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RESEARCH ARTICLE

Diverse mid-Miocene silicic volcanism associated with the Yellowstone–Newberry thermal anomaly

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Abstract The Santa Rosa–Calico volcanic field (SC) of northern Nevada is a complex, multi-vent mid-Miocene eruptive complex that formed in response to regional lithospheric extension and flood basalt volcanism. Santa Rosa–Calico volcanism initiated at ~16.7 Ma, concurrent with regional Steens–Columbia River flood basalt activity and is characterized by a complete compositional spectrum of basalt through high-silica rhyolite. To better understand the relationships between upwelling mafic magmatism, coeval extension, and magmatic system development on the Oregon Plateau we have conducted the first comprehensive study of Santa Rosa–Calico silicic volcanism. Detailed stratigraphic-based field sampling and mapping illustrate that silicic activity in this volcanic field was primarily focused along its eastern and western margins. At least five texturally distinct silicic units are found in the western Santa Rosa–Calico volcanic field, including abundant lava flows, near vent deposits, and shallow intrusive bodies. Similar physical features are found in the eastern portion of the volcanic field where four physically distinct units are present. The western and eastern Santa Rosa–Calico units are characterized by abundant macro- and microscopic disequilibrium textures, reflecting a complex petrogenetic history. Additionally, unlike other mid-Miocene Oregon Plateau volcanic fields (e.g. McDermitt), the Santa Rosa–Calico volcanic field is characterized by a paucity of caldera-forming volcanism. Only the Cold Springs tuff, which crops out across the central portion of the volcanic field, was caldera-derived. Major and trace element geochemical variations are present within and between eastern and western Santa Rosa–Calico silicic units and these chemical differences, coupled with the observed disequilibrium textures, illustrate the action of open-system petrogenetic processes and melt derivation from heterogeneous source materials. The processes and styles of Santa Rosa–Calico silicic magmatism are linked to three primary factors, local focusing of and thermal and material contributions from the regional flood basalt event, lithospheric extension within the northern portion of the Northern Nevada rift, and interaction of mid-Miocene silicic magmas with pre-Santa Rosa–Calico lithosphere. Similar processes and styles of mid-Miocene silicic volcanism likely occurred across the Oregon Plateau in regions characterized by both focused lithospheric extension and localized mafic magmatism.

Keywords Miocene · Oregon plateau · Owyhee–Humboldt · Santa Rosa–Calico · Silicic · Steens basalt · Yellowstone

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Introduction

Nowhere is volcanism associated with the Yellowstone–Newberry mantle upwelling more diverse than in the Oregon–Idaho–Nevada tri-state region, the southeastern Oregon Plateau. Continuous mafic volcanism from ~16.7 Ma to the present as well as the only silicic volcanism associated with the initial manifestation of the upwelling is found across this region. Recent studies dealing with mid-Miocene northwestern United States volcanism have focused on the Steens and Columbia River flood basalts, their relationship to younger regional Cenozoic volcanism, and its relationship to mid-Miocene mineralization and rift-development (Fig. 1a; Zoback et al. 1994; Wallace and John 1998; Cummings et al. 2000; John and Wallace 2000; John et al. 2000; John 2001; Camp et al. 2003; Wallace 2003; Camp and Ross 2004; Jordan et al. 2004). While these studies have focused attention on regional mafic volcanism and silicic volcanism peripheral to the loci of mid-Miocene activity (the Oregon Plateau), the details of mid-Miocene Oregon Plateau silicic activity remain poorly understood. The most comprehensive information comes from the McDermitt volcanic field, also often cited as the “ground zero” of the Yellowstone–Snake River plain volcanic system (Pierce and Morgan 1992). However, numerous other large and small, dominantly silicic mid-Miocene volcanic systems are present across the Oregon Plateau (Fig. 1b), including the Santa Rosa–Calico volcanic field (SC) of northern Nevada. The SC lies at the junction of the Northern Nevada rift and Owyhee Plateau (Fig. 1b), an ideal location to further investigate the relationships between mid-Miocene flood basalt volcanism, magmatic system development, and tectonism. In this paper, we present a portion of the results of the first comprehensive field, chronostratigraphic, geochemical, and petrologic study of the SC, focusing on the silicic components (>64 wt% SiO_2). This contribution will (1) distinguish the SC from contemporaneous Oregon Plateau volcanic systems (e.g. McDermitt, Owyhee–Humboldt), (2) formally define the SC as a locus of mid-Miocene volcanism and potential source for regionally exposed tephra, (3) detail the spatial, temporal, physical, and bulk chemical characteristics of the silicic magmatic products, and (4) provide first-order constraints on the petroge-

