arc segment range between ca. 22 and 5 Ma (Table 3). Large deposits (>1 Moz Au production) range in age from ca. 20 to 8 Ma and are both older and younger than Basin and Range extension, which began between ca. 16 and 10 Ma throughout much of the southern arc segment. Although some deposits are inferred to have formed along pre–Basin and Range extensional faults that were active contemporaneously with mineralization, (e.g., John et al., 1989) or by reactivation of transverse structures in basement rocks (Berger et al., 2005), these inferred structures merely seem to localize mineralization and do not fundamentally control the overall distribution of mineral deposits in the southern arc segment. Rather, the entire Great Basin part of the southern arc segment, south of ~40°N latitude (the part of the arc underlain by the North American craton or the Paradise and Pine Nut terranes), appears prospective for epithermal Au-Ag deposits associated with magmatic systems similar to those described above.

The scarcity of epithermal Au-Ag deposits in the northern part of the southern arc segment and in areas overlying the Sierra Nevada batholith may reflect a variety of factors. These include (1) the dearth of intermediate- to silicic-composition (dacite-rhyolite) dome complexes, the dominant magmatic systems with which epithermal Au-Ag deposits are associated; (2) the lack of suitable basement, including the North American continental margin and terranes that contain continentally derived sedimentary and volcanic rocks, which, especially Neoproterozoic siliciclastic sedimentary rocks (Vikre and Henry, 2011), are possible metal sources; and/or (3) the prevalence of relatively thin and/or low-density crust, such as the Sierra Nevada batholith, which fostered direct ascent and eruption of mantle-derived mafic magmas. A regime in which magmas quickly transited the crust may have precluded formation of the intermediate to silicic reservoirs that are characteristic of the mineralized part of the southern arc segment. Lacking these shallowly emplaced reservoirs, the hydrothermal systems required to form epithermal deposits could not develop.

Comparison of the Metallogeny of the Northern and Southern Segments of the Ancestral Cascades Arc and Controls on Mineralization

Deposits related to porphyry copper systems, including porphyry copper deposits, copper-rich breccia pipes, and polymetallic veins, dominate known mineral deposits in the northern arc segment in Oregon and Washington. These deposits are widely exposed in southern Washington and northernmost Oregon and mostly formed between ca. 23 and 16 Ma (du Bray and John, 2011). Epithermal Au-Ag deposits are notably scarce; the ~32,000 oz of gold and 40,500 oz of silver produced from several small mines in the Bohemia district in west-central Oregon represent most of the recorded Au-Ag production in the northern arc segment. In contrast, in the southern arc segment, epithermal Au-Ag deposits are numerous, some are large (>1 Moz Au, >10 Moz Ag; Table 3), and porphyry copper systems appear to be absent. The variation in the types and metal contents of mineral deposits in the two arc segments, and within different parts of the two segments, likely reflect multiple factors, possibly including (1) thickness and composition of the crust, (2) regional stress environment during magma genesis and emplacement, (3) angle of subduction and metasomatism of the subcontinental mantle lithosphere, and (4) depth of erosion.

Du Bray and John (2011) suggested that the distribution of porphyry copper systems in the northern arc segment reflects variations in the regional stress regime during arc magmatism and/or the nature of the underlying crust. They inferred that porphyry copper systems are limited to parts of the arc undergoing transpression to mild compression and underlain by thicker, lower-density crust along the western edge of the North American plate. In contrast, the southern part of the northern arc segment, underlain by young oceanic basaltic (Siletzia terrane), constitutes a framework unfavorable to genesis of the sorts of magmatic systems with which porphyry copper deposits are associated (du Bray and John, 2011). Richards (2009) suggested that metasomatized metal-enriched subcontinental mantle lithosphere, remobilized during subsequent arc magmatism, may be critical to porphyry copper deposit formation in highly productive arcs, such as the Andes; Muntean et al. (2011) suggested that metal-enriched subcontinental mantle lithosphere may have been similarly important to formation of late Eocene Carlin-type gold deposits in the northern Great Basin. Consequently, relatively steep subduction may have precluded preservation of metasomatically metal-enriched...
subcontinental mantle lithosphere beneath the northern part of the northern arc segment. Pending development of suitable isotopic data, the metrics of Putirka et al. (2012) could be used to identify whether asthenospheric mantle wedge or subcontinental lithospheric mantle sources were involved in arc magma genesis and test the viability of the Richards (2009) hypothesis relative to the southern arc segment and its associated mineral ore deposits.

