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GEOLOGY AND PETROLOGY OF THE MID-MIOCENE SANTA ROSA-CALICO VOLCANIC FIELD, NORTHERN NEVADA

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ABSTRACT

This study provides a detailed examination of the physical evolution of a complex continental volcanic field, the Santa Rosa-Calico volcanic field (SC), and provides first-order information on the nature of the magmatic processes responsible for the physical, geochemical, and isotopic diversity documented by the products of this volcanic field. In the SC, numerous mafic through intermediate eruptive loci and shallow intrusive bodies crop out along north-south- and northwest-southeast-trending alignments, just west of the northward projection of the northern Nevada rift. Across the volcanic field, at least 16 physically and compositionally distinct units are present and represent the products of over 2-Ma of volcanism. Local mafic units physically and chemically resemble regional Steens Basalt and high-alumina olivine tholeiite and erupted over the duration of SC volcanism. SC andesite to dacite lava flows are found throughout the volcanic field and represent the products of at least four temporally, geographically, and chemically distinct magmatic systems. Complex open-system magma generation and evolution processes including both magma mixing and assimilation-fractional crystallization gave rise to these intermediate units. Contemporaneous faulting likely stimulated these processes via further emplacing mafic magma into the upper crust and also by providing a mechanism that could drive magma mixing. SC silicic products vary physically, chemically, and isotopically according to geographic location and again, require the presence of numerous magmatic systems throughout the >2-Ma duration of the SC. The physical, chemical, and isotopic characteristics of SC silicic units are also consistent with their derivation via crustal anatexis of local Cretaceous granitoid upper crust, as well as the potential incorporation of Triassic metasedimentary rocks. Similar processes of mafic magma upper crustal intrusion and coeval silicic melt generation appear to have occurred in other regions across the Pacific Northwest during the mid-Miocene flood basalt event. Caldera-derived eruptive products are present in the SC; however, voluminous caldera-forming events did not typify SC activity. Rather, a paucity of caldera-forming silicic volcanism distinguishes the SC from coeval mid-Miocene Oregon Plateau volcanic fields (e.g., McDermitt, Lake Owyhee, northwest Nevada) as well as other silicic-dominated volcanic fields that are typically associated with the younger Snake River Plain-Yellowstone volcanic province.

INTRODUCTION

Mid-Miocene to recent magmatism on and adjacent to the Oregon Plateau of the northwestern U.S.A. is and has been dominated by bimodal, basalt-rhyolite volcanism. The most voluminous volcanism in this timespan occurred from 17 to 14 Ma and was characterized by eruptions of the Steens-Columbia River flood basalts and the coeval formation of the dominantly silicic Oregon Plateau volcanic fields (e.g., McDermitt, Lake Owyhee; hereafter referred to as the Oregon Plateau volcanic province) (Fig. 1a,b; Rytuba and McKee, 1984; Zoback and others, 1994; Wallace and John, 1998; Cummings and others, 2000; John and Wallace, 2000; John and others, 2000; John 2001; Camp and others, 2003; Wallace, 2003; Camp and Ross, 2004; Jordan and others, 2004). Concurrent with this volcanism associated with the Yellowstone-Newberry melting anomaly (Hotspot), was tectonic activity along a focused zone of extension, primarily located against the western margin of the North American craton (Zoback and others, 1994; Cummings and others, 2000). An ~1000 km broadly north-trending zone that encompasses the feeder dikes of the Steens-Columbia River basalts, the Oregon-Idaho graben, and the northern Nevada rift(s) is the manifestation of this short-lived, laterally focused extensional event (Fig. 1a). To better understand this extensional event, particularly the interplay between upwelling mantle melt and the formation of multi-vent Oregon Plateau volcanic fields, it is essential to decipher the evolution of these complex volcanic systems. To this end, a detailed field, chronologic, geochemical, and petrologic study of the mid-Miocene Santa Rosa-Calico volcanic field of northern Nevada has been performed (Fig. 1a,b). This volcanic field will be simply referred to as the SC throughout the remainder of this publication.

The SC provides an ideal physical setting to better understand the evolution of the Oregon Plateau volcanic province and the volcanotectonic processes that affected this region in the mid-Miocene. It is located within the focused zone of mid-Miocene extension and at the approximate common intersection of the northwest trending High Lava Plains-Newberry and northeast trending Snake River Plain-Yellowstone volcanic trends. Furthermore, unlike other mid-Miocene Oregon Plateau volcanic fields, the SC was characterized by abundant intermediate-composition volcanism during its >2-Ma duration.

GEOLOGIC SETTING

The SC lies along the southern margin of the Oregon and Owyhee Plateaus. The Idaho-Oregon-Nevada tri-state region has long been associated with the initial manifestation of the Yellowstone-Newberry melt anomaly (Yellowstone hotspot; Pierce and Morgan, 1992). At 16.7 Ma, this region was affected by the initial outpouring of regional flood basalt volcanism (Steens) and the development of large silicic volcanic fields temporally and spatially associated with this flood basalt event (Fig. 1a,b). While the ultimate cause of this voluminous magmatic event is debatable, this part of the Oregon Plateau is the only location where the flood basalt lava flows and the dominantly silicic volcanic fields formed/erupted coevally. Since the mid-Miocene, basaltic volcanism has continued to the present on the Oregon Plateau, making it the only region in the Pacific Northwest where basaltic magmatism has continued over this duration (Hart, 1985; Shoemaker, 2004). During the initial flood basalt event, basalt through basaltic andesitic lava flows erupted from scattered loci across the Oregon Plateau, coeval with eruption and emplacement of the Columbia River Basalt Group (Brueseke and others, 2007a). The most intensively studied eruptive loci and package of Oregon Plateau flood basalt is exposed at Steens Mountain, where ~1 km of lava flows are cut by numerous feeder dikes (Hart and Carlson, 1985; Carlson and Hart, 1987). Other packages of chemically distinct mid-Miocene mafic lava flows and intrusive bodies around the Oregon Plateau are found as far east as the Jarbidge Mountains, Nevada (Seventy-Six Basalt; Hart and Carlson, 1985; Rahl and others, 2002), as far west as the Honey Lake region of western California (Lovejoy Basalt; Wagner and others, 2000; Coe and others, 2005), and as far south as the Roberts Mountains region of central Nevada (Zoback and others, 1994).

Regional mid-Miocene silicic volcanism began at 16.6-Ma and continued to 12 Ma. The initial stage of regional silicic activity was characterized by the eruption of voluminous ash flows from large caldera complexes (e.g., McDermitt, northwest Nevada, and Lake Owyhee volcanic fields; Noble and others, 1970; Greene and Plouff, 1981; Rytuba and McKee 1984; Ach and Swisher 1990; Rytuba and others, 1991; Bussey 1995; Castor and Henry, 2000). These volcanic systems were present across the entire Oregon Plateau. Also present were numerous small volume rhyolite dome complexes (Fig. 1a,b; Coats, 1968; Walker, 1969, 1974; MacLeod and others, 1975; Legge, 1988; Brueseke and others, 2004; Manley and McIntosh, 2004; Pasquale and Hart, 2006). By 14 to 12 Ma, Oregon Plateau silicic activity was waning and the locus of silicic activity diverged to the northwest and northeast, forming the High Lava Plains-Newberry and Snake River Plain-Yellowstone trends (Walker, 1969; 1974; MacLeod and others, 1975; Pierce and Morgan, 1992; Christiansen and others, 2002; Jordan and others, 2004).

Concurrent with the extensive, dominantly bimodal basalt-rhyolite volcanism, the Oregon Plateau region was affected by a focused “event” of lithospheric extension. The formation of an ~1000-km zone of continental extension spanning from Washington south into central Nevada commenced at 16.7 Ma and ended at 14 Ma (Fig. 1a,b; Zoback and Thompson, 1978; McKee and Noble, 1986; Carlson and Hart, 1987; Hart and Carlson 1987; Blakely and Jachens 1991; Zoback and others, 1994; Cummings and others, 2000; John and others, 2000; Ponce and Glen, 2002; Glen and Ponce, 2002; this study). This event was characterized by small net extension compared to other continental rifts (John and others, 2000) and is best expressed as subsurface gravity and aeromagnetic anomalies and the exposure of approximately north-northwest-trending mafic dike swarms (Zoback and others, 1994; John and others, 2000). Throughout the northern Nevada rift and this ~1000-km zone, this extension allowed the emplacement of basaltic magmas into the upper crust and had a profound effect on the formation and genesis of the SC. Abundant and often isolated basins and lacustrine systems formed across the southern Oregon Plateau concurrent with mid-Miocene rift related extension, and they were locally associated with epithermal precious metal mineralization (Vikre, 1985a; Vikre, 1987; Castor and Henry, 2000; Wallace, 2003). These deposits provide a detailed record of the regional silicic volcanic record as a result of the numerous tephra horizons preserved within the basin sediments (Perkins and others, 1998; Perkins and Nash, 2002; Gilbert and others, 2003).

At 11 to 12 Ma, basin-and-range-style extensional tectonism started affecting the region, coeval with the formation of the western Snake River Plain graben, and the onset of small-volume, Oregon Plateau-wide HAOT (low-K, high-alumina olivine tholeiite) volcanism (Hart, 1985; Bonnichsen and others, 2004; Colgan and others, 2004; Shoemaker and Hart, 2004; Jordan and others, 2004; Colgan and others, 2006). This same tectonic regime has persevered to the present day; faults along the eastern Santa Rosa Range front have been active in the last 15 Ka, and < 2-Ma HAOT and mildly-alkaline basaltic lava flows are found across the Oregon Plateau and western Snake River Plain (Hart, 1985; Jordan and others, 2004; Personius and others, 2004; Shoemaker, 2004).

GENERAL SANTA ROSA-CALICO GEOLOGY

Work in the SC area falls into four broad categories: [1] studies of the metamorphic and granitoid rocks that form the core of Santa Rosa Range (e.g., Compton, 1960; Shieh and Taylor, 1969; Wodzicki, 1971; Stuck, 1993), [2] reconnaissance studies along the margins of the Santa Rosa Range (western SC from Hinkey Summit north through Buckskin Mountain and in the southern Santa Rosa Range) (e.g., LeMasurier, 1965, 1968; Larson and others, 1971; Stewart and Carlson, 1976; Hart and Carlson, 1985; Carlson and Hart, 1987; Mellott, 1987); [3] studies of local mid-Miocene epithermal mineralization (e.g., Winchell, 1912; Lindgren, 1915; Roberts, 1940; Willden, 1964; Vikre, 1985a,b), and [4] studies of local and regional eruptive loci and fault patterns (e.g., King, 1984; McCormack, 1996; Colgan and others, 2004; Personius and others, 2004). This study represents the first attempt to fully define and integrate the areal extent, chronostratigraphy, lithostratigraphy, chemostratigraphy, physical volcanology, and petrologic and tectonic processes of the multi-vent volcanic field that herein is formally defined as the Santa Rosa-Calico volcanic field (Fig. 2).

The SC lies just west of the northern projection of the northern Nevada rift along the southern Oregon Plateau boundary almost due north of Winnemucca, Nevada and between two volcanic fields associated with the Yellowstone-Newberry melting anomaly, the McDermitt and "Owyhee-Humboldt" volcanic fields (Fig. 1b). The SC is roughly oval and bounded by the northern part of the Santa Rosa Range (western boundary), a basin-bounding normal fault at the north end of Paradise Valley (southern boundary; not shown on Fig. 2), the Calico Mountains (eastern boundary), and the Owyhee Plateau (northern boundary) (Figs. 1, 2). Elevations in the SC range from over 2500 m along its margins to less than 1500 m in the central part, a topographic depression called the Goosey Lake depression (Vikre, 1985a, b). The Goosey Lake depression is divided into two sub-basins (the western and eastern Goosey Lake depressions) by a zone of broadly north-northwest-trending faults (Fig. 2). The SC lies mainly in the Humboldt-Toiyabe National Forest and within Bureau of Land Management-administered lands and access is limited to intermittently maintained unpaved roads. Rugged topography is present throughout the SC and primarily results from post- and syn-SC faulting and Pleistocene glaciation. Field and aerial image observations suggest that erosive glacial activity occurred in the vicinity of Capitol Peak (in the western SC) and along the southern and western SC margins from Coal-Pit Peak through the Hinkey Summit/Granite Peak region, north to at least Buckskin Mountain (Fig. 2).

Beneath the package of SC-derived mid-Miocene volcanic rocks is a diverse assemblage of older material. Intensely deformed Triassic (Norian) metasedimentary strata are intruded by 102- to 85-Ma granitoid plutonic bodies (Compton, 1960; Willden, 1964; Stuck, 1993; Wyld and others, 2001). Following Cretaceous magmatism, a cessation in local activity occurred until the mid-Eocene, when most of Nevada experienced an ~20-Ma period of andesite-rhyolite volcanism related to subduction and extensional processes, often referred to as the "Cenozoic ignimbrite flare-up" (Coney, 1978; Armstrong and Ward, 1991; Christiansen and Yeats, 1992; Humphreys, 1995). In northern Nevada, lava and ash flows related to this magmatic event are best exposed in the vicinity of the Tuscarora volcanic field, east of the SC, and they are poorly exposed (where present) in northwestern Nevada (Castor and others, 2003; Colgan and others, 2006). At ~22 Ma, volcanism in the northern Great Basin became dominated by lava flows and intrusive bodies of dominantly intermediate composition that were emplaced as part of an extensive arc system along the North American margin (Christiansen and Yeats, 1992). These dominantly calc-alkaline, western andesite assemblage lava flows are found across the eastern Oregon Plateau and include the Steens Mountain volcanics that directly underlie the mid-Miocene Steens Basalt at Steens Mountain (Fuller, 1931; John, 2001). On the Oregon Plateau, this magmatic event ended at 20 to 19 Ma.

At 16.7 Ma, SC volcanic activity began (Table 1), coeval with regional Oregon Plateau bimodal basalt-rhyolite volcanism (this study). The up-to-1500-m-thick package of mafic through silicic lava flows, eruptive loci, and hypabyssal bodies associated with this event are well exposed in the SC and are the focus of the current study. At minimum, volcanic products derived from vents within the SC occur over an ~840 km^2 area. Using a minimum thickness of 150 m, this represents ~126 km^3 of volcanic products, not including unidentified outflow. This volume estimate may be closer to 400 km^3 because much of the SC pile is buried. Previous work indicates that magma generation and emplacement associated with the western Santa Rosa-Calico volcanic field took place between approximately 16.5 and 14 Ma (e.g., Larson and others, 1971; Carlson and Hart, 1983; Hart and Carlson,

1985; Vikre, 1985b; Carlson and Hart, 1987; Mankinen and others, 1987; Mellott, 1987). The same time span of local eruptive activity is recorded across the Oregon Plateau in the McDermitt, Northwest Nevada, and Lake Owyhee volcanic fields (Noble and others, 1970; Greene and Plouff, 1981; Rytuba and McKee, 1984; Ach and Swisher, 1990; Rytuba and others, 1991; Bussey, 1995; Perkins and others, 1998; Castor and Henry, 2000; Perkins and Nash, 2002). Also, fallout and flow facies likely associated with caldera-forming eruptions in the McDermitt volcanic field are preserved along the western flank of the SC (Mellott, 1987) and have been suggested to exist within the study area (King, 1984; Rytuba and McKee, 1984; Vikre, 1985a, b). Also present along the western flank is a thick (at least 200 m; Larson and others, 1971) pile of basalt derived from eruptions at or adjacent to Steens Mountain (Larson and others, 1971; Carlson and Hart, 1983; Hart and Carlson, 1985; Mankinen and others, 1987). Previous workers have also suggested that the central SC (Goosey Lake depression) formed in response to caldera-forming volcanism and represents a central caldera structure (Ekren and others, 1984; Vikre, 1985a). Bordering the eastern margin of the SC is the Owyhee Plateau, an intermontane plateau covered by <11-Ma basaltic lava flows and shield volcanoes (Shoemaker, 2004). Where canyons have cut into these younger basalts, silicic lava flows and lava-like ignimbrites are well exposed. These 14- to 12-Ma silicic units onlap SC outflow in some locations along the western SC margin, and they have been used by past workers to define the southern Owyhee Plateau as the "Owyhee-Humboldt" eruptive center (Bonnichsen, 1985; Brueseke and others, 2004; Manley and McIntosh, 2004; this study).

SAMPLING STRATEGY AND ANALYTICAL METHODS

Over 270 representative samples were collected from throughout the area depicted in Figure 2 in five field seasons from 2000 to 2004 (see Appendix 2; Sample Locations and Descriptions). Sample collection was guided by the earlier work of LeMasurier (1965, 1968), Vikre (1985a, b), Mellott (1987), and preliminary reconnaissance data of W.K. Hart (personal commun.). The sampling strategy was designed to maximize information on stratigraphic and spatial relationships throughout the volcanic field. Vertical and horizontal sampling traverses by foot provided the necessary means for sample collection and the gathering of stratigraphic data in most cases. Topographic highs were also targeted in the event that well-exposed (and thick) stratigraphic sections may be present nearby and to identify whether these high regions were SC eruptive loci. All regional highs with the exception of McConnell Peak (along the northern SC margin, north of the National mining district) were accessed. Known mines (e.g., National, Buckskin-National, and Spring City region) were not targeted for sampling and minimal time was spent in these locations due to the large amount of post-magmatic alteration and mineralization present in outcropping units. Figure 3 schematically depicts the generalized volcanic stratigraphy of the SC. This diagram illustrates the overall stratigraphic complexity found across the SC and the different types of eruptive products that crop out in the volcanic field. It is important to note that at any given time in its history, SC volcanism was characterized by a spectrum of differing magma compositions that led to different local eruptive histories across the volcanic field.

Field relationships guided the selection of 250 samples for geochemical analytical work. Before analysis, weathering rinds were removed from all samples and then each was split and carefully examined to make sure that only the freshest material possible would be further powdered and prepared for analytical work. No attempt was made to remove all potential syn-magmatic contaminants from each sample before geochemical analyses, but, obvious contaminants were removed by hand-picking before processing.

Complete analytical data are presented in Appendix 3 (Major, Trace, and Isotope Data) and a detailed discussion of the analytical procedures and methods used is presented in Appendix 1 (Analytical Methods). Major element analyses were performed by DCP-AES at Miami University following the procedures outlined in Katoh and others (1999). All major element data reported in the following discussion have been normalized to 100% anhydrous after adjusting the FeO/Fe_2O_3 as outlined by LeMaitre (1976). Trace element analyses were performed at Franklin and Marshall College by XRF (techniques outlined in Mertzman, 2000) and a subset of samples was analyzed at Washington State University by ICP-MS (techniques outlined at: www.wsu.edu:8080/~geology/geolab/note/icpms.html).

Based on data from the above techniques, a suite of samples was chosen for Sr, Pb, and Nd isotopic measurements. For these measurements, approximately 0.1 to 0.2 g of whole-rock powder was dissolved in HF-HNO_3, before chemical separation. Sr and Pb separations follow the procedures of Walker and others (1989). Sm - Nd separations were performed by methods similar to those used by Pin and Zalduegui (1997), using EiChrom Ln-Spec resin. Isotopic compositions were measured by thermal ionization mass spectrometry (TIMS) at Miami University, using a Finnigan Triton mass spectrometer. Strontium isotopic ratios were fractionation-corrected using $^{86}Sr/^{88}Sr = 0.1194$. Sixty-eight measurements of the NBS 987 strontium standard gave an average of $^{87}Sr/^{86}Sr = 0.710236 \pm 0.000014$ (1 SD). $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ were fractionation-corrected by 0.1% per amu based on NBS 981 data from Todt and others (1996). Errors on measured values of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ were ± 0.01, ± 0.02, and ± 0.06 respectively. Neodymium isotopic ratios were fractionation corrected using $^{143}Nd/^{146}Nd = 0.7219$. Sixty-one measurements of the La Jolla neodymium standard gave an average of $^{143}Nd/^{144}Nd = 0.511846 \pm 0.000007$ (2 SD).