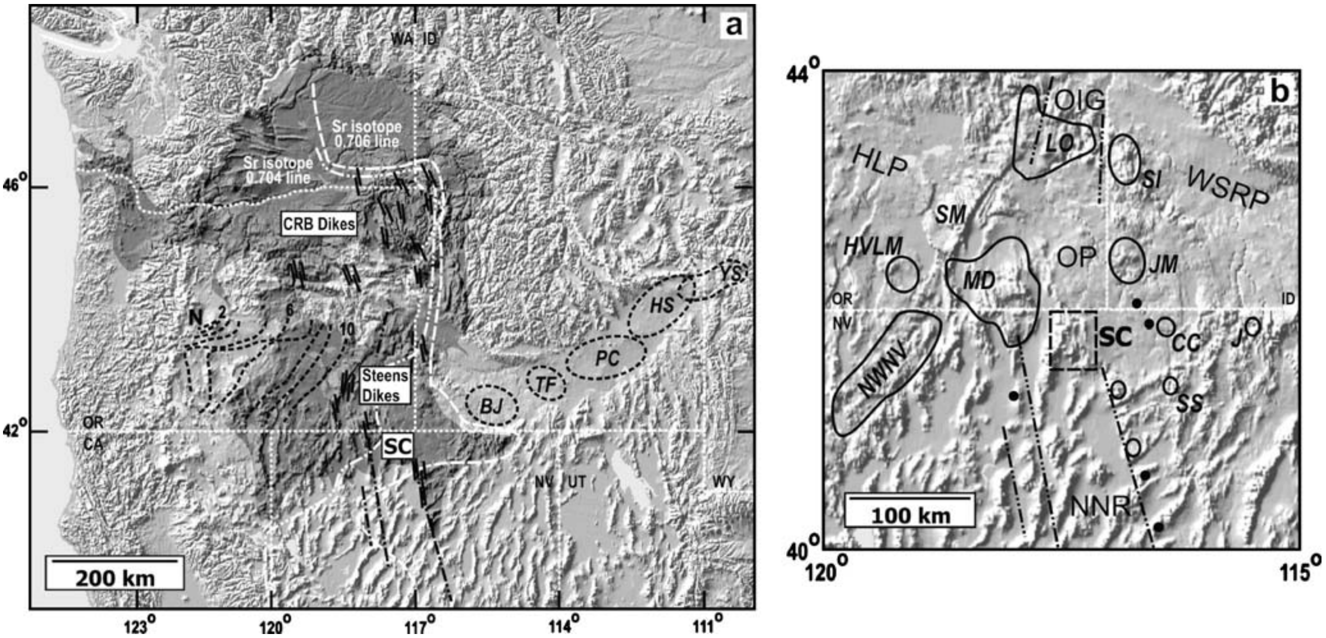


Fig. 1 **a** Map of the northwestern USA depicting select Cenozoic tectonomagmatic features. *Shaded region* is the approximate extent of mid-Miocene flood basalt volcanism (after Hart and Carlson 1985; Camp and Ross 2004). Also shown are major flood basalt dike swarms/eruptive loci (*black lines*), Oregon–Idaho graben and magnetic anomalies in Nevada corresponding to zones of lithospheric extension/mafic magma emplacement (*black dotted-dashed lines*; Cummings et al. 2000; Glen and Ponce 2002), major volcanic fields of the Yellowstone–Snake River plain province (*dashed circles*); BJ, Bruneau–Jarbidge (~12.5–<11 Ma); TF, Twin Falls (~10–8.6 Ma); PC, Picabo (~10 Ma); HS, Heise (~6.7–4.3 Ma); and YS, Yellowstone (<2.5 Ma), and age isochrons (*dashed black lines*, ages in Ma) of Oregon High Lava Plains silicic volcanism (*N* Newberry Volcano; after Jordan et al. 2004). The *SC* lies between the initial $^{87}Sr/^{86}Sr$ 0.706 and 0.704 isopleths (after Armstrong et al. 1977; Kistler and Peterman 1978; Leeman et al. 1992; Crafford and Grauch 2002). **b** Shaded relief map of the southern Oregon Plateau illustrating the locations of major mid-Miocene silicic volcanic systems. *SC* Santa Rosa–Calico volcanic field, *MD* McDermitt volcanic field, *LO* Lake Owyhee volcanic field, *NWNV* Northwest Nevada volcanic field (e.g. Virgin Valley, High Rock, Hog Ranch, and unnamed calderas), *HVLM* Hawks Valley–Lone Mountain dome complex, *SI* Silver City–DeLamar dome complex, *JM* Juniper Mountain volcanic center, *CC* Circle Creek volcanic center, *J* Jarbidge Rhyolite loci, *SS* Snowstorm Mountains dome complex. Unnamed *black circles* are other rhyolite dome complexes/eruptive loci/shallow intrusive bodies. *HLP* High Lava Plains, *SM* Steens Mountain, *OIG* Oregon–Idaho graben, *WSRP* western Snake River Plain, *OP* Owyhee Plateau, *NNR* Northern Nevada rift and related lineaments. Mid-Miocene extensional features from **a** are also depicted

netic processes active within the SC. Isotopic studies now underway will allow for a more detailed petrogenetic treatment and will be presented elsewhere in the context of the entire suite of SC magmatic products.

Field sampling and mapping, major and trace element geochemical data, and ^{40}Ar/^{39}Ar radiometric dating provide a comprehensive examination of the physical, chemical, and temporal diversity of SC silicic units. A detailed discussion of the specific techniques employed and the chronologic results are presented as Appendix 1 in Electronic supplementary material. Supplemental figures and a table of representative major and trace element geochemical data that are discussed in the text are found as Appendix 2 in Electronic supplementary material.