The near absence of phaneritic plutonic rocks in the southern arc segment suggests that the level of erosion there is generally less than in the northern part of the northern arc segment and that the lack of exposed porphyry copper systems in the southern ancestral arc may be due to insufficient erosion. Abundant high-sulfidation epithermal deposits and quartz-alunite alteration, which may constitute lithocaps such as those that commonly overlie porphyry copper systems (Sillitoe, 2010), also indicate the potential for unexposed porphyry copper systems in the southern arc segment. However, the generally neutral to moderately extensional or trans-tensional regional stress regime inferred for the southern arc segment (John, 2001; Pluhar et al., 2009; John et al., 2012; Busby et al., 2013) contrasts with the compressional or transpressional stress environment inferred during formation of porphyry copper systems in the northern arc segment (du Bray and John, 2011). Consequently, the prevailing regional stress regime in the southern arc segment may not have been favorable for porphyry copper deposit formation (Tosdal and Richards, 2001; Richards, 2003).

The scarcity of epithermal Au-Ag deposits in the northern arc segment may reflect the type of crust underlying the arc, level of erosion, and the sparse presence of silicic dome complexes (du Bray and John, 2011) in the north half of the southern arc segment. In addition, the relatively neutral to weakly extensional and/or trans-tensional regional stress field characteristic of the southern arc segment (John, 2001; Pluhar et al., 2009; John et al., 2012; Busby et al., 2013) may have been more conducive to shallow hydrothermal system development than the mostly compressional stress field that prevailed in the northern arc segment (du Bray and John, 2011).

CONCLUSIONS

Modern High Cascades arc magmatism along western North America was preceded by subduction-related ancestral arc magmatism that began ca. 45 Ma and continued until initiation of modern High Cascades arc volcanism between ca. 4 and 2 Ma. Ancestral arc magmatism extended from near the Canada-USA border in Washington southward to near Goldfield, Nevada, and includes northern and southern segments separated by a subducting-slab tear between the Mount Shasta and Lassen Peak volcanic centers. The southern half of this ancestral arc extends between about latitudes 42°N in northern California and 37°N in western Nevada and was active from ca. 30 to 3 Ma; erupted volumes were greatest during the 17–8 Ma period. The southern arc segment is approximately bounded on the east by the east edge of the Walker Lane; to the west, rocks erupted along the axis of the arc flowed down the west flank of the Sierra Nevada. Southern arc segment rocks are mostly between 25 and ca. 4 Ma and consist of potassic, calc-alkaline intermediate-composition lava and associated volcaniclastic deposits, presumably products mostly of stratovolcanoes and lava domes aligned along the axis of the ancestral arc and genetically associated with subduction of the Farallon plate to the west. The silica content of these subalkaline rocks ranges continuously from ~55 to 77 wt%. In contrast to the northern arc segment, the compositions of southern arc segment rocks are essentially invariant with respect to time, which suggests that subduction and associated magma genesis processes were fundamentally uniform during development of the southern arc segment.

Close spatial, temporal, and geochemical (John, 2001; Vikre and Henry, 2011) associations between mineral deposits, particularly epithermal deposits, and southern ancestral arc segment volcanic fields suggests a genetic relationship. In contrast, only sparse, small epithermal deposits are known in the northern part of the arc. Correspondingly, plutonic rocks and genetically related porphyry copper and related deposits are abundant in the northern arc segment, whereas plutonic rocks are rare and porphyry copper and skarn deposits are unknown in the southern arc segment. Distinctive mineralizing processes and the resulting deposits reflect the distinct tectonic and magmatic regimes within which northern versus southern arc segment systems evolved.