Geochronology was performed by the $^{40}Ar/^{39}Ar$ method at the New Mexico Geochronological Research Laboratory, under the direction of Matthew T. Heizler (Table 1). Mafic and intermediate units were dated by whole-rock methods when possible to minimize the use of potential xenocrystic plagioclase feldspars. For each of the silicic units, 15 sanidine crystals were analyzed by the laser fusion method. Errors associated with $^{40}Ar/^{39}Ar$ ages discussed herein are given as two sigma. Additionally, the newly reported data from this study have been combined with SC geochemical data collected by Mellott (1987) and W.K. Hart (personal commun.) to form one master database. Only the new data generated in this study are reported in Appendix 4.

SC units discussed below are defined based on their physical and petrographic characteristics. Silicic units across the SC are physically and petrographically distinct from each other, while morphologic differences among mafic and intermediate composition units are much less pronounced (Fig. 4). However, geochemical characteristics allow these units to be distinguished from each other. Figure 5 illustrates the complete compositional spectrum of basalt through high-silica rhyolite present within the SC. Of the 286 analyses shown on Figure 5a, 26% lie between 52 to 63 wt% SiO_2, indicating that the SC is not just a bimodal basalt-rhyolite volcanic field. Geochemical differences present between SC silicic units mirror the physical differences and also help define these units. Additionally, physical and geochemical data suggest that at least one widespread unit present within the SC volcanic assemblage was not locally derived (Tp_1; peralkaline ignimbrite). Figure 6 depicts the generalized geology of the SC and illustrates the location of pre-SC units, SC vents, and vent alignments, and it highlights the overall complexity of the volcanic field.

PHYSICAL AND PETROGRAPHIC CHARACTERISTICS OF LOCAL UNITS

This section introduces and defines the local SC lithologies (units) primarily on the basis of spatial, temporal, and physical (outcrop to microscopic scale) features. As previously mentioned, geochemical properties also have played an important role in these definitions and these properties will be discussed in detail in the following section. The combined features of the SC volcanic suite defy simple unit designations that define mappable field assemblages, <u>and</u> coherent chronostratigraphic levels, <u>and</u> petrographically and geochemically unique materials. In other words, the SC volcanic pile is very complex with, for example, physically and chemically distinct units that are substantially time transgressive. In order to provide a reasonable representation of the lithologies mappable in any given area as well as the complexities present, two separate but interrelated unit designations are used throughout the remainder of this paper; [1] Map units - units that serve as the basis for a generalized geologic map and stratigraphic framework (Fig. 6b), and [2] Petrologic units - units that represent the primary observed physical, petrographic, and geochemical heterogeneities. The discussions in this and the following section define the petrologic unit designations and the materials so designated. Information presented in Table 2 and in the key to Figure 6 illustrates how the defined petrologic units link to the designated map units. For example, the Ta petrologic unit (Tertiary andesite of Black Ridge) is widely distributed in space and time throughout the study area, thus can be found locally within the following map units; Thc, Twsc, Tgl, and Tcm (Table 2 and Fig. 6b).

Pre-SC Units

A diverse package of Triassic to Neogene metamorphic and igneous rocks stratigraphically underlies the SC volcanic suite. The designations for these pre-SC units defined below are the same as those used in the simplified geologic map of Figure 6b.

Triassic metasedimentary strata (*TRms*)

The oldest package of rocks exposed in the SC consists of ~6 km of metamorphosed Triassic (Norian) sedimentary back-arc basinal strata. These rocks were formed in an outer submarine fan to basin plain environment, and sediments were derived from continental sources to the east (Wyld and others, 2001). Compton (1960) divided this assemblage into six units: the Grass Valley, Winnemucca, O'Neill, Singas, Andorno, and Mullinix Formations (up-section). Slates and phyllite dominate each unit and make up 80% of the metasedimentary package (Wyld and others, 2001). Also present within each unit are interlayered quartzite and calcareous shales and siltstones (Wyld and others, 2001). Following deposition, the strata were deformed and metamorphosed during two regional Jurassic compressional events related to the formation of the Luning-Fencemaker fold-thrust belt (Wyld and others, 2001). Metamorphism during these deformation events reached greenschist grade, and subsequent contact metamorphism overprinted this regional event during the intrusion of the 102- to 85-Ma Santa Rosa granitoid suite (Compton, 1960; Rogers, 1999; Wyld and others, 2001). During this intrusive event, rocks in some locations were metamorphosed to an upper amphibolite facies (Compton, 1960). In the SC, these Triassic rocks are best exposed in the vicinity of Hinkey Summit and along the southern SC margin, and along the western SC margin (Figs. 4a, 6b). No metasedimentary rocks were encountered in the eastern SC at the base of the Calico Mountains; however, King (1984) suggested the presence of these rocks in this location, which we were unable to verify.

***Cretaceous granitoid* (Kg)**

Granitoid intrusions are best exposed in the main Santa Rosa Range, where they underlie the high (>2400 m) crest of the range in most locations. At least six surficially isolated plutonic bodies are present and are divided into two Kg groups based on chemical, isotopic, and chronologic differences: the 85-Ma Granite Peak-Sawtooth group and the 102-Ma Santa Rosa-Andorno group (Stuck, 1993). Granitoid exposures in the SC are limited to three locations (Fig. 6b): [1] at Granite Peak (Fig. 4a, g; Granite Peak-Sawtooth group), [2] at the base of the Calico Mountains (Fig. 4c; Santa Rosa-Andorno group), and [3] along the southern SC margin (Santa Rosa-Andorno group). Wyld and others (2001) dated the Andorno stock by U-Pb methods that yielded an age of 102.4 ± 1.0 Ma, similar to the earlier chronologic results of Smith and others (1971) and Stuck (1993). Rb-Sr isochron dating of the Granite Peak stock by Stuck (1993) yielded an age of 85 Ma. These temporal differences mirror chemical and isotopic differences that illustrate that Santa Rosa Range granitoids make up at least two petrogenetically unrelated intrusive suites (Stuck, 1993). Santa Rosa Range granitoids include biotite granodiorite, quartz monzonite, quartz monzodiorite, biotite granite, and granite. Aplite dikes are also present throughout the larger plutonic bodies (Stuck, 1993). The 102-Ma Santa Rosa-Andorno group ($^{87}Sr/^{86}Sr_{@16.5\text{-}Ma}$ = 0.7048 to 0.7058) is interpreted as the end result of mantle melts that underwent crystal fractionation and crustal assimilation in a continental arc setting (Stuck, 1993). The 85-Ma Granite Peak-Sawtooth group ($^{87}Sr/^{86}Sr_{@16.5\text{-}Ma}$ = 0.7061 to >0.7070) is interpreted to have either a crustal source (melting of terriginous sediment) or an enriched mantle source (Stuck, 1993). Aplite dikes are also present that cross-cut both types of granitoid ($^{87}Sr/^{86}Sr_{@16.5\text{-}Ma}$ = 0.7095 to >0.7400).

Cenozoic calc-alkaline arc lava flows (*Tarc*)

A suite of Cenozoic, dominantly calc-alkaline, lava flows underlies SC eruptive products in the southern part of the volcanic field (Tarc; Fig. 4a,d; Fig. 6b). Andesitic to dacitic members of this suite can be thick (up to 150 m) and are characterized by occasional columnar joints that weather to platy talus (Fig. 4d and similar to platy-weathering Tct in Fig. 4p), vesiculated flow tops, spheroidal weathering, tan to red color, and thick (often > 20 m) basal and upper brecciated zones. These breccias contain abundant dark glassy clasts that resemble clasts associated with upper breccias of SC silicic units (e.g., Tad_2 and Tem). Locally, flow units are separated by breccia zones, such as along the fault scarp defining the southern margin of the SC (northern boundary of Paradise Valley). Plagioclase ($An_{30\text{-}58}$), orthopyroxene, clinopyroxene, olivine, and Fe-Ti oxides dominate the groundmass, and either olivine or plagioclase and orthopyroxene are present as phenocrysts (Mellott, 1987). The olivine is mostly altered to iddingsite, chlorophaeite,

and serpentine and optically appears to be Mg-rich. Mellott (1987) showed that Tarc lava flows (his acid andesite 1 and 3 groups) are physically and compositionally distinct from the younger SC intermediate composition units. He also demonstrated that east-dipping Tarc lava flows are found along the western side of Paradise Valley (along the eastern side of the main Santa Rosa Range) and along Indian Creek near Hinkey Summit. K-Ar ages from Tarc lava flows obtained by Mellott (1987) are 19.6 to 22.8 Ma. Tarc lava flows are temporally correlative with the Steens Mountain Volcanics, which underlie Steens Basalt at Steens Mountain. The present study documented Tarc lava flows along the western SC margin between Granite Peak and Buckskin Mountain and also as far east as Black Dome (Fig. 6b). Additionally, at least one highly eroded Tarc eruptive center may be present just north of Granite Peak along the western SC margin. North of this location, Tarc lava flows along the western margin uncomfortably overlie Trms and include mafic (basalt to basaltic andesite) lava flows. New $^{40}Ar/^{39}Ar$ ages confirm the earlier ages of Mellott (1987) and expand the age range represented by local Tarc lava flows (Table 1). A basal Tarc lava flow exposed along the western margin of the SC directly overlying Trms yielded a $^{40}Ar/^{39}Ar$ age of 35.52 ± 0.34 Ma. This is the oldest Cenozoic volcanic material documented in this part of the Oregon Plateau. The dated sampled petrographically resembles some of the younger (ca. 23 to 20 Ma) Tarc lava flows exposed in the SC and more work must be performed to confirm the areal extent and significance of this 35-Ma eruptive package. The overlying Tarc lava flow is a basaltic andesite and yields a $^{40}Ar/^{39}Ar$ age of 23.50 ± 0.24 Ma, similar to the older ages of Mellott (1987). At Hinkey Summit, a Tarc lava flow directly underlying the basal package of 16.7-Ma SC-derived Tba lava flows yielded a $^{40}Ar/^{39}Ar$ age of 22.48 ± 0.08 Ma.

Tarc lava flows are calc-alkaline and have $^{87}Sr/^{86}Sr_{@16\text{-}Ma}$ = 0.7040 to 0.7050 (Mellott, 1987). Mellott used the geochemical and isotopic characteristics of these lava flows to conclude that they were the end result of subduction-related mantle melting and differentiation. This interpretation temporally fits with regional models of northwestern U.S. tectonomagmatism, and similar interpretations have been made for other temporally identical regionally exposed calc-alkaline volcanic suites (Christiansen and Yeats, 1992; Dickinson, 2004). In addition to their physical characteristics, major and trace element chemical variations are used to distinguish Tarc lava flows from the younger SC-derived units.

Mafic SC Units

Santa Rosa-Calico mafic lava flows, shallow intrusive bodies, and eruptive loci resemble mafic units exposed across the Oregon Plateau and are divided into distinct units on the basis of chemical composition. Included within these mafic SC units are the Ta_1 and Ta_2 units of Vikre (1985a, b) and the Tb and Tbi units of LeMasurier (1965, 1968).

***Tertiary basalt* (Tb)**

Mafic lava flows of unit Tb have only been found in the southwestern SC in the greater Hinkey Summit-Granite Peak region (Fig. 6b). Exposures are up to 10 m thick and characterized by a tortoise shell-like fracturing and red/black ophiomottling (poikilomosaic texture; Shelley, 1993). Visible 1- to 4-mm plagioclase crystals and barely visible olivine (<1 mm) are typically found in a dark-gray/bluish, dense to crystalline matrix. Plagioclase ($An_{45\text{-}60}$), clinopyroxene, olivine, and Fe-Ti oxides are present in this unit. Minor (<1 to 2 %) disequilibrium textures (resorbed plagioclase phenocryts) are also occasionally present. In two locations along the western SC margin, siliceous sinter and red-green mineralization (hot spring deposits) appear to be stratigraphically below Tb lava flows, and likely reflect the same stratigraphic horizon. One dike of Tb was sampled. This dike, which strikes 65º, crops out in close proximity to three of the four locations where Tb lava flows were sampled and provides evidence for a local origin of these lava flows. In the vicinity of Hinkey Summit and Granite Peak, Tb and the stratigraphically oldest Tba lava flows show interbedded relationships. Two $^{40}Ar/^{39}Ar$ ages were obtained on lava flows from this unit and yield a weighted mean age of 16.36 ± 0.82-Ma (Table 1). These ages are consistent with field and stratigraphic evidence that suggests Tb lava flows represent exposures of one basalt flow-field confined to a small part of the southwestern SC (centered just north of Granite Peak) that was active at the onset of SC activity.

***Tertiary locally erupted Steens Basalt* (Tba)**

The second mafic unit present is exposed as lava flows (Fig. 4f), shallow intrusive bodies (e.g., dikes and plugs; Fig. 4g,h), and eruptive loci with accompanying pyroclastic deposits (e.g., bombs and scoria). Tba lava flows are best exposed in the western SC; however, at least one Tba lava flow crops out in the eastern SC and was likely sourced locally from within the Calico Mountains region (Fig. 6b). Tba lava flows are thin (5 to

10 m) and resemble Tb lava flows, but they lack the tortoise shell weathering. Upper flow surfaces typically show pahoehoe features (ropes), and the basal parts of these lava flows are brecciated, similar to regionally exposed Steens Basalt lava flows. Plugs and dikes crop out between Hinkey Summit and Buckskin Mountain, along the western SC margin. The best-exposed shallow intrusive body is Chocolate Mountain, a large dome-shaped plug that dominates the view to the west-northwest from Forest Service road 084 north of Hinkey Summit (Fig. 4g,h). At least three other smaller stocks are exposed just north of Chocolate Mountain, suggesting that the greater Hinkey Summit-Granite Peak region was a focus of localized Tba magmatism. Measured strikes of Tba dikes range from 266º to 15º. Mafic dikes tentatively grouped into Tba are also present in the vicinity of the National district (Vikre, 1985a, b). Eroded Tba eruptive loci and pyroclastic deposits are present along the western SC margin on the range-crest of the northern extension of the Santa Rosa Range. This relation, coupled with the fact that over 97% of all Tba and Tb exposures in the SC occur along the western margin of the field, suggests that the western part of the SC was the focal point of local mafic magma upwelling.

Tba lava flows and intrusive bodies texturally resemble the intermediate-plagioclase and aphyric petrographic types of regionally exposed Steens Basalt (Brueseke and others, 2007a). Plagioclase (An_{25-62}), olivine, clinopyroxene, and Fe-Ti oxide are the dominant phases. Disequilibrium textures are often present as crystal clots of clinopyroxene ± plagioclase ± Fe-Ti oxide, and highly resorbed/spongy-sieved plagioclase crystals, like those present in SC intermediate units depicted in Figure 7. Plagioclase separates from a Tba lava flow near the base of the mid-Miocene section at Hinkey Summit yielded a $^{40}Ar/^{39}Ar$ age of 16.45 ± 0.34-Ma (Table 1). This is similar to a whole-rock $^{40}Ar/^{39}Ar$ age obtained on the basal mafic lava flow exposed in the Hinkey Summit region (overlies Triassic metased-imentary rocks), which yielded an age of 16.73 ± 0.04 Ma (Brueseke and others, 2003; Table 1). The Tba lava flow exposed in the Calico Mountains is also at least 16.5 Ma based on its stratigraphic position and relationship to locally exposed, newly dated eastern SC units. Tba exposed in the Chocolate Mountain plug yielded a $^{40}Ar/^{39}Ar$ age of 15.97 ± 0.20 Ma (Brueseke and others, 2003; Table 1). Chemically and physically similar plugs and lava flows crop out nearby, suggesting that a period of heightened Tba activity occurred at 16 to 15.8 Ma. Additional younger Tba crops out along the western SC margin north of Hinkey Summit, where a lava flow associated with a Tba vent yielded a $^{40}Ar/^{39}Ar$ age of 14.35 ± 0.38 Ma. These new $^{40}Ar/^{39}Ar$ ages and field relationships illustrate that Tba lava flows were being emplaced and locally erupting throughout the entire duration of SC volcanism.

Interestingly, all sampled Tba products lack the 1- to 4-cm plagioclase crystals that characterize plagioclase-phyric Steens Basalt lava flows (Brueseke and others, 2007a). A well-exposed 240-m-thick package of mafic lava flows that was tentatively correlated with the Steens Basalt at Steens Mountain by paleomagnetic methods (Larson and others, 1971) occurs along the western margin of the SC downslope and just west of Buckskin Mountain (included in unit Tsb; Fig. 6b). Furthermore, Carlson and Hart (1983) and Hart and Carlson (1985) used isotopic data to suggest that this package erupted from a source at or near Steens Mountain and flowed to the SC. Plagioclase-phyric lava flows within this package resemble the plagioclase-phyric variety of Steens Basalt so commonly observed elsewhere on the Oregon Plateau (Brueseke and others, 2007a). The lack of plagioclase-phyric products in Tba and the presence of plagioclase-phyric lava flows along the western SC margin further suggests that this latter, poorly studied package of Steens lava flows was derived from a regional Steens eruptive center and flowed up against and onlapped the topographic high created by the northern extension of the main Santa Rosa Range. More work is needed to better place this plag-phyric package of lava flows in a regional and local chronostratigraphic framework and also to determine whether they did erupt from a regional, rather than local, magmatic system.

Intermediate SC Units

Santa Rosa-Calico intermediate-composition units (Ta, Tad_1, Tad_2, and Tad_3) are defined by geographic, temporal, and major and trace element chemical differences. Like SC mafic units, textural differences among these units are slight and it is often impossible to distinguish one unit from another in the field. SC intermediate-composition lava flows are physically different than "typical" andesite and dacite lava flows found in other geologic settings (e.g., volcanic arcs). In general, andesite and dacite lava flows are usually thick (>10 m) and characteristically possess thick upper and lower flow-margin brecciated zones (Francis and Oppenheimer, 2004; Schmincke, 2004). The older pre-SC arc lava flows that in places underlie the SC volcanic assemblage illustrate these "typical" intermediate-composition flow features quite well. However, most

broadly andesitic SC lava flows are usually thin (<5 to 7 m thick) and resemble simple (one cooling unit) mafic lava flows (Fig. 4i,j). Regionally this type of lava flow is associated with mid-Miocene and younger mafic eruptions (e.g., Steens and younger tholeiitic basalts). Consequently, "flood andesite" may be an appropriate term to describe their overall physical character. Only one intermediate-composition volcano was identified in the field; however, field relationships combined with chronologic and geochemical data allow for the identification of vent regions for the three Tad units. Volume estimates for Tad units were calculated by measuring a minimum areal extent using the known outcrop pattern via ArcView GIS 3.2 and multiplying by a minimum thickness of 150 m, which is the approximate average thickness of the Tad_2 and Tad_3 packages based on our field observations and the mapping of Vikre (1985b). These calculations yield volumes of 18.5, 17.7, and 15.8 km^3 for Tad_1, Tad_2, and Tad_3 respectively. These estimates indicate that, combined, Tad units may represent as much as 40% of the entire volume of SC products. Included with these units are the Tql (Tertiary quartz latite) units of Vikre (1985b), which are now much better defined geochemically and chronologically. LeMasurier (1965, 1968) grouped all "andesitic" material into one unit (Ta) and did not differentiate between pre-SC Tarc lava flows and SC-derived intermediate eruptive products.