The Santa Rosa–Calico volcanic field: regional overview and geologic setting

At ~16.7 Ma, the Steens flood basalt started erupting across the Oregon Plateau. This unit is best known at its Steens Mountain type section where ~1 km of ~16.6 Ma lava flows crop out; however, other regionally exposed Steens basalt eruptive loci and flows are found across the Oregon Plateau (Hart and Carlson 1985; Carlson and Hart 1987; Camp et al. 2003; Brueseke et al. 2007). The geologic, chemical, and chronologic evidence found in the Oregon Plateau flood basalt record suggest that Steens Basalt lava flows erupted for at least ~2 Ma, coeval with the development and inception of regional silicic activity (Brueseke and Hart 2004; Brueseke et al. 2007). Regional flood basalt activity ceased at ~14 Ma, following which, small volume monogenetic basaltic eruptions have occurred to the present across the region (Hart 1985; Jordan et al. 2004; Shoemaker 2004).

Silicic activity ceased in the Idaho–Oregon–Nevada border region at ~14 to 12 Ma and progressed toward the northeast and northwest, forming the Yellowstone and Newberry trends of caldera/dome development (Walker 1969, 1974; MacLeod et al. 1975; Pierce and Morgan 1992; Christiansen et al. 2002; Jordan et al. 2004). Initial ~16.7 to 14 Ma Oregon Plateau silicic volcanism was diffuse across the entire region and consisted largely of voluminous ash flow eruptions from large, nested caldera complexes. The best known of these is the McDermitt volcanic field, however; the Northwest Nevada and Lake Owyhee volcanic fields were also active during this period (Noble et al. 1970; Greene and Plouff 1981; Rytuba and McKee 1984; Ach and Swisher 1990; Rytuba et al. 1991; Bussey 1995; Castor and Henry 2000). These mid-Miocene systems were characterized by multiple eruptions of extensive ash-flow sheets and subsequent rhyolite dome formation (Fig. 1b). Less well documented are the abundant rhyolite dome complexes that also formed during the mid-Miocene (Fig. 1b). Regionally, the eruptive products of these mid-Miocene systems are best represented in the tephra fall record and numerous studies have been performed to better characterize these deposits (Perkins et al. 1998; Perkins and Nash 2002).