Large epithermal gold-silver deposits (<1 Moz gold production) and large areas of hydrothermally altered rock are abundant in early Miocene to early Pliocene rocks of the southern arc segment, especially south of latitude 40°N. These deposits are principally hosted by intermediate to silicic lava dome complexes; few deposits are associated with more mafic composite volcanoes. Mineral deposits are also most abundant and well developed in volcanic fields whose evolution spanned millions of years. Most deposits are hundreds of thousands to several million years younger than their host rocks, although some high-sulfidation epithermal deposits are essentially coeval with their host rocks. Variable composition and thickness of crustal basement also appear to have influenced the extent and intensity of mineralizing processes along the length of the southern arc segment; most deposits are localized in basement rock terranes with a strong continental affinity. Relatively thick continental crust that prevailed throughout much of the southern arc segment fostered development of crustal magma reservoirs that stalled and fractionated to yield the magma compositions and magmatic-hydrothermal fluids conducive to epithermal deposit formation. Walker Lane structures do not appear to have exerted strong regional control on deposit localization. Instead, these features may have served as local-scale conduits for mineralizing fluids.

The time-space-compositional evolution of southern arc segment magmatism is distinct from that of the northern arc segment. Whereas the axis of northern ancestral arc magmatism migrated slowly eastward with time, as subducted slab rollback beneath the southern arc segment ensued, southern arc segment magmatism migrated westward. Southern arc segment rocks have generally lower TiO₂, FeO*, CaO, and Na₂O contents and higher K₂O contents, and exhibit less compositional variation through time, than the northern arc segment rocks, which are also distinctly more ferroan and tholeiitic. The presence of amphibole in many southern arc segment rocks implies that the associated magmas were hydrous and systematic decreases in TiO₂ and V abundances with increasing SiO₂ suggest early magmatic crystallization under relatively oxidizing conditions. Southern arc segment rocks have high LILE and low HFSE abundances similar to those of other convergent-margin magmatic arc rocks. Whereas the northern segment rocks become progressively REE depleted with time, the southern segment rocks contain progressively greater total REE contents, particularly LREE, with decreasing age. The southern arc segment rocks are LREE enriched relative to the northern arc segment rocks and have distinctly U-shaped patterns in their middle to heavy REE segments. Elevated Sr abundances and insignificant negative Eu anomalies are diagnostic of plagioclase instability in the source region, which in turn is consistent with genesis of southern arc segment magmas at depths >70 km beneath relatively thick continental crust. In contrast, compositional features of most northern arc segment rocks are consistent with their genesis beneath thinner, primitive crust. Compositional variations among the northern and southern arc segment rocks primarily reflect different crustal thicknesses that influenced the depth at which their respective magmas were
generated. Magma reservoirs formed beneath and fractionated within the thicker crust that hosted the southern arc segment. Some southern arc segment magmas were also distinctly contaminated by assimilation of Sierra Nevada batholith components. Compositions of rocks in the Warner Range, in the northernmost part of the southern arc segment, are distinct relative to those of all other southern arc segment rocks and may reflect asthenospheric mantle wedge flow around the edge of the subducted slab in the vicinity of a proposed slab tear or the involvement of a crustal contaminant unique to this part of the southern arc segment. In the southern arc segment region, compositional similarities between southern ancestral arc segment rocks and those of the co-modern high Cascades arc rocks suggest that magmatism transitioned continuously from that associated with the ancestral arc to that associated with the modern High Cascades arc.

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REFERENCES CITED


Albinato, G.V., and Boyer, C., 1992, Lithologic and structural similarities between southern ancestral arc segment rocks and those of the co-modern high Cascades arc rocks suggest that magmatism transitioned continuously from that associated with the ancestral arc to that associated with the modern High Cascades arc.


Petrology of the ancestral Cascades arc, southern segment