***Tertiary andesite of Black Ridge* (Ta)**

Black Ridge andesite lava flows (Ta) crop out across the SC and are the most areally extensive intermediate unit in the map area (Fig. 4 i,j; included in Tcm, Thc, Twsc, and Tgl of Fig. 6b). The best exposures are present in the vicinity of Holloway Meadows and where Forest Service road 531 cuts Black Ridge in the North Fork of the Little Humboldt River canyon (Fig. 2). Here, and further south along Black Ridge, these lava flows are interbedded with and underlie Tad_1 lava flows (Fig. 4j). One Ta lava flow from Black Ridge yielded a $^{40}Ar/^{39}Ar$ age of 14.94 ± 0.24-Ma (Table 1). Just north of Holloway Meadows, Ta lava flows onlap flow lobes of <15.8-Ma Tem lava flows (Fig. 4i). Ta lava flows also crop out at the base of the exposed section in the southern Calico Mountains, interbedded with the package of >16.2-Ma Tba, Tad_1 and Thc lava flows exposed in the greater Hinkey Summit region, and along the western SC margin stratigraphically under Tpr lava flows (within the Tql_2 of Vikre, 1985b). Ta lava flows also occur across the eastern Goosey Lake depression where they are the stratigraphically oldest encountered unit. Ta lava flows are thin (<6 m) and are simple flows with highly vesiculated upper flow tops (vesicles are usually stretched and up to 1 to 3 cm long) and rubbly bases. Thicker Ta lava flows often have a massive, weathered interior, while thin flows are highly vesiculated throughout. These thin andesitic lava flows physically resemble lava flows associated with flood basalts and are easily mistaken for Tba lava flows in the field. Ta shallow intrusive bodies were sampled, and chemical similarities suggest that at least one source of Ta lava flows was a low shield volcano located between Coyote Mountain and the southern Calico Mountains, along the eastern SC margin (hill 6648 on the Coyote Mountain 7.5-minute Quadrangle). Lobes of Ta lava flows also emanate from this location. This vent appears to be onlapped in places by 16.4-Ma Tct ash flows, again illustrating that Ta lava flows were time-transgressive throughout the duration of SC volcanism. Given the complex stratigraphic relationships outlined above and wide areal distribution of Ta lava flows, it is likely that hill 6648 was not the sole Ta eruptive locus.

Plagioclase, clinopyroxene, orthopyroxene, olivine, and Fe-Ti oxide are the dominant phases in Ta lava flows. Ta flows are texturally variable; some lava flows are much finer grained than others regardless of bulk chemical composition. This likely reflects differences in cooling rates and thickness between individual Ta lava flows. Additionally, Ta lava flows show variable evidence of disequilibrium. Like some Tba products, some Ta lava flows contain crystal clots of plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide and occasional highly resorbed/sieved plagioclase phenocrysts (when present, less than 2% modally). These resemble the clots depicted in Figure 7e-h.

***Tertiary andesite-dacites of Hinkey Summit-Coal Pit Peak* (Tad_1)**

Hinkey Summit-Coal Pit Peak intermediate-composition lava flows (Tad_1) are the most voluminous of the four SC intermediate units. The thickest exposures (over 300 m) crop out in the vicinity of Coal Pit Peak, along the southern SC margin (Fig. 6b). Tad_1 lava flows crop out at the top of Coal Pit Peak and are the stratigraphically oldest unit exposed just to the north in the Martin Creek canyon. Tad_1 lava flows overlie 16.4-Ma Thc rhyolite flows at Hinkey Summit and north of Hinkey Summit, and this relationship provides a maximum age for the oldest exposed Tad_1 lava flows. Throughout the greater Hinkey-Coal Pit region, they also underlie 16.2-Ma Tpr

rhyolite lava flows. Tad_1 lava flows are also exposed in patches along the eastern margin of the main Santa Rosa Range (in Paradise Valley) overlying Tarc. Along Black Ridge between Coal Pit Peak and where the ridge is cut by the North Fork of the Little Humboldt River, Tad_1 lava flows are interbedded with 14.9-Ma Ta lava flows (Figure 4j). The stratigraphically highest exposed Tad_1 lava flow from Coal Pit Peak yielded a $^{40}Ar/^{39}Ar$ isochron age of 13.90 ± 0.60 Ma, which is the youngest age reported for any SC eruptive product (Table 1). These ages and stratigraphic relationships demonstrate that this unit was time-transgressive and erupted throughout most of the SC's history. In the Coal Pit Peak region, no direct evidence for local eruption/magma emplacement was encountered. However, topographic highs in the SC were extensively glaciated during the Pleistocene and the youngest, near-vent material may have been eroded during local glaciation. Tad_1 lava flows are only present in the southern part of the SC with increasing abundance toward Coal Pit Peak. Additionally, all exposures thicken toward Coal Pit Peak. Based on these spatial relationships, the eruptive locus for Tad_1 lava flows was in the Coal Pit Peak region and likely was a large shield volcano. Alternatively, the volcano could have been located just to the south of Coal Pit Peak and eroded/buried during the post-SC faulting which formed Paradise Valley. Like Ta lava flows, Tad_1 lava flows are thin (<6 m) and characterized by a thin (<2 m) rubbly base and more massive, often vesiculated, interior. Also like Ta lava flows, these are easily misidentified as more mafic units in the field. When exposed, Tad_1 flow surfaces are highly oxidized and show abundant ramp structures. However, their overall outcrop pattern is similar to Ta lava flows and resembles that of simple basalt flows (basalt flows with a single flow unit).

Tad_1 lava flows were originally named acid andesite 3 by Mellott (1987) who distinguished them from the earlier arc lava flows by their abundant disequilibrium features. These features distinguish Tad_1 lava flows from the three other SC intermediate groups. Plagioclase, orthopyroxene, clinopyroxene, olivine, and Fe-Ti oxide are the dominant phases present in Tad_1 lava flows. The most apparent textural characteristic of this unit are the abundant disequilibrium features, typically 8 to 15 % modally. Extremely resorbed/sieved and sometimes complexly zone plagioclase crystals are ubiquitous (Fig. 7). Macro and microscopic xenoliths are also abundant and are present as three types. The most common are [1] plagioclase- and potassium feldspar-dominated xenoliths that resemble granitoid, and [2] crystal clots of plagioclase (often oscillatory zoned) ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide, similar to what is found in other SC units (Fig. 7b, d-g). However, one sampled Tad_1 lava flow has an ~3-cm-long metamorphic xenolith, the only TRms xenolith observed in an SC unit (Fig. 8a,b). While the metamorphic xenolith-host contact is overall fairly abrupt, locally it is diffuse and appears that partial melting of the xenolith along this contact occurred (Fig. 8b).

***Tertiary andesite-dacites of Staunton Ridge* (Tad$_2$)**

Lava flows of Tad_2 are exposed in the northwestern SC underlying Tem lava flows (Fig. 4m). These Tad_2 lava flows were originally included by Vikre (1985b) in his Tql_1 and Tql_2 map units and are best exposed at Staunton Ridge, where a section of 190 m of flow-on-flow stratigraphy is present (Figs. 2, 6b). No shallow intrusive bodies or near-vent facies were observed that could be associated with this unit. However, Tad_2 lava flows are not found anywhere else in the volcanic field, and this limited spatial occurrence suggests the presence of a localized magmatic system. Within this package, the 5th flow stratigraphically down from the top of Staunton Ridge yielded a $^{40}Ar/^{39}Ar$ age of 15.76 ± 0.28 Ma. There, Tad_2 lava flows are 4 to 12 m thick and, in places, much platier than Ta, Tad_1, and Tad_3 lava flows. Upper parts of Tad_2 flows weather to plates, which are occasionally vertical in outcrops. Above this platy zone, the lava flows are vesiculated and then grade into an upper flow-top oxidized breccia. Included within these brecciated zones are dense, glassy clasts, similar to those found within the pre-SC Tarc units. The central, more massive parts of these flows are platy, but jointing is horizontal. Morphologically, these Tad_2 lava flows exhibit characteristics that are more similar to "typical" intermediate-composition lava flows.

Texturally, these lava flows are much more aphyric than other SC intermediate units. In hand sample, crystals are barely visible and Tad_2 pieces fracture conchoidally when broken by a hammer. In thin section, plagioclase, clinopyroxene, orthopyroxene, and Fe-Ti oxide are the dominant phases. Disequilibrium textures are sparse (typically less than 1% modally) but include resorbed, sieved, and embayed plagioclase. Xenocrystic olivine (1 to 1.5-mm euhedral and iddingsitized phenocrysts) was observed in one sample, and rims of <1 mm pyroxene crystals on these xeno/phenocrysts are occasionally present. The ubiquitous plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots that are present in other SC units were not observed in Tad_2 lava flows.

Tertiary andesite-dacites of the Calico Mountains (Tad$_3$)
Within the lower half of the 400-m-thick, 16.5-Ma package of lava and ash flows exposed in the Calico Mountains are Tad$_3$ lava flows. These flows were mapped by King (1984) and included his u1 and u2 map units. Like Tad$_2$ lava flows, no shallow intrusive bodies, near-vent facies, or eruptive loci were identified that could be associated with this unit. On the eastern side of the Calico Mountains, a Tad$_3$ lava flow unconformably overlies 102-Ma granitoid and yields a $^{40}Ar/^{39}Ar$ age of 16.54 ± 0.16-Ma (Fig. 4c). Lava flows and ash flows exposed in the upper part of the Calico volcanic pile that overlie Tad$_3$ lava flows yielded identical 16.5-Ma ages. Additionally, these Tad$_3$ lava flows are not exposed anywhere else in the SC. These observations indicate that Tad$_3$ lava flows erupted from a magmatic system that was separate from those associated with other SC intermediate units. Tad$_3$ lava flows are typically 10 to 20 m thick and, when exposed, are characterized by basal and upper brecciated zones that are highly vesiculated and monolithologic. Occasional auto-injection squeeze-ups are also present in association with Tad$_3$ upper brecciated zones. Above the lower breccia, a platy zone typically grades into a massive and jointed interior, similar to Tad$_2$ lava flows.

Tad$_3$ lava flows are extremely fine-grained and again resemble Tad$_2$ lava flows. In hand sample, 1- to 3-mm feldspars are visible. In thin section, plagioclase, clinopyroxene, orthopyroxene, and Fe-Ti oxide are the dominant phases. Like other SC intermediate units, disequilibrium textures are present in Tad$_3$ lava flows. Both 1- to 5-mm granitoid xenoliths and <1 mm plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots (like other SC units) are present and modally make up <5 % by volume (Fig. 7).

Silicic SC Units

Silicic eruptive loci were primarily focused along the eastern and western margins of the SC and were dominated by domal and fissural sources. Silicic units in the SC are divided into ten physically and chemically distinct units. In summary, five silicic units are found only in the western SC: Thc, Tbr, Twsc, Tpr, and Tem. These units erupted over an ~1-Ma duration and represent the products of separately evolving magmatic systems. In the eastern SC, silicic volcanism occurred from 16.5 to 16.4 Ma and produced three silicic units: Tom, Tcm, and Tct. Two other silicic units that represent the products of caldera-forming volcanism in the SC are best exposed in the Goosey Lake depression. Tp$_1$ ash flows are the only peralkaline silicic material present within the SC and likely were sourced in the nearby McDermitt volcanic field. Tcst ash flows were locally derived, are the youngest SC silicic eruptive products, and are the only identified SC-derived products associated with caldera-forming volcanism. Typical ignimbrite flow-unit stratigraphy is identifiable in some SC ash flows; however, these relationships are often obscured and difficult to identify (Fig. 9). The following provides brief summaries of these silicic units based on the more detailed discussion presented in Brueseke and others (2007b). Silicic units that crop out around Hinkey Summit and were earlier defined by LeMasurier (1965) have been included within these units.

Tertiary Hinkey Summit-Coal Pit Peak dacites-rhyolites **(**Thc**)**
Thc lava flows are best exposed between Hinkey Summit and Coal Pit Peak, where they form a massive, 100-m wall and overlie the basal package of Tba and Ta lava flows (Fig. 4a). This same package is exposed south of Granite Peak in the vicinity of Solid Silver Creek, where it was down dropped to the south along the basin-bounding normal fault that defines the southern SC margin (Figs. 2, 4a, 6b). Included within Thc are the Trd lava flows of LeMasurier (1965). These lava flows are also exposed just north of Hinkey Summit along Forest Service road 084 at the turn-off for Lye Creek campground and in the region between Lye Creek and Buckskin Mountain (Figs. 2, 6b). The lava flow exposed at the Lye Creek turn-off yielded a $^{40}Ar/^{39}Ar$ age of 16.36 ± 0.10-Ma (Brueseke and others, 2003; Table 1). Where fully exposed, these lava flows are between 15 and 120 m thick and are thickest between Hinkey Summit and Coal Pit Peak. No Thc near-vent facies or eruptive loci were encountered; however, their source is inferred to be in the Hinkey-Coal Pit region based on the thick local exposures. Thc lava flows form cliffs and characterized by ubiquitous flow bands and upper flow margin breccias and joints, causing them to weather into piles of thin plates. Because of their platy appearance, Thc lava flows resemble Tarc lava flows. However, Thc lava flows are easily distinguished by the presence of abundant phenocrysts of feldspar in a light gray to purple matrix. Quartz, biotite, clinopyroxene, and orthopyroxene are also present, in addition to plagioclase and potassium feldspar.

Tertiary porphyritic rhyolite (Tpr)
Porphyritic rhyolite lava flows and shallow intrusive bodies are exposed throughout the southern and southwestern SC (Figs. 2, 6b). LeMasurier (1965)

included these in his Tr and Tri groups. The best exposures are found just south of Hinkey Summit along Forest Service road 084 as it climbs into the SC (Fig. 4f,g,h,k), and along the southern and western margins of the Goosey Lake depression (Fig. 4l). South of Hinkey Summit, a large shallow intrusive body is exposed and intrudes the pre-SC igneous and metamorphic assemblage (Fig. 4f,k). Along the western and southern Goosey Lake depression margins, two Tpr flow-dome complexes (coulees) are well exposed (Fig. 6b). The western flow can be easily traced back to its source along the western SC margin, an eroded plug with underlying near-vent, bedded pyroclastic fall deposits (Fig. 4l). The source for the southern flow is identified based on aerial imagery (Figs. 2, 6b). Also present throughout this part of the SC are numerous Tpr dikes that strike north-northwest trending between 280º and 23º (Fig. 4f,g,h). The weighted mean of four $^{40}Ar/^{39}Ar$ ages from Tpr intrusive bodies and lava flows is 16.19 ± 0.04-Ma (Table 1), which is consistent with stratigraphic relationships. Because both the southern and western Tpr lava flows flowed eastward into a topographic low and the western flow overlies a sedimentary package, these ages also provide a minimum age for the formation of the Goosey Lake depression.

Tpr lava flows and intrusive bodies are extremely crystal rich (25 to 50% modally) and are the only amphibole-bearing (hornblende) unit present in the SC suite. Plagioclase feldspar, quartz, potassium feldspar, biotite, Fe-Ti oxides, and pyroxene occur as phenocrysts and microphenocrysts. One- to 10-mm granitoid xenoliths and plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots are present in Tpr flows and intrusive bodies (Fig. 7e, f). Additionally, 1- to 5-cm mafic xenoliths are visible in some Tpr dikes.

Tertiary Eightmile Mountain lava flows (Tem)

Eightmile Mountain area lava flows were originally mapped by Vikre (1985b) as the rhyolite of Buckskin Mountain (Tr_3, Trt, Tbx), and they crop out to the north and east of Buckskin Mountain (Figs. 4m,i, 6b). Near Eightmile Mountain, oxidized pyroclastic deposits are present in close spatial association with dikes that strike between 5º and 35º. These features and the thickest exposures of Tem represent a near-vent facies. These field relationships and the lack of any type of associated domal body suggest a fissural origin for Tem lava flows. A similar eruptive style has been proposed for ~11-Ma lava flows exposed along the southern margin of the western Snake River Plain graben (Bonnichsen and others, 2004). Tem lava flow(s) overlie Tad_2 lava flows in the vicinity of Buckskin Mountain, whereas, near Odell Mountain, they overlie Tom lava flows and eruptive loci (Fig. 4m). This stratigraphic relationship with Tad_2 lava flows indicates that Tem lava flows are younger than 15.8 Ma.

Like Tarc, Thc, and Twsc lava flows, Tem lava flows are highly jointed and develop platy talus slopes (like Fig. 4p). Macroscopically they resemble Thc lava flows and are characterized by 1- to 3-mm feldspars in an aphanitic, purple matrix. Microscopically, plagioclase feldspar, Fe-Ti oxide, apatite, and zircon are present. While disequilibrium textures are present in Tem lava flows (resorbed and sieved plagioclase, plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots, and fractured Mg-rich olivine), they are much less abundant than in other SC silicic units (<1 %).

Tertiary flow-banded rhyolite lava (Tbr)

Tbr lava flows and shallow intrusive bodies are well exposed in the southwestern SC (Fig. 6b; Thc, Tsi, and Tpr map units). These shallow intrusive bodies cut older SC units, and Tbr lava flows overlie Tpr lava flows. Their most distinguishing characteristic is a lack of phenocrysts and abundant 1- to 3-mm laminations in a white aphanitic open-textured matrix. Shallow intrusive bodies are commonly columnar jointed and extremely flow-banded. Microscopically, Tbr lava flows and shallow intrusive bodies are extremely fine-grained, and contain <1 mm crystals of plagioclase, potassium feldspar, quartz, biotite, Fe-Ti oxide, and apatite. These units also lack disequilibrium textures. Like Tpr lava flows and shallow intrusive bodies, these were not differentiated by LeMasurier (1965) as a separate unit and were included with his Tr and Tri units.

Tertiary western margin lava flows (Twsc)

Western margin lava flows are exposed between Buckskin Mountain and Granite Peak (Fig. 6b). Macroscopically, low-silica Thc lava flows resemble SC intermediate units. However, most Twsc lava flows resemble Thc and Tem and crop out as 25- to 35-m cliffs and/or slopes of platy talus similar to that depicted in Figure 4p. Vikre (1985b) included Twsc lava flows in his crystal-lithic rhyolite tuff unit (Tr_2) and LeMasurier (1965) included them in his Trd unit. One Twsc dike was sampled and strikes 353º. Stratigraphically, Twsc lava flows overlie 16.5-Ma Ta and Tba lava flows, but their relationship with 16.2-Ma Tpr lava flows was obscured by glaciation. Plagioclase (with and without disequilibrium textures) and potassium feldspar, clinopyroxene, orthopyroxene, biotite, and quartz are present in this unit.

Tertiary Odell Mountain area silicic units (Tom)

In the vicinity of Odell Mountain, 295 m of silicic lava and ash flows are overlain by younger SC silicic units and considered Tom (Fig. 6b). At least one eroded rhyolite dome that was likely the source for some Tom flows is exposed at the head of Klondike Canyon (Fig. 4n). Stratigraphically, the lowest units that crop out in this region are rhyolite lava flows that are best exposed along the South Fork of the Quinn River. At Odell Mountain, these lava flows are overlain by a series of interbedded ash flows, air-fall tuffs, and lava flows. The uppermost unit (flow-banded lava flow) yielded a $^{40}Ar/^{39}Ar$ age of 16.55 ± 0.04 Ma. The eroded rhyolite dome yielded a similar $^{40}Ar/^{39}Ar$ age of 16.43 ± 0.06 Ma (Table 1).

Sanidine, quartz, plagioclase feldspar, Fe-Ti oxide, pyroxene (opx and cpx), zircon, and apatite are present in Tom units. Sparse (<0.4 %) biotite was also observed in one Tom lava flow. Additionally, resorbed sanidine and quartz were also observed in Tom eruptive products.