General geology

The Santa Rosa–Calico volcanic field is located in north-central Humboldt County, Nevada, overlapping with the northern portion of the Santa Rosa mountain range, which forms its western boundary (Fig. 2a). The eastern SC boundary is defined by the Calico Mountains and the southern SC boundary is defined by the basin bounding normal fault at the northern end of Paradise Valley; the northern boundary is less well defined physically (Fig. 2a, b). The northern Santa Rosa Range and the Calico Mountains help delineate the central SC, an oval topographic depression (the Goosey Lake depression), which is divided into two distinct sub-basins. Most of the SC lies within the Humboldt–Toiyabe National Forest and topography in the SC is rugged. Pleistocene glaciation and syn- and post-SC faulting provide excellent exposures, and numerous unimproved roads allow reasonable access to most portions of the SC. Prior work includes mapping±petrologic/geochemical studies of the metamorphic and granitoid core of the Santa Rosa Range (e.g., Compton 1960; Shieh and Taylor 1969; Stuck 1993), reconnaissance stratigraphic, chronologic, and petrologic/geochemical studies of volcanism along the margins of the Santa Rosa Range (e.g., LeMasurier 1965, 1968; Larson et al. 1971; Hart and Carlson 1985; Carlson and Hart 1987; Mellott 1987), mapping and geochemical studies of volcanic formations and volcanic-hosted epithermal mineral deposits in the Buckskin—National region of the northern SC (e.g., Winchell 1912; Lindgren 1915; Roberts 1940; Willden 1964; Vikre 1985a, b), and mapping and remote sensing studies of regional fault and vent patterns (e.g., King 1984; McCormack 1996).

A package of Triassic metasedimentary rocks and a suite of Cretaceous granitoid plutonic bodies are exposed throughout both the main Santa Rosa Range and its southern extension, the Bloody Run Hills (Compton 1960; Stuck 1993; Wyld et al. 2001; Wyld et al. 2003). Within the granitoid suite, two isotopically and chemically distinct intrusive events are recognized; the ~102 Ma Santa Rosa–Andorno group and the ~85 Ma Granite Peak–Sawtooth group (Stuck 1993). Santa Rosa–Andorno group granitoid is also exposed along the basin bounding fault at the southern SC margin, as well as along the eastern base of the Calico Mountains. The Santa Rosa Range is being affected by Recent Basin and Range block faulting along its western and southern margins, causing exposed SC units to dip east and north toward the Goosey Lake Depression at ~10–15°. This style of deforma-

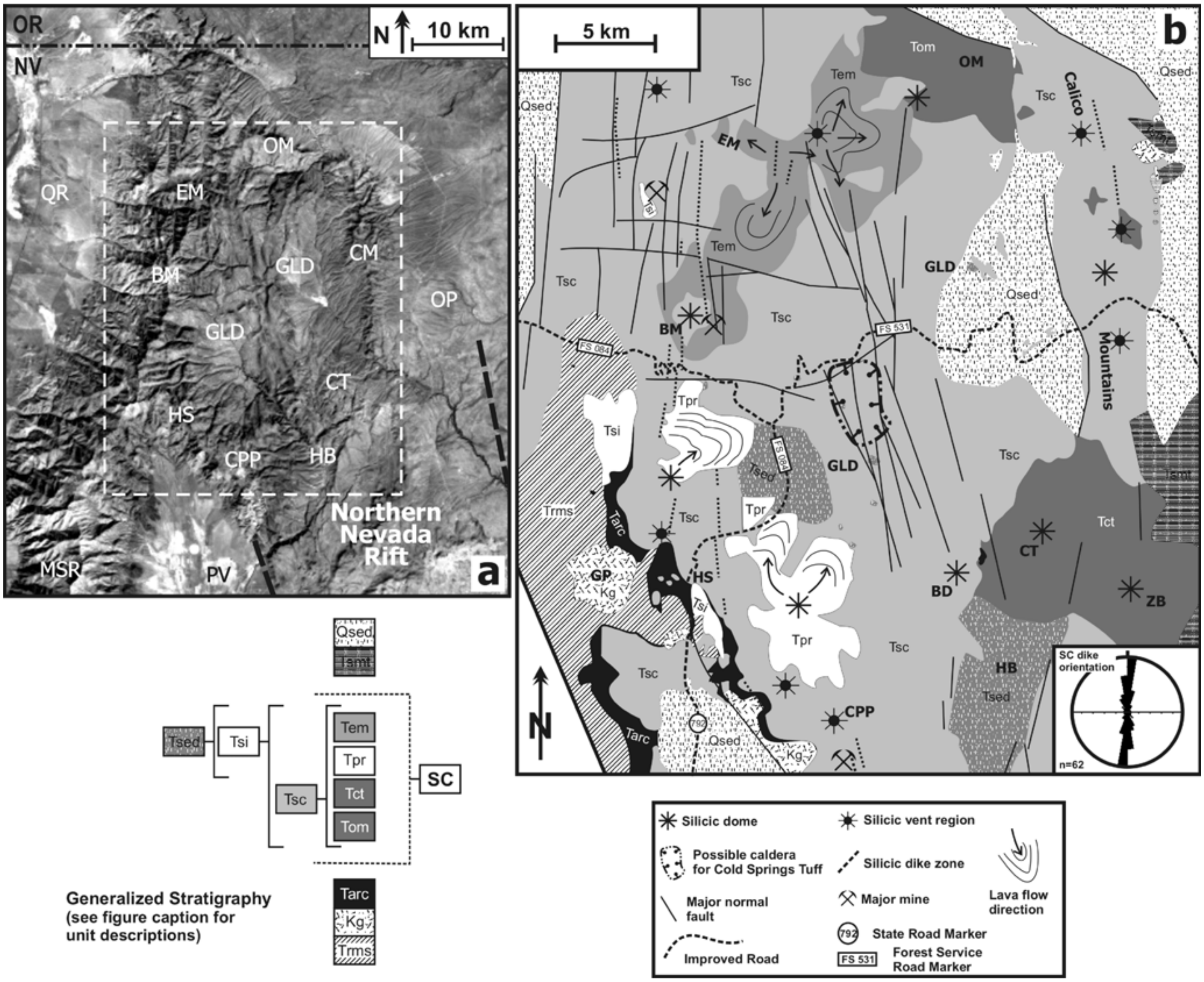


Fig. 2 **a** Landsat 7 image of the Santa Rosa–Calico volcanic field. Geographic features within the SC are: *CPP* Coal-Pit Peak, *HS* Hinkey Summit, *GLD* Goosey Lake depression, *BM* Buckskin Mountain, *EM* Eightmile Mountain, *OM* Odell Mountain, *CM* Calico Mountains, *HB* Hardscrabble Basin. Features peripheral to the SC are: *PV* Paradise Valley, *MSR* main Santa Rosa range, *QR* Quinn River Valley, *OP* Owyhee Plateau. *Dashed white box* is the approximate region shown in **b**. **b** Generalized geologic map of the SC (after LeMasurier 1965, 1968; Vikre 1985b; Mellott 1987; King 1984; Brueseke and Hart, this study). Units and symbols are depicted in *legend*. Geographic features not present on **a** are: *GP* Granite Peak, *ZB* Zymns Butte, *BD* Black Dome. Major Au–Ag–Hg mines from north to south are: National, Buckskin-National, and Spring City. Map units are as follows: *Trms* Triassic metasediments (Norian), *Kg* Cretaceous granitoid, *Tarc* undivided arc volcanics (late Eocene to early Miocene); *Tom* Odell Mountain area units, *Tct* Coyote Mountain area units, *Tpr* porphyritic rhyolite, *Tem* Eightmile Mountain lava area lava flows, *Tsc* Other mid-Miocene volcanic units including Calico Mountain silicic units and Goosey Lake depression ash-flow tuffs, *Tsi* silicic intrusive bodies (mainly porphyritic rhyolite), *Tsed* undivided Miocene sediment including lacustrine and fluvial basin deposits and interlayered tephra fall deposits. Hardscrabble basin sedimentary sequence includes distal Cold Springs tuff exposures; *Tsmt* Miocene Swisher Mountain tuff (likely derived from the mid-Miocene Juniper Mountain eruptive center), *Qsed* undivided Holocene and Pliocene sediment