Tertiary Calico Mountains area silicic units (Tcm)

Tcm lava and ash flows are exposed in the Calico Mountains along the eastern SC border (Fig. 6b). These units are physically diverse and include lava flows, ash flows, and lava-like ignimbrites. Commonly, Tcm products are interbedded with Tad_3 lava flows. Within the 400-m-thick package of SC products that overlies Cretaceous granitoid in the Calico Mountains, Tcm products in the lower 230 m of section are typically lava-like ignimbrites. We interpret these to be lava-like ignimbrites and not lava flows, based on physical features that together can be interpreted to indicate a pyroclastic origin. These include a lack of basal breccias (when their bases are exposed), overall sheet-like geometry, extensive rheomorphism, shard-like morphologies and broken phenocrysts (when present in thin section), and abundant lithic fragments (Henry and Wolff, 1992). In the upper part of this section, the 130-m-thick Capitol Peak ash flow underlies a package of rhyolite lava flows. These lava flows, best exposed at Capitol Peak, physically resemble and are chemically identical to Tom lava flows. They were likely sourced from near Odell Mountain and are included with Tom furthering later discussions. Sanidine separates from the uppermost of these lava flows yielded a $^{40}Ar/^{39}Ar$ age of 16.50 ± 0.04 Ma. To the south, thick exposures of rhyolite lava crop out along the range crest. One of these lava flows is exposed at Mahogany Pass where it overlies Tad_2 and Tba lava flows. This flow yielded a $^{40}Ar/^{39}Ar$ age of 16.51 ± 0.04 Ma, and it erupted from a small eroded dome just to the north of Mahogany Pass (Hill 7502 on the Capitol Peak Quadrangle). Farther south, more rhyolite lava flows overlie the Mahogany Pass rhyolite. Sanidine crystals from one of these flows yielded a $^{40}Ar/^{39}Ar$ age of 16.47 ± 0.04 Ma (Table 1). Based on this age and on stratigraphic relationships, it appears that these southern Calico Tcm lava flows were locally derived. One Tcm dike was sampled on the eastern side of the Calico Range and strikes 350º, further confirming a local Tcm source.

Tcm silicic units are petrographically variable. Tcm ash flows are xenolith-rich (plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots and xenoliths that resemble SC Tba and Ta lava flows), feldspar bearing, and in thin section, characterized by abundant disequilibrium textures. In most cases, flattened and compressed glass shards related to welding are visible, and textures that are consistent with magma mixing/mingling are also present locally (e.g., banding and round blobs; Fig. 7c). Tcm lava flows are difficult to distinguish petrographically from each other. Plagioclase and potassium feldspar, quartz, Fe-Ti oxide, pyroxene, apatite, and zircon are all present in these lava flows. Additionally, granitoid xenoliths are also present locally.

Tertiary Coyote Mountain-Zymns Butte area silicic units (Tct)

Coyote Mountain, Zymns Butte, and Black Dome are three silicic eruptive centers found in the southeastern part of the SC (Figs. 2, 6b). Physiographically, Black Dome is the most prominent of these three loci, situated at the southern end of Black Ridge. However, Coyote Mountain is the best-exposed eruptive center. The highly welded Coyote Mountain ash flow is exposed on the flanks of Coyote Mountain and in its vicinity (Fig. 10). Sanidine from block and ash deposits exposed on Coyote Mountain that stratigraphically overlie the rheomorphic Coyote Mountain ash flow yielded a $^{40}Ar/^{39}Ar$ age of 16.44 ± 0.06 Ma (Table 1). Black Dome outflow overlies the Coyote Mountain ash flow. The stratigraphic relationship between Zymns Butte and Coyote Mountain outflow is hard to discern, but it appears that Zymns Butte is younger than Coyote Mountain. Outflow from all three loci exhibit disequilibrium textures, including resorbed and sieved feldspars, and plagioclase ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots (like Fig. 7e-h).

Tertiary Cold Springs tuff (Tcst)

Two pyroclastic flow units that represent local and regional pyroclastic volcanism are best exposed in the Goosey Lake depression. The Cold Springs tuff is one of

these units with its type locality in the vicinity of Cold Springs Butte, along the eastern margin of the western Goosey Lake depression (Figs. 2, 6, 11, 12). Because of the post-SC faulting (and erosion) that was concentrated within the central part of the Goosey Lake depression, reconstruction of the areal extent and distribution of distinct Tcst flow units using stratigraphic and petrographic data (e.g., elevation differences, welding facies, etc.) is difficult. In this context, at least two separate depositional flow units are present in the central SC, and composite Tcst sections that include these units reach a maximum thickness of 50 m (Fig. 11). However, the maximum Tcst thickness is likely greater. Where exposed elsewhere, Tcst deposits range from 12 to 45 m in thickness and these variations may reflect the influence of substantial pre-Tcst local topography.

Just east of Cold Springs Butte, the basal part of one Tcst flow unit overlies inferred bedded Tcst fall deposits (Figs. 11, 12). These fall deposits overlie buff to tan lacustrine sedimentary strata, similar to deposits exposed in small patches across the Goosey Lake depression and along the eastern SC margin. Above these fall deposits is 2 m of a poorly welded ground surge that grades upward into the lower 5 m of a Tcst main ignimbrite body (Fig. 12a). This lower part of the main body is a poorly welded, crystal-rich unit that lies below 5 m of extremely welded Tcst. Within this zone of extremely welded deposits, a lower 1.5 m spheriodially weathering and dark glassy zone grades into a blocky lighter zone (<1 m thick), that directly grades into a thin (<1 m), highly welded white-colored zone. This upper highly welded zone texturally resembles other parts of highly welded Tcst deposits. Above these highly welded deposits is 20 m of poorly welded Tcst that physically resemble and are interpreted to be main body deposits. These stratigraphic-based changes in welding are inferred to reflect a more densely welded zone near the central part of the main ignimbrite body (classic welding profile of a simple ignimbrite cooling unit; Best and Christiansen, 2001). Just south of these exposures and south of Cold Springs Butte in the western Goosey Lake depression is an oval 2.5- by 3.5-km region of low (relative to its surroundings) topography which is visible both in the field and on aerial imagery (Figs. 2, 6). Where fully exposed, measured Tcst thicknesses are greatest near this depression and the only observed lithic fragments within Tcst deposits are locally present. Also, rare imbricated Tcst pumice clasts were observed at one location directly north of this depression and reflect a northward-directed flow. While no near-vent lag breccia was observed, these other geologic features together suggest that this depression may have been the source for Tcst pyroclastic deposits. In this scenario, this small, localized depression (found within the larger, western Goosey Lake depression) is likely the remnant of a caldera, the only caldera identified within the SC (Cold Springs caldera). The entire Goosey Lake depression appears to have formed as a fault-bounded, structural depression coeval with (and also after) SC volcanism (Gilbert and others, 2003; this study). As a result, it is possible that Tcst pyroclastic deposits could have been derived from "trap-door" style subsidence or fissural-style eruptions (Lipman, 1997; Bonnichsen and others, 2004) along an active zone of syn-volcanic faults within the east-central Goosey Lake depression. However, the caldera-source interpretation fits best with the observed geologic data. It is important to note that the proposed Cold Springs caldera is much smaller than the entire Goosey Lake depression structural basin as well as other mid-Miocene calderas that are present in regional volcanic fields (e.g., McDermitt). Interestingly, the timing of Tcst volcanism appears to be nearly identical to revised ages for the mineralization event(s) that formed portions of the National District (e.g., Buckskin-National; P.G. Vikre, personal commun.) and the two events (Tcst volcanism and local mineralization) appear to be related.

As mentioned previously, Tcst welding and facies changes make linking exposures across the SC difficult. Observed Tcst deposits are found as far south as the Hardscrabble basin (Figs. 2, 6, 9, 12c) where at least two flow units are exposed and separated by at least 70 m of interbedded lacustrine strata and air-fall tuffs. The uppermost Tcst flow unit at this location yielded a $^{40}Ar/^{39}Ar$ age of 15.40 ± 0.08 Ma, constraining the age of the underlying deposits (Table 1). At Cold Springs Butte, a poorly welded main body deposit from a 30-m-thick Tcst outcrop exposed along the eastern side of the inferred caldera yielded a $^{40}Ar/^{39}Ar$ age of 15.46 ± 0.04-Ma (Table 1). These two ages likely reflect the same eruptive event. Just north of Holloway Meadows, 18 m of Tcst is exposed lying on a package of Ta lava flows. Here, the basal poorly welded part of the unit yielded a $^{40}Ar/^{39}Ar$ age of 15.75 ± 0.16-Ma (Table 1). Above this poorly welded zone, the Tcst deposit becomes increasingly more welded (and devitrified) up-section and texturally is identical to the welding variations present near Cold Springs Butte described earlier (Fig. 11). However, unlike the highly welded zone near Cold Springs Butte, this Holloway Meadows highly welded zone lacks overlying main body deposits.

Texturally, Tcst deposits vary based on their degree of welding and devitrification. The highly welded zones are also the most devitrified. At an outcrop scale, poorly welded Tcst main-body deposits are monotonous and no normal or reverse grading was observed (Fig. 12a). Approximately 1- to 7-cm gray pumice clasts are often present and in some cases flattened (Fig. 12a). Also present in these deposits are 1- to 3-cm blocky glass fragments that resemble rhyolite vitrophyre. As welding increases, the pumice fragments become more flattened and in highly welded Tcst zones, all ignimbritic textures are obliterated and the deposit physically resembles a rhyolite lava flow. North of Cold Springs Butte in the Groundhog Meadows region (eastern Goosey Lake depression), extremely welded Tcst deposits are locally present up to 18 m thick and are lithophysae-rich (Fig. 12b).

Tcst glass shards are light brown under plane light. In addition to glass, sanidine, anorthoclase, plagioclase feldspar, clinopyroxene (pigeonite), Fe-Ti oxides, apatite, and zircon are present. Disequilibrium textures are present in Tcst pheno/xenocrysts, and include resorbed and highly zoned plagioclase and 1- to 3-mm crystal clots of plagioclase ± potassium feldspar ± clinopyroxene ± orthopyroxene ± Fe-Ti oxide clots. Typically, these clots resemble those found in other SC units (Fig. 7e-h).

Tertiary ignimbrite (Tp_1)

Tp_1 outcrops are found across the Goosey Lake depression and in other scattered locations in the western SC (Fig. 12d; unit Twt of Vikre, 1985b). Where fully exposed, Tp_1 outcrops are typically 1 to 5 m thick and appear to represent one simple depositional flow unit. However, exposures up to 25 m thick are present along the northern SC margin, east of Odell Mountain. Tp_1 ash flows are characterized by the ubiquitous presence of 1- to 4-cm-long devitrified pumice in a highly welded, gray/beige/yellow/pink matrix that was affected by high-temperature vapor-phase alteration. Occasional 1-mm sanidine and highly altered pyroxene crystals are present and make up <2 % by mode. Additionally, this unit is the only peralkaline silicic unit exposed in the SC. Just northwest of Hinkey Summit (NW¼ of Section 25, Hinkey Summit Quadrangle), a 3 m-thick exposure of Tp_1 is present on a topographic bench at ~8020 feet elevation. Here, the Tp_1 that crops out appears to follow the classic welding profile of a single cooling unit. In other locations in the Odell Mountain region and on Eightmile Mountain, Tp_1 outcrops include an exposed basal vitrophyre. The vitrophyre is less welded than overlying deposits and is composed of >95 % flattened pumice.

Sanidine from a Tp_1 deposit exposed in the southern part of the eastern Goosey Lake depression that overlies sedimentary strata and Tad_1 lava flows yielded a $^{40}Ar/^{39}Ar$ age of 16.45 ± 0.12 Ma (Table 1). This age is in agreement with locally observed stratigraphic relationships, and recent $^{40}Ar/^{39}Ar$ age determinations on silicic units from the McDermitt volcanic field demonstrate that peralkaline McDermitt activity was occurring before 16.3 Ma (Castor and Henry, 2000). Tp_1 clasts are also present as lithic fragments in 15.4-Ma Tcst deposits in at least one location, also suggesting that Tp_1 ash flows were locally present before Tcst volcanism. However, in other locations in the Goosey Lake depression, Tp_1 directly overlies Tcst ash flows and Tem lava flows, implying that these Tp_1 deposits are much younger than the 16.5-Ma age obtained on the dated Tp_1 ash flow. Together, these field and chronologic relationships indicate that more than one Tp_1 flow unit is exposed within the SC. No local SC source for Tp_1 flow units can be deduced or inferred from the field observations.

Tertiary air-fall tuffs (Tp_2)

Tuffaceous horizons are exposed throughout the SC in a variety of stratigraphic contexts. The best exposures are interbedded with sedimentary strata in the basin fill of the Goosey Lake depression; however, silicic fall deposits are also found interstratified with lava and ash flows in the SC volcanic pile and underlying locally erupted rhyolite lava flows. Gilbert and others (2003) chemically correlated subalkaline vitric fall deposits found within an 18-m-thick package of volcanogenic sedimentary strata that stratigraphically underlie Tcst ash flows (just south of the Cold Springs caldera) with 15.84- to 15.76-Ma Buffalo Canyon type ash beds and the 15.6-Ma Virgin Valley 1 ash bed of Perkins and Nash (2002). These interpretations agree with local stratigraphic data and illustrate that this part of the Goosey Lake depression was a sedimentary depocenter by 15.8 Ma. Along the western Goosey Lake depression margin, fall deposits directly underlie the eastern lobe of the western Tpr lava flow. These deposits overlie sedimentary strata, are chemically similar to the Tpr flow, and further illustrate that at least a part of the Goosey Lake depression defined a region of low topography and sedimentation as early as 16.2 Ma.

SUMMARY OF CHRONO- AND CHEMOSTRATIGRAPHIC RELATIONSHIPS AND SC ERUPTIVE HISTORY

Chrono- and Chemostratigraphic Relationships Across the SC

Comprehensive field observations and new $^{40}Ar/^{39}Ar$ geochronology allow for the reconstruction of SC eruptive events throughout the volcanic field. Figure 13 illustrates detailed stratigraphic relationships at ten different locations across the SC and provides a glimpse into the complex development of this volcanic field. These sections are composited from numerous studied and measured sections exposed in the vicinity of each location. The locations and geographic descriptions of the numbered sections and the general geologic relationships are provided in Figure 14, which consolidates information previously presented in Figures 2 and 6.

SC products overlie well exposed and highly brecciated 20- to 23-Ma Tarc lava flows and older Trms metasedimentary rocks at Hinkey Summit (section #1). At the base of the SC package, less than 5 m of interbedded tuffaceous sedimentary strata and tuffs are directly overlain by at least three 16.7-Ma Tba lava flows (20 to 30 m thick combined). Just to the east toward Granite Peak, Tb and Ta lava flows are interbedded with Tba lava flows. These are then overlain by another thin and discontinuous zone of tuffaceous strata (<5 m thick) that in turn is overlain by a dominantly silicic sequence that includes the thick cliff-forming 16.4-Ma Thc lava flows exposed at Hinkey Summit. The Thc flows dip away from Hinkey Summit to the east-northeast and are exposed along the southern SC margin toward Coal Pit Peak (see section #10) and along Forest Service road 084 before it drops into the Goosey Lake depression. Above these silicic lava flows are Ta and Tad_1 lava flows. These Tad_1 lava flows thicken toward their inferred Coal Pit Peak source to the east. Younger Tpr and Tba intrusive bodies cut older mafic and intermediate lava flows in the vicinity of Hinkey Summit. The best examples of these intrusive bodies are the 16.2-Ma Tpr hypabyssal body south of Hinkey Summit, the spectacularly jointed and arched Tpr dike that cuts Tba lava flows and tuffaceous strata at Hinkey Summit, and 16.0-Ma Chocolate Mountain, the best-exposed mafic (Tba) shallow intrusive body present in the SC.

Farther to the northwest along the western SC margin is section #2, where relationships are similar to those present at Hinkey Summit. Again, Tarc lava flows crop out and unconformably overlie Trms rocks. Tarc rocks are basaltic and basaltic andesite lava flows, including the stratigraphically oldest flow encountered (the 35-Ma basalt flow discussed previously). SC derived units are exposed above the almost 200-m-thick Tarc rocks. Like at Hinkey Summit, a thin (<5 m) zone of tuffaceous sedimentary strata and air-fall tuff directly underlies the mafic lava flows. The dominantly mafic lava flows are much thicker than at Hinkey Summit (>120 m) and include 16.7-Ma Tb, Tba, and Ta lava flows. Also present is tuffaceous strata that overlie the Ta lava flows. Associated with these sedimentary strata are sinter deposits and minor amounts of mineralized rocks that together occur in a less than 5-m-thick interval. Near the top of this section are Twsc silicic lava flows that physically resemble Thc lava flows. These are exposed along the range-crest of the northern Santa Rosa Range. The entire package of SC-derived material is cut by younger Tba dikes, and the stratigraphically youngest unit at this location is a small and eroded 14.4-Ma Tba vent, exposed near the topographic base of the section.

Section #3 is located just north of Holloway Meadows at Quinn Pasture. There, some of the youngest SC units crop out. Locally, Tem and Ta lava flows and Tcst ash flows are exposed in northwest-trending fault blocks. Additionally, the distal lobe of a Tem lava flow is onlapped by a series of Ta lava flows and illustrates that some Ta lava flows in the SC are >15.8 Ma. The Tem lava flow thins toward the south and is interpreted to be the direct result of it flowing from sources near Eightmile Mountain down into the actively forming Goosey Lake depression. Overlying these lava flows are outcrops of 15.5 to 15.8-Ma Tcst that vary in thickness, but are thinner than Tcst exposures near Cold Springs Butte.

Section #4 summarizes the relationships observed at the southeast end of Odell Mountain. There, 255 m of 16.5-Ma Tom lava and ash flows are overlain by 5 to 10 m of Tp_1 deposits. Most of the stratigraphic thickness present at this location is made up of rhyolite lava flows, some of which likely erupted from the eroded vent at the head of Klondike Canyon. The interbedded ash flows are chemically similar to the lava flows and may represent a pyroclastic episode preceding lava flow eruption from the same vent. The Tp_1 deposits in this region are the thickest in the SC, which suggests that they were either erupted from a nearby source or flowed into the SC via this region from an external source (e.g., McDermitt). Directly east of section #4, Tp_1 deposits overlie lobes of Tem. Directly south, thick exposures of variably welded and, in some cases, lithophysae-rich Tcst deposits overlie

Tem and Tom lava/ash flows. Like locally exposed Tp_1 ash flows, these Tcst deposits appear to have flowed into a local region of low topography.

Section #5 is located along the eastern margin of the Calico Mountains (and the SC). There, along the base of the Calico Range, highly jointed and weathered 102-Ma Santa Rosa-Andorno group Kg is overlain by 400 m of locally derived effusive and pyroclastic materials (Fig. 2). Unconformably overlying this granitoid are 16.5-Ma Tad_2 and Tcm lava and ash flows. Tad_2 lava flows dominate the lower part of this section, but up-section, Tcm ash flows interbedded with Tad_2 lava flows become more prevalent. The Tcm ash flows are highly welded, rheomorphic, and lava-like. In the upper 175 m of section, the Capitol Peak ash flow is overlain by silicic units that include the capping 16.5-Ma Tom lava flows exposed at Capitol Peak.

Section #6 is located near the center of the SC, in the Goosey Lake depression along the North Fork of the Little Humboldt River. There, the stratigraphic relationships that typify those present throughout the depression are well exposed. Throughout the depression, Tcst ash flows overlie intermediate lava flows. About 80 m of Tcst overlie 140 m of Ta lava flows that are well exposed in the cliffs on both sides of the North Fork of the Little Humboldt River and locally interlayered with Tad_1 lava flows. Tcst and Tp_1 ash flows conformably overlie the lava flows and both ash flow exposures are discontinuous, either Tcst or Tp_1 (or both), may be present directly overlying Ta lava flows. This relationship is common across the Goosey Lake depression where these ash flows are exposed.

The most complete exposures of 16.4-Ma Coyote Mountain tuff (Tct) are in the vicinity of their Coyote Mountain source at section #7. There, Tct lava flows are well exposed and interfinger with locally derived Tct ash flows at the base of the assemblage. Conformably overlying these lava and ash flows is the Coyote Mountain tuff and associated pyroclastic deposits. Tct pyroclastic materials include the block and ash deposits exposed in patches along the flanks of Coyote Mountain and the welded fall deposits that underlie the Coyote Mountain tuff. The composite thickness of these units varies, but the Coyote Mountain tuff is 35 m thick at the section location.

Section #8 is located along the southeastern margin of the SC in the Hardscrabble Basin. There, Tad_1 lava flows are overlain by more than 100 m of mid-Miocene sedimentary strata. Two Tcst ash flows and at least 14 distinct air-fall tuff horizons and crop out within this sedimentary pile. The Tcst ash flows are much thinner than those present to the northwest near Cold Springs Butte (<5 m thick) and likely represent distal facies. Their separation by 80 m of sedimentary strata illustrates that multiple eruptive events characterized Tcst volcanism. The air-fall tuffs are all between 1 and 2 m thick, much thicker than other SC fall deposits (Tp_2). The interbedded sedimentary strata are similar to those present beneath the Cold Springs tuff near Cold Springs Butte. No apparent fluvial material crops out; instead, the entire sedimentary sequence appears to be comprised of tuffaceous, buff- to salmon-colored massive silts and silty clays. Physically, these resemble mid-Miocene lacustrine strata found across the southern Oregon Plateau and in the central SC (Wallace, 2003; this study). In places, occasional root casts are also present within the sediments. These observations suggest that the entire sedimentary sequence was deposited in a lacustrine environment that may have been subarielly exposed on an intermittent basis. The limited areal extent and overall physical characteristics of the sedimentary strata as well as the interbedded fall deposits and ash flows, suggest that these materials were deposited in an actively forming basin that was a continuous topographic low during SC volcanism.

Section #9 is located along the southern boundary of the SC between Black Dome and Coal Pit Peak. There, at least 330 m and at least 40 flows of Tad_1 lava flows are well exposed. This flow-on-flow stratigraphy is best exposed in the Martin Creek canyon, where reconnaissance sampling indicates that these lava flows are all Tad_1. This large number of compositionally similar lava flows is the thickest continuous package of Tad_1 lava flows present in the SC, and provides evidence that the Tad_1 source, likely a shield volcano, was nearby in the vicinity of Coal Pit Peak. Farther from this location, the overall thickness of the Tad_1 package decreases and Tad_1 lava flows are often found interbedded with other SC units. Within the package, the basal lava flows exposed near Martin Creek are andesitic, while the overlying lava flows are broadly dacitic.

Section #10 is located along the southern SC boundary, between Hinkey Summit and Coal Pit Peak. Stratigraphic relationships are more complex at this locality than at section #9. There, Tarc and SC-derived eruptive products were emplaced over Kg. This relationship, like elsewhere in the SC, implies that at least local uplift and exhumation of these Cretaceous plutons occurred before initial Tarc volcanism (35 Ma). Overlying the Kg is a package of Tarc lava flows that vary in thickness along the southern SC margin. In the vicinity of section #10, Tba lava flows crop out directly above the Tarc package, similar to the situation at

Hinkey Summit and north of Granite Peak (Wes LeMasurier, personal commun.). However, at section #10, >100 m of 16.4-Ma Thc lava flows overlie Tarc lava flows. Above this silicic package are 150 m of Tad_1 lava flows. This Tad_1 package thins along the southern margin, toward Hinkey Summit. Both the Thc and some of the Tad_1 lava flows are cut by north-northwest trending 16.2-Ma Tpr dikes (Fig. 6b) and hypabyssal bodies, some of which are also exposed near the topographic top of the section.

This discussion illustrates one key point that is essential to understanding the eruptive history of the SC: relief was variable before and during SC volcanism. The variable pre-SC relief likely had a profound influence on the areal distribution and subsequent outcrop pattern of SC volcanic units. Preexisting paleovalleys formed topographic lows that helped confine SC eruptive units. During SC activity, the eruption of units from multiple vents and ongoing faulting also contributed to a dynamic environment of changing topography. Distribution of SC pyroclastic units was highly influenced by local relief. These paleotopographic variations have contributed to the complexity of the volcanic field stratigraphy by making simple elevation-based stratigraphic correlations nearly impossible. The end result of SC volcanism is a complexly developed volcanic field with a wide array of physically and chemically variable eruptive products.

Eruptive history summary

To reconstruct the active SC volcanic field and provide the framework for a petrologic discussion of SC units, it is necessary to summarize the most important physical observations: [1] SC eruptive loci are numerous and concentrated along the margins of the volcanic field; [2] combined field, physical, and temporal, characteristics of SC units suggest that multiple magmatic systems dominated SC volcanism, rather than one (or a few) large magmatic system; [3] substantial intermediate composition suites were erupted during SC activity; and [4] SC eruptive loci are characterized by fissure-sources, domes, and at least one small, 2.5- by 3.5-km caldera. Figure 15 illustrates these observations and relationships and provides a summary of Santa Rosa-Calico volcanic activity through time. Figure 16 illustrates the compositional variation of SC eruptive products through the same time slices depicted in Figure 15.

Pre-SC *(Figs. 15a, 16a)*

Regional <11-Ma and younger basin-and-range block faulting and volcanism has made reconstructing the mid Miocene paleogeography of the southern Oregon Plateau difficult. The observed stratigraphic relationships present in the SC provide first-order constraints on the local pre-SC paleogeography. The unconformities between SC and pre-SC units which exist primarily along the southern, southeastern, and eastern SC margins require the presence of variable pre-SC relief. Just to the north of Granite Peak, Tarc lava flows as old as 35-Ma directly overlie Triassic metasedimentary rocks (Fig. 13, Sections 1, 2, 10) and this relationship illustrates that the greater Hinkey Summit region was characterized by variable relief before the onset of SC volcanism. Documented Tarc lava flows and probable near-vent facies also illustrate that at least some of these lava flows were derived locally from loci near Hinkey Summit, as illustrated in Figure 15a. Other regions of variable relief that existed before the onset of SC volcanism include the Calico Mountains, where Tad_2 lava flows locally overlie Cretaceous granitoid and near Black Dome.

16.7 to 16.3 Ma, initial SC volcanism *(Figs. 15b, 16b)*

At 16.7 Ma, SC volcanism initiated. The oldest eruptive products are the Tb and Tba lava flows exposed in the vicinity of Hinkey Summit that overlie Tarc lava flows. Here and to the north past Buckskin Mountain, Tba lava flows erupted from north-northwest-trending fissural sources (Fig. 6b) coeval with the most voluminous pulse of regional flood basalt volcanism. Just north of Granite Peak, at least one small Tb eruptive loci and flow field formed. Silicic volcanism in this part of the SC began at 16.4 Ma and led to the emplacement of Thc lava flows from a source(s) along the southern SC margin. Discrete silicic eruptive loci also were present along the northwestern margin of the SC, in the vicinity of Buckskin Mountain and the National district (Vikre, 1985a, b). Almost simultaneously, volcanism began along the northeastern margin of the SC. There, Tom and Tcm rhyolite domes formed and erupted along with pyroclastic flows along broadly north-south-trending fissural systems parallel to the eastern SC margin. Tad_2 and Tba lava flows also erupted locally in the Calico Mountains. Farther south, Coyote Mountain, Zymns Butte, and Black Dome were active and their eruptive products flowed over a surface floored by slightly older intermediate-composition (Tct and Tad_1) lava flows. The Tad_1 magmatic system initiated in the greater Coal Pit Peak region during this time. Sedimentation in the Goosey Lake depression also was occurring before 16.2 Ma; but the areal extent and maximum age of the sedimentary strata is unknown.

16.2 to 16 Ma *(Figs. 15c, 16c)*

By 16.2 Ma, SC volcanism was focused in the southwestern part of the volcanic field and volcanic activity in the eastern SC had ceased. At 16.2 Ma, Tpr magmas were emplaced and locally erupted from discrete loci along the southern and western SC margins. Tpr lava flows flowed down into the Goosey Lake depression, where continued sedimentation was occurring. Tba volcanism continued in the greater Hinkey Summit region, Tad_1 lava flows continued to be erupted from their source near Coal Pit Peak and Ta lava flows continued to erupt from unknown loci (likely fissural).

16 to 14 Ma *(Figs. 15d, 16d)*

During the last two million years of SC volcanism, activity was mainly concentrated in a northwest-trending zone, broadly cutting through the center of the Goosey Lake depression. Sporadic Tba volcanism also continued along the western SC margin. At 15.8 Ma, Tad_2 lava flows erupted from a source near Staunton Ridge. Shortly following the eruption of these intermediate-composition lava flows, Tem lava flows erupted from fissures at and just east of Eightmile Mountain. Due to post-SC erosion, the pre-erosion areal extent of Tem lava flows is hard to discern, but may have been similar to that depicted in Figure 15d. Tem lava flows did flow to the south and east into the Goosey Lake depression, where they were onlapped by Ta lava flows. At 15.8 to 15.5 Ma, the Cold Springs tuff magmatic system was active, and the eruption of Tcst ash flows formed a small caldera in the western Goosey Lake depression, within the actively forming Goosey Lake depression. Tcst ash flows flowed over earlier SC products and also into the sedimentary depocenters present in and peripheral to the Goosey Lake depression (e.g., the Hardscrabble Basin). Also, mineralization leading to the National district deposits likely occurred during this time. Additional Tad_1 volcanism continued to 14 Ma, when SC volcanic activity ceased. During this waning stage of SC activity, Swisher Mountain-tuff equivalent ash flows (Manley and McIntosh, 2004) erupted from unknown regional sources and onlapped eastern SC volcanic units (Fig. 6b). Additional <16-Ma Swisher Mountain-tuff equivalent units are found outside of the SC along its southeastern margin (e.g., the 15.5-Ma Little Humboldt Rhyolite; Alan Wallace, personal commun.).

PETROLOGIC CHARACTERISTICS OF SC UNITS

SC products range from basalt to high-silica rhyolite (Fig. 5; Table 3) and the entire suite approximates a subalkaline differentiation trend. Major and trace element data are used to distinguish pre-SC Tarc lava flows from SC derived units (Fig. 17a,b). SC mafic and intermediate units are dominantly tholeiitic, but span the tholeiitic/calc-alkaline boundary (Fig. 17b). SC silicic units are predominantly peraluminous to metaluminous and the only peralkaline unit (Tp_1) was likely not derived locally (Fig. 17c). SC units are characterized by a wide range in REE concentrations and are isotopically diverse. The following sections first introduce and discuss the major and trace element characteristics of the mafic, intermediate, and silicic units, then present the isotopic characteristics of the suite as a whole, followed by preliminary petrogenetic interpretations based on these data. In the context of this discussion, the phrase “more evolved” is based on the fundamental concept of magma differentiation where as magma chemically changes over time through closed-system fractional crystallization, its original composition is modified and it becomes more silica-rich. Additionally, the SiO_2 content of a magma body typically increases with time; more evolved magmas have higher wt% SiO_2 than less evolved magmas (as well as corresponding major and trace element differences).

Mafic Units

Tertiary basalt (Tb)

Tb lava flows are the least evolved materials erupted within the SC and have high Al_2O_3 (avg. 17.13 wt%), low K_2O (avg. 0.32 wt%), and low TiO_2 (avg. 1.35 wt%) and are incompatible (in a mafic liquid) element concentrations (Fig. 18a,b; Table 3; Appendix 3). These and other major and trace element characteristics are similar to regionally exposed HAOT lava flows, which are the dominant basalt type erupted across the Oregon Plateau over the last 11 Ma (Hart, 1985; Shoemaker, 2004). Before identifying these Tb lava flows as HAOT, the oldest documented HAOT-like lava flows and eruptive loci identified were 13 Ma, from the Oregon-Idaho graben (Camp and others, 2003). HAOT-like dikes cut the granitoid exposed in the main Santa Rosa Range and may be related to these newly identified mid-Miocene units, rather than younger Miocene-Pliocene HAOT volcanism (Stuck, 1993).

The Tb lava flows form a cluster on all major and trace element Harker diagrams. No discernable trends are present within the Tb group. However, because Tb is the most mafic rock encountered in this study, it represents the mafic end-member on all Harker diagrams (Fig. 18a,b). Figure 19a depicts elemental variations of SC mafic units normalized to mid-ocean ridge basalt (MORB) (Pearce, 1983). Mafic magmas with large ion lithophile element (LILE; typically Cs, Rb, K, Ba, Sr, Th, U, Pb, La, Ce, and the light rare earth elements) enrichments and high field strength element (HFSE; typically Ti, Zr, Hf, Nb, Ta, P, and Y) depletions are commonly associated with subduction zone environments (affected by subduction-related fluids and/or sediments), or were derived from a subduction modified source; these characteristics are observable on multi-element diagrams like Figure 19a (Hawksworth and others, 1993; Plank and Langmuir, 1998; Davidson and others, 2005). One Tb sample is depicted and it is slightly enriched in LILE, with the exception of a pronounced positive Ba anomaly. This pattern is nearly identical to younger, Oregon Plateau area HAOT (Shoemaker, 2004). Tb exhibits a flat light rare earth element (LREE) pattern and LREEs are slightly more enriched than heavy rare earth elements (HREE) (Fig. 20a).

Tertiary locally erupted Steens Basalt (Tba)

Tba lava flows and shallow intrusive bodies are much more evolved than Tb, as illustrated by the major and trace element plots on Figure 18a,b. These lava flows are dominantly tholeiitic, though they straddle the tholeiitic to calc-alkaline boundary (Fig. 17b). Compositionally, Tba resembles Steens Basalt lava flows (Fig. 21). Comparisons of major and trace element data illustrate that average Tba is slightly more evolved than average Oregon Plateau Steens Basalt. However, the compositional range represented by Tba overlaps with that found in the Steens Basalt (46 to 56 wt% SiO_2, 0.9 to 3.3 wt% TiO_2, 3.0 to 7.8 wt% MgO, 7.7 to 13.5 wt% FeO*, 6.0 to 10.1 wt% CaO, 0.7 to 2.5 wt% K_2O; Fig. 18). Based on these compositional similarities and the fact that Tba volcanism occurred throughout the duration of SC volcanism, Tba activity is interpreted as local Steens basalt volcanism.

The Tba lava flows are compositionally diverse (Fig. 18a,b), and they define arrays that in some cases suggest multiple parental liquids and/or early differentiation histories (e.g., FeO*, P_2O_5, Ni, and Sr vs. SiO_2). Tba lava flows have pronounced enrichments in LILE but not in the HFSE, normalized to MORB (Fig. 19a). This elemental pattern is similar to regional Oregon Plateau flood basalt lava flows (as previously mentioned; Fig. 21). Tba LREE are moderately enriched relative to their HREE concentrations. Together, LREE and HREEs define a smooth pattern (Fig. 20a).

Intermediate Units

Tertiary andesite of Black Ridge (Ta)

Ta lava flows are chemically similar to the most evolved Tba lava flows and are dominantly tholeiitic basaltic andesites to andesites (Figs. 5a, 17c). They lie across the basic/acid boundary in the andesite classification scheme of Gill (1981) (Fig. 5b). Ta major element concentrations overlap with the most evolved Tba samples and "cluster" between Tba and the three Tad groups (Fig. 18a,b). Trace element variations also overlap with Tba. For example, the ranges in Ni, Sc, Sr, Rb, Zr, La, and Nb concentrations present in Ta lava flows are identical to those of Tba. However, some elements (e.g., Ba and the REE) are more enriched in Ta relative to Tba. While there are slight major and trace element variations within the Ta group, Ta lava flows appear to be a more evolved extension of the dominant mafic SC magma type (Tba).

Ta lava flows are enriched in LILE and have HFSE "troughs" when normalized to MORB (Fig. 19). Their overall MORB-normalized pattern is also nearly identical to Tba lava flows and, with the exception of Ba (slightly more enriched), overlaps with the most enriched Tba. REE patterns for Ta illustrate moderate LREE enrichment with a slight negative Eu anomaly (Fig. 20b). These REE patterns overlap with the most enriched Tba and are consistent with crystal fractionation from a less evolved, Tba-like magma.

Tertiary andesite-dacites of Hinkey Summit-Coal Pit Peak (Tad_1)

Tad_1 lava flows are classified as high-K andesites (Fig. 5). However, lower FeO*/MgO ratios at a given SiO_2 content define these lava flows as calc-alkaline and distinguish them from all other SC intermediate composition units (Fig. 17). Other temporally, compositionally, and physically similar calc-alkaline lava flows are exposed within and to the north of the Oregon-Idaho graben in northeastern Oregon (Robyn, 1979; Hooper and others, 1995; Cummings and others, 2000; Camp and others, 2003). Harker diagrams of major and trace element concentrations also help distinguish Tad_1 lava flows from other SC intermediate composition groups (Fig. 18a,b). Tad_1 lava flows have lower HFSE, REE, and Sr and higher Ni and Sc concentrations than do other SC intermediate units over the same range in silica (Fig. 18b).

Tad_1 chemical characteristics mirror their spatial, temporal, and petrographic attributes by indicating that Tad_1 lava flows were derived from a magmatic system(s) separate from other SC intermediate units.

The Tad_1 lava flows are divided into low (59 to 62 wt% SiO_2) and high (62 to 64 wt%) silica groups (Fig. 18a; see MgO vs. SiO_2) that do not appear to be stratigraphically controlled. On a MORB-normalized multi-element diagram (Fig. 19c), Tad_1 lava flows display overall patterns similar to other SC intermediate units (Ta, Tad_2, Tad_3) and Tba. Tad_1 lava flows have slightly more enriched LILE than Tba, with the exception of Sr. They also have pronounced negative HFSE and P anomalies. Other Tad_1 trace element concentrations normalized to MORB overlap with Tba, although Tad_1 has lower P and Ti and higher Y than Tba. Tad_1 lava flows possess moderate LREE enrichment and obvious negative Eu anomalies (Fig. 20b). This pattern overlaps with Tba and is consistent with fractional crystallization from a Tba-like magma.

Tertiary andesite-dacites of Staunton Ridge (Tad_2)

Tad_2 lava flows are classified as high-K andesites (Fig. 5), but, unlike Tad_1 lava flows, they are tholeiitic. On Harker diagrams of major and trace element concentrations, Tad_2 lava flows are compositionally most similar to Tad_3 lava flows, but they are slightly more alkaline. The similarity to Tad_3 is best seen on plots of SiO_2 vs. MgO, P_2O_5, and Ni (Fig. 18a,b). However, different HFSE and REE concentrations at similar silica contents easily differentiate these two units (Fig. 18b). Major and trace element variations also help illustrate that Tad_2 lava flows are different from Tad_1 (e.g., lower MgO and higher P_2O_5, TiO_2, LILE, HFSE, and REE). Age relationships substantiate these chemical differences and preclude these units from being petrogenetically related (Table 1).

Like Tad_1, some Tad_2 lava flows major and trace element concentrations vary slightly with silica while others remain relatively constant (Fig. 18a,b). Tad_2 flows have more enriched overall trace element patterns than Tba and Tad_1, when normalized to MORB (Fig. 19d). Sr, Ti, and P are the exceptions. Like all other SC mafic and intermediate units, they also exhibit LILE > HFSE enrichments. The shape of their chondrite normalized REE pattern is similar to other SC intermediate units; however, Tad_2 lava flows have overall higher REE abundances than Ta and Tad_1 (Fig. 20b). Tad_2 lava flows also have a slight negative Eu anomaly and this anomaly and the overall REE enrichments are consistent with fractional crystallization of a less evolved mafic magma.

Tertiary andesite-dacites of the Calico Mountains (Tad_3)

Tad_3 lava flows are also classified as high-K andesites (Fig. 5) and are tholeiitic. On major element Harker variation plots, they have similar concentrations as Tad_2 lava flows (slightly higher TiO_2, MgO, and CaO, and slightly lower K_2O; Fig. 18a). Their trace element concentrations are also similar; however, Tad_3 lava flows have higher Sr, HFSE, and REE concentrations than both Tad_2 and Tad_1 lava flows (Fig. 18b). These chemical differences are consistent with substantial spatial and age differences. Together these observations strongly suggest that the individual Tad units erupted from distinct SC magmatic systems.

Tad_3 lava flows have nearly identical MORB-normalized elemental patterns as Tad_2 and have more enriched trace element concentrations than Tba (Fig. 19d). They have the characteristic LILE enrichments and HFSE "troughs" that are found in all SC intermediate units, but they possess the highest concentrations of the HFSE. Their REE pattern is most similar to Tad_2 (Fig. 20b) and Tad_2 also displays a slight Eu anomaly.

Silicic Units

Tertiary Hinkey Summit-Coal Pit Peak dacites - rhyolites (Thc)

Thc lava flows are dacitic to rhyolitic based on their concentrations of total alkalies and silica (Fig. 5). Within this unit, at least three subgroups are present (67 to 69 wt% SiO_2, 70 to 73 wt% SiO_2, and 76 wt% SiO_2; Fig. 22a,b). These distinctions are best evident in the Zr vs. silica plot (Fig. 22b). The two higher silica subgroups also define a single line in element-element space (Fig. 22a,b). The high Ba concentrations (up to 5500 ppm) that characterize low-silica Thc lava flows are unique within the SC silicic suite and distinguish them from other silicic units. The third subgroup of Thc lava flows is characterized by >74 wt% SiO_2 and crops out along the southern SC margin in the massive cliffs north of Paradise Valley (Figs. 2, 6). Major and trace element characteristics help delineate Thc lava flows from other SC silicic units and support physical, spatial, and geochronologic differences that suggest Thc lava flows represent outflow from a distinct SC silicic system.

Overall, Thc lava flows (and most other SC silicic units) exhibit elemental enrichments and depletions compared to average upper continental crust (Fig. 23d).

Thc has pronounced negative Ta, Nb, Ti, and Sr anomalies and slight positive Zr, Hf, and Ba anomalies.

Like the previously described SC intermediate units, Thc displays a LREE enriched pattern (Fig. 20f). However, unlike other units, Thc has a slightly positive Eu anomaly. This Eu anomaly, coupled with the strong negative Sr anomaly (Fig. 23d), suggests that processes more complex than crystal fractionation alone are responsible for the evolution of this unit.

Tertiary porphyritic rhyolite (Tpr)

While all Tpr lava flows and shallow intrusive bodies are petrographically similar (e.g., hornblende and biotite bearing), variations in chemical content are present and to some extent mirrored by geographic and petrographic differences. All Tpr lava flows and shallow intrusive bodies are rhyolitic and span a range in silica from 69 to 78 wt%. Within this range, two subgroups are present: [1] a low silica subgroup between 69 to 71 wt% SiO_2 and [2] a high silica subgroup, with concentrations over 72 wt% (Fig. 22a,b). All samples that make up the low silica subgroup were collected from the Tpr lava flow exposed along the southern SC margin (highly porphyritic and larger phenocrysts), while samples from the less phyric (and smaller phenocrysts) western margin Tpr flow fall within the higher silica subgroup (Fig. 22a,b). Tpr intrusive bodies, including the dikes between Hinkey Summit and Buckskin Mountain and the large hypabyssal body southeast of Hinkey Summit, also fall within the higher silica subgroup, even though they are more petrographically similar to the phenocryst-rich southern SC margin Tpr lava flow (low silica subgroup). Differences between these subgroups are apparent in their trace element compositions (e.g., the low silica subgroup has lower Rb, higher Zr and Sr). The high silica subgroup is more compositionally similar to Tbr lava flows and intrusive bodies than any other SC silicic unit.

Normalized to upper continental crust, Tpr lava flows and intrusive bodies show element enrichments that vary depending on mode of occurrence (Fig. 23a). The two Tpr samples depicted on Figure 23a were collected from the western and southern margin Tpr lava flows. The low silica southern margin Tpr lava flow is less enriched relative to upper continental crust and has small negative Sr and Ti anomalies and a small positive Ba anomaly. However the western margin higher silica Tpr lava flow is more enriched than the southern flow overall and has substantial negative Ba, Sr, and Ti anomalies that likely reflect fractionation of phases such as feldspar and magnetite. Tpr REE patterns are characterized by LREE enrichment (Fig. 20c), with the degree of enrichment following the relationships discussed above. Both varieties have a negative Eu anomaly; however, the high silica variety has a much more pronounced anomaly.

Tertiary Eightmile Mountain lava flows (Tem)

Tem pyroclastic material and lava flows are dacitic to rhyolitic and span a range in silica from 65 to 74 wt% (Fig. 22a,b). On Harker diagrams, Tem samples typically define linear patterns that, with decreasing silica, project back toward Tad_2 compositions. This potential petrogenetic link is supported by the previously discussed spatial and temporal relationships between these two units. As silica increases, CaO, MgO, FeO*, TiO_2, P_2O_5, Rb, HFSE, and REE increase while K_2O, Na_2O, Sr, and Sc decrease (Fig. 22a,b). Tem eruptive products have higher Na_2O, Al_2O_3, Sr, and lower TiO_2 and MgO than most other SC silicic units. Overall, they are most compositionally similar to Twsc, but trace element differences (e.g., Zr) distinguish these two units, as do field and chronologic relationships.

Tem lava flows have a similar upper continental crust-normalized elemental pattern as Thc (Fig. 23d). Tem has negative Eu, Ti, Ta, and Nb anomalies and a positive Ba anomaly. The Tem REE pattern is smooth and there is a slight range in enrichment in HREE within the Tem group (Fig. 20f). Like most other SC silicic units, Tem also has a negative Eu anomaly.

Tertiary flow-banded rhyolite lava (Tbr)

Tbr lava flows and intrusive bodies are high silica rhyolites (>76 wt% SiO_2) and are easily distinguished from other SC silicic units by their limited bulk composition range (Fig. 22a,b). Additionally, the abundant obsidian clasts in Holocene SC sedimentary deposits are chemically identical to Tbr. No obsidian domes were identified in the field so these clasts likely reflect weathering of Tbr vitrophyre rather than the presence of a now eroded, Tbr obsidian dome.

On Figure 23, Tbr lava flows and shallow intrusive bodies exhibit elemental patterns similar to those of Tpr lava flows and intrusive bodies. When normalized to upper continental crust, the most characteristic elemental features of Tbr are the large negative Ba, Sr, and Ti anomalies (Fig. 23a). Chondrite-normalized Tbr REE patterns differ slightly from Tpr because the overall Tbr pattern is nearly flat with the exception of the pronounced negative Eu anomaly (Fig. 20c). The very pronounced negative Ba, Sr, Ti, and Eu anomalies exhibited by Tbr rocks suggest a significant role for crystal fractionation in their petrogenesis.

Tertiary western margin lava flows (Twsc)

Twsc lava flows are dominantly dacites to rhyolites, with one sample falling along the andesite-dacite boundary. Overall, their major and trace element characteristics are quite variable (Fig. 22a,b). Although they physically resemble Tem lava flows, the Twsc lava flows are readily distinguished based on many major and trace element characteristics (Fig. 22a,b). Their trace element concentrations also distinguish them from similarly evolved Thc flow units as noted, for example, on a plot of SiO_2 vs. Zr (Fig. 22b).

One low silica Twsc lava flow was analyzed for a full suite of trace element and REE concentrations. On MORB-normalized trace element plots, the flow has a nearly identical pattern to Tad_3, including enriched LILEs and HFSE "troughs" that characterize other compositionally similar SC units (Fig. 19d). Low silica Twsc displays a LREE enriched pattern and a slight negative Eu anomaly (Fig. 20b). This pattern is nearly identical to those of Ta, Tad_2, and Tad_3.

Tertiary Odell Mountain area silicic units (Tom)

Tom lava and ash flows are rhyolitic with the highest silica contents of all eastern SC silicic units (> 73 wt% SiO_2; Fig. 22a,b). Tom lava flows are also distinguished from other eastern SC silicic units by their higher HFSE and lower LILE concentrations (Fig. 22b). Two distinct subgroups are present within the Tom chemical group as differentiated by their silica content (<74 wt% SiO_2 and >75 wt% SiO_2). Tom lava flows rich in mafic-xenoliths make up this lower silica group, while the higher silica group includes the stratigraphically youngest Tom lava flows and the eroded rhyolite dome at the mouth of Klondike Canyon. Presumably, this difference in silica is at least partially related to the abundant mafic xenoliths in the low-silica subgroup.

When normalized to upper continental crust, Tom lava and ash flows have the most pronounced negative Sr anomalies of any SC unit together with pronounced negative Ba and Ti anomalies (Fig. 23b). Tom lava and ash flows exhibit LREE enriched patterns with large negative Eu anomalies (Fig. 20d).

Tertiary Calico Mountains area silicic units (Tcm)

Tcm lava and ash flows range from 63 to 76 wt% SiO_2 (Fig. 22a,b). This compositional variation roughly follows stratigraphic position, where the most evolved samples are at the highest stratigraphic levels. Within this range, Tcm subgroups are present and represent: [1] the xenolith bearing ash flows exposed below the Capitol Peak ash flow (<70 wt% SiO_2), [2] the lava flow(s) exposed at Mahogany Pass (71 to 73 wt% SiO_2), and [3] the southern Calico rhyolite lava flows that overlie the Mahogany Pass rhyolite (73 to 76 wt% SiO_2). The stratigraphically highest units at Capitol Peak (above the Capitol Peak ash flow) also have high SiO_2; however, their overall major and trace element composition are virtually identical to Tom lava and ash flows and are likely related (and therefore should be classified as Tom). On Harker diagrams, the xenolith bearing ash flows have higher MgO and Ni, and lower Ba concentrations than other Tcm silicic units (Fig. 22a,b). As a group, Tcm silicic units have nearly constant HFSE and REE concentrations (Fig. 22b). This lack of variation is particularly apparent on plots of SiO_2 vs. La and Nb.

Tcm lava and ash flows have similar elemental patterns on multi-element plots (Figs. 20, 19b), although a lower Tcm ash flow lacks the negative Eu anomaly (Fig. 20d). When normalized to upper continental crust, Tcm lava and ash flows have variable, but typically negative, Sr and Ta anomalies and positive Ba anomalies (Fig. 23b). The lower Tcm ash flows do not have a negative Ti anomaly and positive Ba anomaly as compared to the upper units.

Tertiary Coyote Mountain-Zymns Butte area silicic units (Tct)

Major and trace element data illustrate that Tct silicic products are broadly similar to Tcm lava and ash flows (Fig. 22a,b). Additionally, the products of all three loci (Coyote Mountain, Zymns Butte, and Black Dome) show the same approximate compositional range as Tcm. Like in the Calico Mountains, the stratigraphically lowest Tct silicic products are the least evolved. Samples collected from the Coyote Mountain ash flow define a range in silica (69 to 75 wt%) that likely reflects pre-eruption chemical zonation in the magmatic system. However, this upward zonation is the reverse of what is typically found in silicic pyroclastic deposits, where the lower part of the deposit is usually the most evolved and higher zones are increasingly less evolved, reflecting the eruption of a chemically-stratified magma chamber (normal-zonation; Smith, 1979; Hildreth, 1979). As deeper portions of a normally-zoned magma chamber are tapped, greater volumes of less-evolved magmas are erupted. The reverse-zonation present in the Coyote Mountain ash flow may be a function of the Tct magma chamber being normally zoned, but emptied from the bottom to top. Conversely, it could be that the Tct magma chamber was normally zoned, but the upper-portion of the magma chamber was characterized by the interaction of Tct magma with less-evolved contaminants (e.g., local crust or mafic and intermediate magmas). Analogous roof and

side-wall contamination has been proposed to explain similar occurrences of reverse-zonation in ash-flow tuffs (Duffield and Ruiz, 1992; duBray, 1995). In addition to the upper part of the Coyote Mountain ash flow, higher silica Tct products (>74 wt%) include pyroclastic deposits exposed at Coyote Mountain and Zymns Butte.

Normalized to upper continental crust, Tct deposits have pronounced negative Sr and Ti anomalies and overall, have similar patterns to Tcm (Fig. 23c). Overall, Tct lava and ash flows have smooth REE patterns and are enriched in LREE relative to HREEs (Fig. 20e). Each sample analyzed is characterized by a negative Eu anomaly and the overall range in REE enrichment roughly corresponds to silica content (e.g., the most enriched Tct has the highest silica content).

Tertiary Cold Springs tuff (Tcst)

Bulk analyses of Tcst deposits span a range in silica from 67 to 77 wt% (Fig. 22a,b). Major and trace element data illustrate that the Tcst is chemically dissimilar from other SC silicic units and likely represents a separate magmatic system. This interpretation is best illustrated by the concentrations of K, Al, Zr, Nb, and REE. Pure glass separates were extracted from three bulk Tcst samples spanning the observed silica range. These pure glass separates defined a range of 73 to 76 wt% SiO_2 (Knight and others, 2004), at the upper end of the range defined by whole rock analyses. Additionally, pumice clasts from Tcst main body deposits exposed at Cold Springs Butte are less silicic than the purified glass shards (71.5 wt% SiO_2). Together, these bulk and purified Tcst chemical differences illustrate that the Tcst magmatic system was chemically heterogeneous. These major and trace element variations also make using bulk chemical characteristics to correlate Tcst outcrops difficult. Knight and others (2004) demonstrated that some of the bulk Tcst variation is a function of crystal content and that up-section welding variations often are accompanied by up-section chemical variations. However, welding variations in the Tcst near Cold Springs Butte are not accompanied by substantial (>1 wt% SiO_2) chemical variation. Tcst magma temperatures were estimated using the relationship derived by Watson and Harrison (1983) and modified by Perkins and others (1995): $10{,}000/T = -1.02 + 1.27 * \ln(500{,}000/X_{Zr})$, where T= degrees Kelvin and X_{Zr} = zirconium concentration in glass shards (ppm). Tcst magma temperatures for the purified glass separates and pumice calculated using this expression range from 1047° to 1093°C, consistent with magma temperatures from regional mid-Miocene silicic eruptive systems (>1000°C; Perkins and Nash, 2002).

Elemental variations of Tcst ash flows normalized to upper continental crust are depicted on Figure 23d. Here, it is apparent that Tcst has high concentrations of Zr, Hf, Ta, Nb, and LREE, suggesting that zircon (and other trace phases) were not major fractionating phases. Tcst REE patterns are among the most enriched of all SC silicic units (Fig. 20f). High silica Tcst has an identically shaped, but more enriched pattern relative to low silica Tcst and also has a more prominent negative Eu anomaly (than low silica Tcst). These characteristics are consistent with a major role for fractional crystallization in the Tcst magmatic system.

Tertiary ignimbrite (Tp_1)

As stated earlier, field relationships suggest that more than one Tp_1 flow unit is present across the SC. Overall, Tp_1 deposits are peralkaline to mildly metaluminous and range from 73 to 77 wt% SiO_2 (Fig. 22a,b). The one high silica sample (76.6 wt %) overlies less welded Tp_1 that falls within a more limited silica range defined by all other samples (73 to 75 wt% SiO_2). Its high SiO_2 content may reflect secondary silicification. Tp_1 major element oxide concentrations illustrate that these ash flows are chemically distinct from other SC silicic units (Fig. 17c). Chemical variation within the Tp_1 group is present (Fig. 22) and this variation makes chemical correlation of Tp_1 outcrops difficult. Tp_1 ash flows are peralkaline, as are the voluminous >16-Ma ash flows that were erupted during caldera-forming events associated with the McDermitt volcanic field. However, the Tp_1 deposits have not been conclusively linked to any major McDermitt units. In summary, Tp_1 deposits across the SC are likely the remnants of more than one regionally derived peralkaline ash flow sheet(s).

Tertiary air-fall tuffs (Tp_2)

A subset of SC tephra was studied by Gilbert and others (2003). Pure glass separates were analyzed to determine their major and trace element composition. These tuffs are rhyolitic and subalkaline. Gilbert and others (2003) compared these tephra chemically to published analyses of regional mid-Miocene pyroclastic units and lava flows. They demonstrated that at least some of the tephra could have a local derivation, while others were chemically similar to material sourced in the McDermitt and Owyhee-Humboldt volcanic fields. Now with more SC data in hand it is apparent that links to other SC units can be made. For example, a tuff exposed in sedimentary strata directly underlying the western Tpr lava flow is chemically similar to Tpr lava flows. This tuff is also pumiceous and relatively thick, consistent with a nearby

eruptive source. As previously discussed, tuffs exposed in the sparse sedimentary pile in the Goosey Lake depression near the Cold Springs caldera are chemically similar to regionally exposed tuffs (e.g., 15- to 16-Ma tephra; Perkins and Nash, 2002). A stratigraphically older tuff exposed within a sedimentary pile along the southern Goosey Lake depression is tentatively correlated with the Tcm rhyolitic lava flows exposed in the southern Calico Range. Thus, our current understanding is that SC tephras are the products of both proximal and distal explosive eruptions.

Isotopic Variations of SC Units

To further constrain the petrologic characteristics of the SC, a subset of samples was chosen for Sr, Nd, and Pb isotopic analyses (Table 3). This subset was chosen to represent the chemically diverse SC eruptive package and emphasis was placed on representing the previously defined petrologic units. These data are combined with Sr-Nd-Pb isotopic measurements of Mellott (1987) and W.K. Hart (unpublished data) to better represent the SC eruptive assemblage, although not all samples in this combined database have a full suite of Sr-Nd-Pb isotopic analyses. Only samples from this current study are reported in Table 3 and Appendix 3. Also, in Table 3, initial $^{87}Sr/^{86}Sr$ ratios (Sr_i) are not reported for certain high Rb/Sr silicic units because of post-eruptive modification of this ratio due to hydrothermal alteration.

The combined Sr-Nd isotopic characteristics of the units defined in this study are depicted on Figure 24. Initial $^{87}Sr/^{86}Sr$ ratios (Sr_i; all samples from the combined data base) range from 0.70378 to 0.70764 and initial $^{143}Nd/^{144}Nd$ ratios (Nd_i) from 0.51241 to 0.51288 (Table 3). SC mafic units (Tb, Tba) have Sr_i and Nd_i values of 0.70378 to 0.70445 and 0.51263 to 0.51288, respectively, with Tba exhibiting higher Sr_i and lower Nd_i values than Tb (Fig. 24). SC intermediate units (Ta, Tad_1, Tad_2, and Tad_3) have Sr_i = 0.70440 to 0.70583 and Nd_i = 0.51263 to 0.51273. Of the four intermediate-composition petrologic groups, Tad_1 has the highest Sr_i values; however, Tad_1 has Nd_i values similar to the other groups (Fig. 24). SC silicic units (Tem, Twsc, Tcst, Tbr, Tpr, Tcm, Tom, and Tcm) have Sr_i = 0.70479 to 0.70764 and Nd_i = 0.51241 to 0.51268 (Fig. 24). Figures 25a and b illustrate these Sr-Nd variations vs. wt% SiO_2. These Sr-Nd vs. SiO_2 diagrams also illustrate that, like some of the local granitoid basement (Granite Peak-Sawtooth group Kg; Stuck, 1993), some SC silicic units are characterized by Sr_i >0.706 (Tpr, Tbr, and Tcst).

When considered together on Figure 25, SC mafic units and Ta form an array of increasing SiO_2 from 47 to 58 wt%, increasing Sr_i from 0.7038 to 0.7045, and decreasing Nd_i from 0.51288 to 0.51268. With continued increasing SiO_2, Nd_i for the majority of the intermediate and silicic units remains nearly constant. The Sr_i behavior is more complicated; most units define a relatively flat array as with Nd_i whereas Tad_1 has Sr_i of 0.7058 up to 62 wt% SiO_2. Lying off of the above defined arrays are Tcst and Tbr/Tpr with lower Nd_i and higher Sr_i values (Fig. 25).

Pb isotopic ratios also vary within and between SC units. Figure 26 depicts the measured $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ (Fig. 26a), and $^{208}Pb/^{204}Pb$ compositions (Fig. 26b) of SC units. Overall, $^{206}Pb/^{204}Pb$ ranges from 18.71 to 19.25, $^{207}Pb/^{204}Pb$ from 15.80 to 15.66, and $^{208}Pb/^{204}Pb$ from 38.54 to 39.10. With the exception of Tb and Tcst, SC mafic, intermediate, and silicic units define a small array in Pb isotope space (Fig. 26). There is considerably greater overlap among SC Pb isotope compositions than Sr_i and Nd_i isotope compositions (Figs. 24, 26). Conversely, similar characteristics emerge; intermediate unit Tad_1 contains the most radiogenic Pb isotope ratios while also standing out as different from most of the other SC units with respect to Sr isotope composition (higher Sr_i; Figs. 24, 26). The two Tcst samples analyzed for Pb isotopes have nearly identical $^{206}Pb/^{204}Pb$ values (18.7) that are much lower than values for all other SC units, but higher $^{208}Pb/^{204}Pb$ and similar $^{207}Pb/^{204}Pb$ relative to all other SC silicic units.

Figures 27a and 27b illustrate combined $^{206}Pb/^{204}Pb$, Nd_i, and Sr_i characteristics of SC units. A number of observations are apparent: [1] Tcst is isotopically distinct from all other SC units; [2] Tpr (Nd-Pb) and Tbr (Sr-Nd-Pb) are isotopically similar and also appear to be distinct from all other SC units; [3] Tom and Tcm have similar Sr-Nd-Pb characteristics but the other main eastern SC silicic unit, Tct, is distinct; [4] Tad_1, Tad_2, and Tad_3 are isotopically distinct from each other and form "tight" groups when multiple samples are represented; [5] Tb and Tba are isotopically distinct.

Figure 28 compares the Nd_i and Sr_i of SC units with regionally erupted Steens Basalt (Carlson and Hart, 1987) and the known isotopic compositions of local crust that may have interacted with or produced SC magmas (Kg and Tarc, calculated at 16.5 Ma; Mellott, 1987; Stuck, 1993). Tarc Sri and Ndi overlap with Tba, but define an array that extends to higher Sr_i and lower Nd_i. Shaded fields depict the Sr-Nd isotopic characteristics of the two main Cretaceous granitoid groups (Kg; 102-Ma Santa Rosa-Andorno and 85-Ma Granite Peak-Sawtooth; Stuck, 1993). Also depicted are the Sr_i and Nd_i of Cretaceous aplitic dikes that crosscut the larger plutonic bodies.

These dike compositions form an array extending to more radiogenic Sr_i (0.710 to 0.750) at a relatively constant Nd_i, similar to that which characterizes Santa Rosa-Andorno group rocks. Two important observations can be made from this figure: [1] Tcst has Sr_i and Nd_i isotopic compositions similar to Granite Peak-Sawtooth group granitoid; [2] nearly all other analyzed SC intermediate and silicic samples fall within the field denoting the Sr-Nd isotopic values of Santa Rosa-Andorno group granitoid. The overall Pb isotopic compositions of local granitoids are poorly constrained except for two samples from the Santa Rosa and Bloody Run plutons (Santa Rosa-Andorno group granitoid). Their measured initial Pb isotopic values are similar to SC units ($^{206}Pb/^{204}Pb$ = 19.016, $^{207}Pb/^{204}Pb$ = 15.626 to 15.634, and $^{208}Pb/^{204}Pb$ = 38.621 to 38.650, depicted on Fig. 26; Wooden and others, 1999). The Pb isotope composition of SC units and Santa Rosa-Andorno group granitoid also overlap with regional Pb data obtained from Mesozoic and Tertiary plutonic and volcanic rock rocks exposed west of the Carlin trend and just east of the SC (Wooden and others, 1998).

Sr and Nd isotopic compositions of SC units vary with silica but they do not define any single, simple trend (Fig. 25). These relationships preclude closed-system crystal fractionation of a mafic parental magma(s) as the sole explanation for the geochemical and isotopic diversity of SC magmas. Moreover, the relationships depicted in Figure 25 require a substantial role for crustal reservoirs in either the melting or upper level differentiation histories of SC magmatic systems, or both. Local Kg upper crust could represent such reservoirs (Fig. 20). The presence of Kg xenoliths in some SC lava flows, particularly those that appear to have erupted from vents near present-day exposures of the local granitoid basement, provide direct evidence for this interaction.

Summary of geochemical and isotopic relationships

The following points summarize the pertinent geochemical and isotopic relationships and allow for a first-order discussion of the physical and petrologic evolution of the SC. To help illustrate these points, Figure 29 depicts SC units normalized to an average Tba composition. Major and trace element variations suggest that geochemical heterogeneity is present within the Tba group; therefore, chemical variations present in other SC units relative to a specific Tba composition could partly be a function of this heterogeneity. However, an average Tba composition provides the best estimate for the volumetrically dominant mafic component and end-member involved in SC petrogenesis.

1. SC mafic volcanism is characterized by two distinct tholeiitic groups: a less voluminous, more primitive, and chemically homogenous group that resembles regional HAOT (Tb) and the volumetrically dominant, more evolved Tba (Steens Basalt). The chemical difference between these groups is evident on Figure 29a. Additionally, Tba has higher Sr_i and lower Nd_i as well as different Pb isotopic values (Fig. 27). These isotopic characteristics agree with petrographic and chemical evidence that SC mafic magmas interacted with more evolved and isotopically distinct reservoirs, including local Kg and silicic melts.
2. SC intermediate volcanism is characterized by at least four distinct units. Ta lava flows are the least evolved of these units and are dominantly tholeiitic, like Tad_2 and Tad_3. Tad_1 lava flows are more evolved than Ta and are the only dominantly calc-alkaline mafic to intermediate unit exposed in the SC. Relative to average Tba, these units all have similar major and trace element enrichments and depletions (Fig. 29b). Isotopic differences do exist between these units (Fig. 27); geochemical and isotopic variations support field, physical, and chronologic observations that suggest these intermediate units represent products from different magmatic systems.
3. Overall, SC silicic units are metaluminous to peraluminous and, unlike some other regional volcanic systems (e.g., some McDermitt, Lake Owyhee, and northwest Nevada), not peralkaline. Major element variations as well as variations in Ba, Sr, Ti, Eu, and other HFSE and REE help distinguish between SC silicic units and likely reflect specific petrogenetic processes. Within-unit chemical variations are present in most units and likely reflect heterogeneous differentiation processes. Figure 29 clearly illustrates some of these variations within and between units. Isotopic differences also exist between units; however most units (except Tpr, Tbr, and Tcst) define a field in Sr-Nd-Pb isotopic space that is also shared by SC intermediate units (Fig. 27). The isotopic differences that are exhibited by Tpr, Tbr, and Tcst enforce the spatial, physical, and chronologic data which distinguish these units from other SC silicic activity.

Implications of SC Physical and Petrologic Characteristics

The diverse physical and petrologic characteristics of SC units illustrate that a complex set of petrogenetic processes must have played a role in SC magma generation and evolution. Previous work directed toward understanding the petrogenesis of western SC units was performed by LeMasurier (1965, 1968) and Mellott (1987). LeMasurier (1965, 1968) invoked crystal fractionation from Tb-like basaltic parental magma to explain the chemical characteristics of Tarc, Tba, Ta, Tad_1, Thc, Tpr, and Tbr. However, his specific Tb-like parental magma was later demonstrated to be <10 Ma, thus unrelated to SC magmatism (Hart and others, 1984). Mellott (1987) provided the first isotopic evidence that processes other than crystal fractionation were required and called upon open-system magmatic processes to explain the isotopic heterogeneity. Additionally, Maloy and others (2004) demonstrated that assimilation-fractional crystallization (AFC) could be a viable mechanism to explain the chemical and isotopic characteristics of Tad_1. The physical, chemical, and isotopic data presented in this study from the entire SC support these previous interpretations and allow for additional details to be inferred.

Before discussing the petrogenesis of SC silicic and intermediate units, it must be restated that Tba appears to exhibit geochemical heterogeneity (Fig. 18a,b). Therefore, if differentiation from a more mafic liquid (Tba) is one of the important petrogenetic processes that acted in the SC to generate intermediate and silicic liquids, then a variety of potential mafic end-members likely were involved.

Generation and evolution of SC intermediate units - first order models

Four major intermediate composition units are present across the SC. Two of these are time-transgressive (Ta and Tad_1), erupting throughout the duration of SC volcanism. The other two, Tad_2 and Tad_3, likely represent two additional and separate magmatic systems that erupted at 15.8-Ma and 16.5 Ma, and are spatially associated with coeval silicic products (Table 1). All four units exhibit disequilibrium mineralogies and textures, though as previously mentioned, Tad_1 is dominated by these features at a microscopic scale. These disequilibrium mineralogies and textures include xenoliths of Kg in Tad_1 and Tad_3 and one observed xenolith of Trms in Tad_1.

Whole-rock major and trace element data provide evidence that crystal fractionation occurred during the formation of SC magmas, particularly within individual units. Although the overall pattern of the arrays present on Harker diagrams (Figs. 18, 22) are fairly linear, inflections are present within groups that likely reflect changes in the crystal fractionation process. For example, on plots of CaO, MgO, and Sc vs. SiO_2, there is an obvious inflection at 62 wt% within Tad_1 that likely reflects the role of increased clinopyroxene fractionation. Sr and Al_2O_3 also decrease with increasing SiO_2 for SC intermediate and mafic units, consistent with plagioclase fractionation. Also, the pronounced negative Eu, Sr, and Ba anomalies of many SC units, as illustrated on Figures 20, 23, and 29, are consistent with plagioclase and potassium feldspar fractionation. These patterns are best seen on Figure 29 where SC units are normalized relative to an average Tba. As silica content increases across the SC suite, the negative anomalies become more pronounced. However, the disequilibrium mineralogies and textures preserved in SC units and the overall trace element and isotopic diversity within and between units require a role for open-system processes. Figures 30 and 31 illustrate this for SC mafic and intermediate units. Figure 30 illustrates the variation of Zr with Ba and K_2O/MgO for SC mafic and intermediate units and also depicts a compositional field for locally exposed Kg. If closed-system crystal fractionation of a more mafic parental magma was the primary petrogenetic process from which SC intermediate units were derived, then HFSE (Zr) and LILE (K, Ba) concentrations should increase with increased fractionation as a continuation of the array defined by Tba (Fig. 30, labeled crystallization). However, the arrays exhibited by SC intermediate units differ considerably and exhibit substantial Ba and K_2O/MgO variations over a narrow range in Zr, which cannot easily be explained by crystal fractionation but can be explained by open-system processes (e.g., magma mixing and/or assimilation-fractional crystallization). It is also evident that some Tba samples lie off the mafic "crystallization array" and appear to lie along mixing lines with the intermediate units. This supports physical and isotopic evidence that at least some of the chemical variation present within Tba is a function of open-system processes. Furthermore, Tad_1 lava flows form an array that intersects the field of local granitoid, while Tad_2 and Tad_3 do not. This suggests that Tad_1 may have interacted with local Kg upper crust, which is validated by the occurrence of Kg xenoliths in Tad_1 (Fig. 7a). The chemical and isotopic variations illustrated on Figure 31 substantiate the relationships depicted on Figure 30a. Here, K/P and $^{87}Sr/^{86}Sr$ increase with increasing differentiation, consistent

with the addition of heterogeneous evolved crustal material or magma to crystallizing mafic melt (AFC). This covariance (including increasing SiO_2 with $^{87}Sr/^{86}Sr$) suggests that the "crystallization array" exhibited by SC mafic units on Figure 30 may actually represent fractional crystallization plus assimilation of local crust. Additionally, there is a positive relationship between the increased proportion of xenolithic and xenocrystic material in Tad_1 and elevated K/P and $^{87}Sr/^{86}Sr$. Moreover, Tad_1 is the only calc-alkaline composition intermediate unit in the SC. Similar LILE-enriched and HFSE-depleted calc-alkaline magmas were also generated in extensional settings north of the SC (e.g., in the Miocene Powder River volcanic field in northeastern Oregon), where their genesis has been attributed to decompression melting of lithospheric mantle that was enriched by earlier subduction (Hooper and others, 1995). Similar scenarios have been proposed for the generation of calc-alkaline magmas that erupted across the Basin and Range before the mid-Miocene (Gans and others, 1989; Leeman and Harry, 1993). Alternatively, the addition of Fe-poor material (local upper crust and/or silicic melts) can explain the lack of Fe enrichment in Tad_1. A similar explanation was proposed to explain the chemical characteristics of younger calc-alkaline intermediate lava flows that are associated with the Oregon-Idaho graben (Camp and others, 2003). The presence of granitoid xenoliths in Tad_1, together with the geochemical and isotopic information depicted in Figures 30 and 31, strongly suggest that crustal assimilation and/or interaction with more evolved material played a role in the genesis of this unit and likely contributed to its calc-alkaline nature. The increased K/P of Tad_1 relative to other intermediate units depicted on Figure 30 and arrays present on Figure 30 could, therefore, be a function of increased crustal interaction and bulk assimilation of Kg (± interaction with silicic melts). Granitoid xenoliths are also present in some Tad_3 lava flows, further illustrating that those SC units that erupted in close proximity to and/or through granitoid outcrops interacted with these bodies. However, this interaction may not have been sufficient to substantially change their bulk chemical signatures.

Another potential open-system process that could have acted during the generation of SC magmas is magma mixing. For example, the nearly vertical arrays exhibited by SC intermediate units (and to some extent Tba) on Figure 30 are also consistent with magma mixing. Two locations where mixing may have occurred are the Calico Mountains and in the Staunton Ridge/Eightmile Mountain region (Figs. 2, 6). In both of these locations, intermediate and silicic lava/ash flows form thick packages consisting of numerous individual flows and flow units that erupted nearly simultaneously (16.5 Ma in the Calico pile and 15.8 Ma in the Staunton Ridge/Eightmile region; Table 1). The physical characteristics of silicic units from both locations and their vent patterns also indicate that local extensional tectonism was occurring simultaneously (Brueseke and others, 2007b). Similar associations of intermediate and silicic outflow and coeval faulting are present along the margins of and on the eastern Snake River Plain in Idaho (Leeman, 1982; Honjo and Leeman, 1987; McCurry and others, 1999), and at the Duck Butte eruptive center in southeastern Oregon (Johnson and Grunder, 2000). Furthermore, the onset of SC mafic activity and a period of heightened mafic volcanism (e.g., Chocolate Mountain and related intrusive bodies/lava flows) temporally coincide with the formation and eruption of these two intermediate systems. While physical evidence indicates that some Calico lava flows interacted with local basement granitoid, Tad_3 and Tcm lava/ash flows typically define linear trends on Harker diagrams consistent with magma mixing (Figs. 18, 22). Similar trends and an overall lack of inflections that could reflect magma mixing are also present on Harker diagrams of Tad_2 and Tem (Figs. 18, 22).

To test whether binary mixing was a viable process in the evolution of SC eruptive units from these two locations, a simple least squares binary mixing model was applied toward two crystal-poor samples from both locations. Table 4 illustrates the results of these calculations. On the left side of the table, a Tcm ash flow (MB01-50) is modeled as a mix of 63.4% of a Tad_3 (MB01-47) lava flow and 36.6% of Tcm lava flow (MB00-32B). The lower part of Figure 32a and b illustrates the nearly identical elemental patterns of the calculated mix (thick solid line), relative to the observed characteristics (MB01-50) and parental liquids. Additionally, the modeled ash flow is extremely rheomorphic and has textural characteristics suggesting substantial open system behavior, including magma mixing/mingling (Fig. 7c). The right side of Table 4 shows the results of mixing a Tad_2 lava flow with the most evolved Tem to generate less silicic Tem. Elemental similarities between the calculated mixture and the observed composition are depicted in Figure 32a and b. The modeled Tem lava flow (and nearly all other Tad_2/Tem samples) lacks granitoid xenoliths and is characterized by less disequilibrium textures than other similarly evolved SC units. Like Tad_3/Tcm, Tad_2 and Tem lava flows appear to have erupted nearly coevally.

These simple calculations illustrate that magma mixing is a feasible open-system process that can explain the bulk chemistry of certain SC units.

To summarize, the combined physical, major, trace, and isotopic characteristics of SC intermediate units are clearly consistent with their derivation through open-system magmatic processes. In the intermediate systems that were active during the entire duration of SC volcanism (e.g., Tad_1 and likely Ta), fractional crystallization of less-evolved magmas (Tba) combined with assimilation of local crust, was likely the dominant magma differentiation process. The relationship of increasing SiO_2 with increasing Sr_i and decreasing Nd_i (Fig. 25) is also mirrored by increases in K/P, consistent with interaction with K_2O-rich material such as the local upper crust or melts thereof. In the case of Tad_1, continued and increased interaction with Fe-poor, calc-alkaline Kg may have been the primary contributor to its calc-alkaline composition.

In contrast, magma mixing likely played a much more important role in the evolution of those intermediate systems that were active for only a short duration (Tad_2 and Tad_3). The presence of Kg xenoliths in Tad_3 indicates upper crustal interaction; but the relative paucity of inclusions of Kg and Trms, the intimate field relationship with coeval silicic and mafic activity, the short duration of volcanism, and the nearly linear relationships on elemental plots for both magmatic systems, suggest a greater role for magma mixing in their genesis. Furthermore, the silicic eruptive products that Tad_2 and Tad_3 lava flows are either interbedded with or directly underlie (e.g., Tcm and Tem, respectively) appear to have erupted primarily from fissures or fissure-related sources. This highlights and documents another example of the important role of contemporaneous faulting as a catalyst for magma mixing processes (Johnson and Grunder, 2000).

Generation of SC silicic magmas – first order models

Silicic units in the SC are the products of diverse physical processes and multiple eruptive loci (Brueseke and others, 2007b). Possible explanations for the generation of SC silicic magmas include prolonged fractionation of a more mafic parent coupled with crustal assimilation or mixing of more evolved material, anatectic melting of local crust, or mixing between chemically and isotopically heterogeneous mantle and crustal melts (Mellott, 1987). All of these processes may have occurred to some degree; however, the physical, chemical, and isotopic data reported in this study shed light on whether one or more of these potential processes dominated the generation and evolution of SC silicic magmas.

Recent work on silicic melt generation has illustrated the role that dehydration melting of local crust plays in the generation of silicic melts. Essentially, fluid-absent incongruent melting of hydrous mineral phases forms melt and residual minerals according to studies by Beard and Lofgren (1991), Rapp and others (1991), Wolf and Wyllie (1994), Patiño Douce (1995), Patiño Douce and Beard (1995), Skjerlie and Johnston (1996), McCarthy and Patiño Douce (1997), Patiño Douce (1999), and Petcovic and Grunder (2003). In the studies by Beard and Lofgren (1991), Rapp and others (1991), Wolf and Wyllie (1994), Patiño Douce (1995), Patiño Douce and Beard (1995), Skjerlie and Johnston (1996), McCarthy and Patiño Douce (1997), and Patiño Douce (1999), dehydration melting of amphibole or mica-rich protoliths (that might occur at mid to lower crustal pressures; >10 kbar) produces typically rhyolitic melts and restite dominated by feldspar (plagioclase or potassium feldspar) ± clinopyroxene ± orthopyroxene ± oxide ± quartz ± garnet mineral assemblages. Petcovic and Grunder (2003) studied the in-situ relationship between shallow crustal melt generation (<1 kbar; 2 to 2.5 km depth) induced by the emplacement of Columbia River Basalt Group (CRBG) dikes into biotite-hornblende granitoid rocks in the Wallowa Mountains. In the Wallowa Mountains, partially quenched mafic CRBG dikes that are compositionally similar to Tba have melted parts of the granitoid wallrock and generated melt within a restite composed of plagioclase + pyroxene + magnetite (Petcovic and Grunder, 2003). This scenario of mafic magma intruding granitoid upper crust is likely very similar to what occurred in the SC when upwelling Tba magma came in contact with Kg. The Wallowa Mountains melt compositions range from metaluminous to peraluminous and are K-rich (Petcovic and Grunder, 2003). Additionally, the observations of Petcovic and Grunder (2003) indicate that as the degree of melting increased, the resulting melts became less evolved and less K-rich (Petcovic and Grunder, 2003). Furthermore, Petcovic and Grunder (2003) noted that these melt compositions resemble regional silicic volcanic units. The high-silica, low-degree melts resemble high-silica rhyolite domes and ash flows exposed across central Oregon (Fig. 1a, the Oregon High Lava Plains), while the low-silica melts produced by higher degrees of melting resemble the metaluminous rhyodacitic lava flows exposed at the 10.4-Ma Duck Butte, OR eruptive center that were interpreted as crustal melts by Johnson and Grunder (2000). Petcovic and Grunder (2003) suggested that in the Wallowa Mountains, melt production only occurred at specific loci where mafic intrusion was long-

lived and sustained. As a result, the results of Petcovic and Grunder (2003) have important implications for the generation of SC silicic magmas and also illustrate that if silicic melts were produced in the SC through similar processes, granitoid upper crust and long-lived voluminous mafic magmatism were necessary local components. Partial melting of upper crustal granitoid to generate SC silicic magmas also implies that mafic upwelling was occurring throughout the periods that these silicic units were erupting. Furthermore, it suggests that a large volume of mafic magma must have been emplaced at shallow crustal levels beneath the SC to sustain silicic melt generation. Local evidence for shallow emplacement is present (e.g., the numerous Tba plugs in the vicinity of Hinkey Summit; Fig. 4g,h), and regional studies of Steens and Columbia River Basalt Group lava flows indicate that they resided in upper crustal magma chambers before eruption (Johnson and others, 1996; Durand and Sen, 2004). In this scenario, voluminous local mafic volcanism would likely have been inhibited by the presence of less dense, intermediate and silicic melts in the subsurface. Similar scenarios are present in other volcanic fields dominated by silicic products (e.g., Yellowstone; Christiansen, 2001).

The most SC peraluminous units are exposed in the western SC (Tbr and Tpr), while those present in the eastern SC (e.g., Tom, Tcm, and Tct) are dominantly metaluminous (Fig. 13c). The Sr and Nd isotopic compositions of most SC silicic units are similar to Santa Rosa-Andorno group Kg (all but Tpr, Tbr, and Tcst) and Granite Peak-Sawtooth group Kg (Tcst) (Fig. 28). Also, Sr and Nd isotopic characteristics of Tbr and Nd characteristics of Tpr are similar to Granite Peak-Sawtooth group Kg as well as the Kg aplite dikes (Figs. 24, 27). Although the Pb isotopic composition of Kg is poorly constrained, it appears that the Pb isotopic composition of Santa Rosa-Andorno group Kg resembles those SC silicic units that also have similar Sr and Nd isotopic compositions (discussed earlier in section on SC isotopic characteristics; Wooden and others, 1999).

Eastern SC silicic units erupted at 16.5 to 16.4 Ma, essentially coeval with the onset and most voluminous period of local and regional mafic flood basalt volcanism. In the western SC, Tem, Twsc, and Thc are physically and chemically distinct from Tpr and Tbr, and all erupted in close temporal association with a period of enhanced mafic activity. The least-evolved compositions within these units are all high-K and metaluminous, and with the exception of Tom, they are dacitic to rhyodacitic and compositionally similar to the Wallowa Mountains melts studied by Petcovic and Grunder (2003); these melts resulted from higher degrees of melting of Kg-like granitoid by CRBG magmas. Figure 33 depicts major element characteristics of SC silicic units and two (18 and 47 volume % melt) of the melt compositions studied by Petcovic and Grunder (2003). Evident in these diagrams is their general similarity. These similarities coupled with the nearly identical isotopic characteristics of these SC silicic units and locally exposed Santa Rosa-Andorno group Kg, suggest that crustal anatexis of Santa Rosa-Andorno group Kg was likely the primary magma generation process for these silicic units (i.e. Tcm, Tom, Tct, Thc, Twsc, and Tem).

The more evolved character of Tom may simply be a function of smaller degrees of partial melting of the same Santa Rosa-Andorno group or aplitic Kg sources. In this scenario, within-unit chemical and minor isotopic variations reflect heterogeneous magmatic processes (e.g., assimilation upon ascent and eruption and/or magma mixing/mingling) affecting individual magmatic systems, or in the case of eastern SC activity, parts of a larger system (Brueseke and others, 2007b). A similar process may have generated Tcst, Tpr and Tbr magmas, with different protolith(s). Initial Tcst volcanism occurred at 15.8 Ma, soon after the heightened period of local mafic activity that is associated with Chocolate Mountain. Tcst is also isotopically similar to Granite Peak-Sawtooth group Kg. Combined, these data suggest that the generation of Tcst magmas by crustal anatexis of Granite Peak-Sawtooth group Kg is plausible. Similar processes may have led to the generation of Tpr and Tbr magmas. Their identical Pb - Nd isotopic characteristics differentiate them from all other SC silicic units (Figs. 26, 27). If Tbr and Tpr were generated through crustal anatexis, then possible isotopically distinct protoliths could include local Trms or Kg aplitic bodies.

To summarize, the bulk chemical compositions and isotopic characteristics of SC silicic units are consistent with their derivation through partial melting of local granitoid upper crust by upwelling mafic magma, likely followed by subsequent crystal fractionation and interaction with less evolved crust and liquids. As a first-order test of this hypothesis, a simple batch melting calculation was performed using the melt volumes (Stage 3, 18% and Stage 5, 47%) and restite assemblages reported by Petcovic and Grunder (2003) as proxies for the percent melting and restite assemblage produced during the melting of locally exposed Kg. These values are used because they reflect the percent melting that generated the quenched liquids studied by Petcovic and Grunder (2003) that are compositionally similar to SC silicic units (Fig. 33). Seven Kg bulk rock compositions

were selected to reflect the compositional diversity of Kg for use in these calculations. Appropriate distribution coefficients were selected from the Geochemical Earth Reference Model (GERM) Kd database (http://earthref.org/GERM/index.html) when possible. Distribution coefficients were estimated based on similar elemental behavior for those elements that lacked distribution coefficient values in the GERM Kd database. The distribution coefficients and parental compositions used in the batch melting calculations are displayed in Appendix 3**.** Figure 34 illustrates the variation in Zr, Ba, and K_2O/MgO of the calculated melts, SC silicic units, and also depicts fields for the Kg samples used in the batch melting calculations. Zr, Ba, and K_2O/MgO values are depicted because the relationships between calculated melts, their Kg "parents", SC silicic units, and the arrays exhibited by SC mafic and silicic units that suggest open-system behavior (Fig. 30) are readily observed by variations in these elements.

Figure 34 illustrates that melting of Kg can produce liquids with elemental characteristics that overlap with those of certain SC silicic units. Different distribution coefficients and changes in the percent melting could explain some of the variability between calculated melts and SC silicic units. Additionally, post-melt crystal fractionation and assimilation/mixing with local crust and SC mafic and intermediate magmas could also account for some of this variability and the depicted arrays. Figure 35 uses the same information shown on Figure 34 in order to provide a qualitative summary of the fundamental petrogenetic processes affecting SC units: [1] differentiation of Tba accompanied by melting of granitoid upper crust (increasing Zr, Ba, and K_2O/MgO), [2] interaction of differentiated mafic magma with Kg and silicic melts of Kg giving rise to the intermediate units, and [3] fractional crystallization of silicic melts (decreasing Ba, Zr, and increasing K_2O/MgO). The arrows on the diagrams are only depicted to illustrate how specific processes (melting of Kg to generate SC silicic magmas; fractional crystallization of SC mafic magmas; mixing/assimilation of mafic magmas with Kg and/or SC silicic magmas; fractional crystallization of SC silicic magmas) can account for the observed variations in Zr, Ba, and K_2O/MgO. Their positions do not imply any specific evolutionary path. For example, fractional crystallization of zircon and feldspar would decrease the Zr and Ba concentrations in the silicic magmas and move the melt composition along a path in a similar direction as the arrow in Figure 35d. While most SC units do not have pronounced negative Zr anomalies on multi-element plots (Fig. 23), zircon is observed as a trace phase in most units which suggests that this process occurred.

The voluminous eruptions of Steens magmas across the Oregon Plateau and the volumetric dominance of local Steens volcanism (Tba) suggest that upwelling Steens magmas, not upwelling HAOT-like magmas (Tb) induced local crustal melting and subsequent silicic melt generation. The detailed work of Petcovic and Grunder (2003) provides an outstanding example of how dehydration melting of biotite- and hornblende-bearing granitoid can produce silicic melts that are compositionally similar to those that erupted across the SC. Their work, combined with results from this study, also helps to illustrate that similar upper-crustal melting processes were likely occurring across the Oregon Plateau during the mid-Miocene flood basalt event in locations where upwelling Steens-Columbia River Basalt Group magmas came in contact with the upper crustal Mesozoic granitoid bodies. Similar processes likely occurred in the Owyhee Mountains where Steens Basalt eruptive loci and lava flows crop out in close proximity to coeval intermediate-silicic eruptive loci and lava flows, as well as Mesozoic granitoid (Panze, 1975; Halsor and others, 1988; Cupp, 1989). Because the petrologic results discussed above are first-order observations, more detailed work could further test these hypotheses and also better determine the role and extent that melting of crust other than local granitoid (e.g., upper crustal metasedimentary rocks and lower crustal assemblages) played a role in the generation of SC silicic magmas, if at all.

Presence of crystal clots – the smoking gun for open system behavior

Microscopic xenoliths and crystal clots are ubiquitous in most SC intermediate and silicic units (Fig. 7). Some of the larger and coarser-grained inclusions texturally resemble resorbed and partially melted Kg (Fig. 7a,b,c), while others are identical to Tba and Ta (Fig.7c). A third type is composed primarily of intergrown feldspar ± pyroxene ± Fe-Ti oxide crystals that form crystal clots. Additionally, plagioclase phenocrysts in most intermediate and silicic units are typically resorbed and often much more sodic than groundmass plagioclase in the host, suggesting that these sodic plagioclase crystal are xenocrysts associated with the same original material as the associated crystal clots. As previously mentioned, plagioclase feldspar ± orthopyroxene ± clinopyroxene ± oxide restites were the products of the reactions studied by Petcovic and Grunder (2003). Similar restitic material has also been identified in other natural and experimental

studies of melt generation (Beard and Lofgren, 1991; Rapp and others, 1991; Wolf and Wyllie, 1994; Patiño Douce and Beard, 1995; Knesel and Davidson, 1996; Skjerlie and Johnston, 1996). In most of these other studies, quartz, alkali feldspar, and at higher pressures, garnet are also part of the restite assemblage. However, none of these minerals has been observed in SC clots.

Inclusions and xenoliths that are texturally similar to the Tba/Ta-like mafic xenoliths and feldspar ± pyroxene ± Fe-Ti oxide clots found in SC units are commonly reported in studies of silicic and intermediate volcanic systems and typically fall into two categories: [1] inclusions of less evolved magma (in some cases partially to fully disaggregated) entrained into a more silicic host before ascent and eruption (Bacon and Metz, 1984; Bacon, 1986; Clynne, 1989, 1999; Stimac and others, 1990; Tepley and others, 1999; Johnson and Grunder, 2000) and [2] inclusions of crust that were assimilated and partially disaggregated into the host magma (Grove and others, 1988; Green, 1994; Dungan and Davidson, 2004; Dungan, 2005; Beard and others, 2005). In the latter, inclusions vary from much older granitoid country rock (Grove and others, 1988; Beard and others, 2005) to subvolcanic intrusions related to earlier phases of volcanism at the same volcanic center (Dungan and Davidson, 2004; Dungan, 2005).

Tepley and others (1999) studied the Chaos Crags silicic lava domes of the Lassen volcanic center to better understand the genesis of basaltic andesite inclusions that are present within the silicic outflow. They proposed a model that explains the origin of these inclusions as resulting from basaltic magma intruding into a rhyodacitic magma chamber. Subsequently, hybrid basaltic andesite inclusions formed along the basalt-rhyodacite boundary due to the entrainment of rhyodacitic magma into the basaltic magma and subsequent mingling (Tepley and others, 1999). The phenocryst assemblages of these inclusions are a mixture of crystals that originally formed in the mafic and silicic magmas (Tepley and others, 1999). Based on the Sr crystal isotope stratigraphy of plagioclase crystals in all three materials, Tepley and others (1999) demonstrated that disaggregation of the intermediate inclusions physically recycled the plagioclase crystals that originally formed in the silicic magma, back into the silicic magma. Similar processes of crystal formation, entrainment in a different magma, and subsequent liberation/disaggregation into the new (or old) host have been observed in Oligocene silicic ash flows from the Ethiopian Plateau (Barbey and others, 2005). The experimental studies of Huppert and Sparks (1988) also demonstrate that a similar process can occur during the partial melting of granitoid country rock by an intruding mafic sill. A zone of silicic partial melt forms between the sill and the country rock and continues to grow with more mafic magma emplacement (Huppert and Sparks, 1988). As this silicic body grows at the expense of the granitoid basement, refractory phenocrysts from the granitoid are entrained, partially to fully melted, and in some cases, reprecipitated in the silicic host (Huppert and Sparks, 1988). The end result of this process is the coexistence of granitoid restite mineralogies and igneous phenocrysts in the source region of an evolving silicic magma and the availability of these materials for incorporation into that magma before ascent and eruption (Huppert and Sparks, 1988).

Generation of the feldspar ± pyroxene ± Fe-Ti oxide crystal clots observed in SC silicic products could result from: [1] crystal growth in an evolving silicic magma body followed by subsequent mixing with a different magma, [2] restite generation through biotite ± amphibole dehydration of local granitoid crust followed by assimilation, disaggregation, and melting/recrystallization in an evolved liquid, and [3] assimilation of the plutonic roots of locally erupted Tarc lava flows. Detailed study of these crystal clots and their relationship with SC units and local crust should provide conclusive evidence for the specific type(s) of open-system process(s) that acted upon individual SC magmatic systems. However, their presence illustrates that SC eruptive units are the physical record of a complex magmatic history.

The physical, chemical, and isotopic data from this study provide first-order constraints on the petrogenesis of a complexly developed volcanic field and indicate that a combination of magmatic processes led to the generation of the SC magmas including:

1. Generation and ascent (± eruption) of mafic magma. This event is interpreted to be the consequence of regional, Steens-Columbia River flood basalt volcanism and lithospheric magma influx.
2. Anatectic melting of granitoid upper crust. Ascent of Tb and Tba magmas into the upper crust initiated melting processes similar to those observed elsewhere in the region (e.g., the Wallowa Mountains; Petcovic and Grunder, 2003). This process led to the generation of silicic liquids that were able to erupt, interact with crust and less evolved melts, and undergo further differentiation.

3. Interaction of Tba with more evolved crustal melts and local upper crust. This interaction, dominated by magma mixing (Tad_2 and Tad_3) and assimilation-fractional crystallization (Tad_1), led to the generation of the temporally, spatially, and compositionally distinct intermediate volcanic units that crop out across the SC.

The timing of SC volcanism and spatial distribution of known and inferred eruptive loci suggests an intimate relationship existed between melt production and coeval extensional tectonism. Extension would have stimulated magma-mixing processes and facilitated ascent and eruption of SC magmas.

SUMMARY AND CONCLUSIONS

At ~16.7 Ma, widespread and voluminous mafic volcanism and mafic magma lithospheric input commenced across the Pacific Northwest (U.S.A.) (Brueseke and others, 2007a). The most apparent manifestation of this event is the voluminous flood basalt lava flow packages that are found across the region. A less obvious manifestation, but just as geologically significant was the widespread silicic magmatism that accompanied this regional mafic activity. This study was undertaken with the goal of better understanding this dominantly bimodal association and how the silicic-dominated mid-Miocene Oregon Plateau volcanic fields formed as a result of their unique association with the emergence of the Yellowstone-Newberry melt anomaly (Hotspot) and coeval lithospheric rifting. Accordingly, it provides the first comprehensive view into the development of a mid-Miocene Oregon Plateau volcanic field and its relationship with regional flood basalt volcanism. It is also the most detailed and complete examination of a volcanic field associated with the Yellowstone-Newberry melt anomaly, besides the Yellowstone volcanic field.

By unraveling the complex volcanic history of the Santa Rosa-Calico volcanic field (SC), this study demonstrates that continued mafic magma input into the lithosphere was necessary to drive Oregon Plateau silicic-dominated volcanism. The igneous products exposed in the SC record a complex set of magmatic processes and the spatial distribution of vents and styles of volcanism illustrate an intimate relationship with coeval extension. Figure 36 is a diagrammatic cross section illustrating how magma generation and eruptive processes may have occurred across the SC in the subsurface. As evident in this diagram and in Figures 15 and 16, magma production and volcanism in the SC varied through space and time and appears to have been most voluminous during the initial development of the volcanic field. Over the next ~2 Ma, voluminous lithospheric mafic magma input appears to have waned and was accompanied by less intermediate and silicic activity. At 14 Ma, SC volcanism ceased while silicic eruptive products continued to erupt from regional eruptive centers, including those intermittently exposed on the Owyhee Plateau. At 11–10 Ma, basin-and-range style block-faulting initiated, which combined with post-SC erosive processes, led to the landscape present today.

SC mafic lava flows and shallow intrusive bodies form two broad chemical groups: a more primitive type that is chemically similar to the dominant basaltic magma erupted across the Oregon Plateau during the last <11-Ma (low-K, high-alumina olivine tholeiite, HAOT) and locally erupted Steens Basalt. HAOT-like lava flows only erupted at the onset of SC volcanism; however, Steens Basalt eruptive loci are as young as 14.4 Ma.

Silicic volcanism was diverse and characterized by multiple, often temporally and spatially unrelated magmatic systems. It was also characterized by effusively erupted lava flows that were sourced from domes and fissures, explosively erupted ash flows that were sourced from fissures and a caldera, and numerous tephra horizons exposed within sedimentary deposits and between SC lava/ash flows that likely represent both proximal and distal eruptive events. Unlike other mid-Miocene Oregon Plateau volcanic fields, the SC silicic record was not dominated by caldera-forming events. Physical, chemical, and isotopic characteristics suggest that most of these silicic magmas were generated through crustal melting (primarily of local Cretaceous granitoid), interacted with less evolved magmas, and at least in the eastern SC, were the products of a larger, possibly batholith-sized magmatic system.

An abundance of locally erupted intermediate products also distinguish the SC from other coeval, regional volcanic fields (e.g., McDermitt). These intermediate lava flows record the presence of at least four chemically and spatially distinct eruptive systems. Major element and isotopic data also indicate that these magmatic systems were characterized by complex open-system processes including magma mixing (Calico Mountains and Staunton Ridge region) and assimilation-fractional crystallization (Hinkey-Coal Pit Peak). Accordingly, the presence of these intermediate products

provides an opportunity to further study the generation of intermediate magmas and ultimately, how they can be related to more mafic and/or more silicic magma.

The styles of volcanism and compositional spectrum of products that characterize the SC provide outstanding examples of the diversity that can be present within intracontinental volcanic fields. As a result, the SC provides an outstanding opportunity to study the generation of intermediate and silicic magmas in a continental setting, as well as the interaction between multiple magma and crustal types. The magmatic and tectonic processes that occurred in the SC provide the most detailed glimpse of the magmatic and tectonic interactions that occurred during the initial development of the Snake River Plain and High Lava Plains volcanic provinces and shed light on how a portion of the North American lithosphere was modified during this event. Furthermore, this study provides a model for the development of physically and compositionally similar volcanic systems and also provides a comprehensive framework that will help future workers better understand the relationship between regional precious metal mineralization and volcanism. In summary, the diverse magmatic products and styles of volcanism that define the SC are interpreted to result from the interplay between regional flood basalt volcanism, focused mid-Miocene extension, and diverse lithospheric processes and assemblages. Accordingly, this study provides a direct link between regional lithospheric extension, Steens-Columbia River flood basalt volcanism, and the development of the coeval Oregon Plateau volcanic fields and silicic-eruptive loci that are found across the Oregon-Idaho-Nevada tristate region. Moreover, the Santa Rosa-Calico volcanic field provides an important window into the magmatic processes that can occur during voluminous mantle upwelling and continental lithospheric extension.

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