tion initiated at ~11–10 Ma (Colgan et al. 2004); however, the Santa Rosa Range must have existed as a basement high prior to the mid-Miocene. Pre-SC (~35–20 Ma) basalt through dacite lava flows unconformably onlap granitoid and metasedimentary basement at high elevations near parts of the northern range crest and locally derived mid-Miocene lava flows onlap granitoid exposed at the base of the Calico Mountains (Figs. 2 and 3). Such paleotopographic irregularities, together with syn-volcanic normal faulting accounts for the variable thickness of the SC assemblage which ranges from at least ~400 to >1,000 m (e.g., LeMasurier 1965; 1968; Vikre 1985a, b; Mellott 1987; Brueseke and Hart, unpublished data).

Mid-Miocene geologic processes

SC volcanism initiated at ~16.7 Ma and continued to at least ~14 Ma, spanning an ~2.7 Ma duration. Silicic activity occurred from ~16.6 to ~15.4 Ma (Table 1 of Electronic supplementary material). Figure 3 illustrates the complex stratigraphic relationships among pre-SC and SC derived units. The most dominant SC mafic units are chemically identical to regionally exposed Steens Basalt, but were derived locally (Brueseke and Hart 2004). Stewart and Carlson (1976) grouped much of the mafic and intermediate SC units into one unit, however, at least four chemically and geographically distinct andesite-dacite packages are observed (Maloy et al. 2003; Brueseke and Hart 2004). Also, some of the intermediate units mapped by Stewart and Carlson (1976) are part of an older, early Miocene suite of calc-alkaline subduction related andesite/dacites correlative to the Steens Mountain volcanics that underlie Steens Basalt at Steens Mountain (Fuller 1931; Mellott 1987). Full details of the mafic to intermediate SC volcanism will be presented elsewhere.

Although sedimentary units are poorly exposed in the study area, lacustrine and fluvial basin-fill strata are present in and proximal to the SC, primarily in two sedimentary depo-centers. The Hardscrabble basin along the southeastern SC margin exposes at least 150 m of interbedded sediment, tephra fall deposits, and ash-flow tuffs. In the Goosey Lake depression, lacustrine and fluvial volcanogenic strata are exposed in patches that reach a maximum thickness of ~20 m. Gilbert et al. (2003) used tephrostratigraphic correlation of tuffs from these central SC deposits to conclude that the Goosey Lake depression was actively subsiding by at least 15.8 Ma ago.

Numerous post-SC faults and fault zones are exposed throughout the study area. The most pronounced zone divides the Goosey Lake depression into two sub-basins and is roughly aligned with numerous silicic eruptive loci, likely reflecting the reactivation of earlier structures. For descriptive purposes throughout the remainder of this paper, we use this fault zone (Fig. 2b) to divide SC silicic volcanism into two broad regions, (1) the western including Eightmile Mountain and vicinity and (2) the eastern including Odell Mountain and Black Dome. The Goosey Lake depression is referred to as the central SC. In addition to discrete silicic domes, abundant dikes, plugs, and shallow intrusive bodies are found throughout the volcanic field and local dikes broadly trend N–S, similar to other regionally exposed mid-Miocene shallow intrusive bodies (e.g. dikes in the Northern Nevada rift; Zoback et al. 1994). Some of these eruptive loci are well exposed and others are highly dissected due to post emplacement faulting and recent glaciation. As a result, in some cases we were unable to identify a specific vent for local units, but facies changes in these units suggested that a vent was nearby (Fig. 2b). This post-eruptive faulting has also helped obscure the areal extent of many SC units. Consequently, volumetric estimates and magma production rates are difficult to estimate without further geologic mapping.

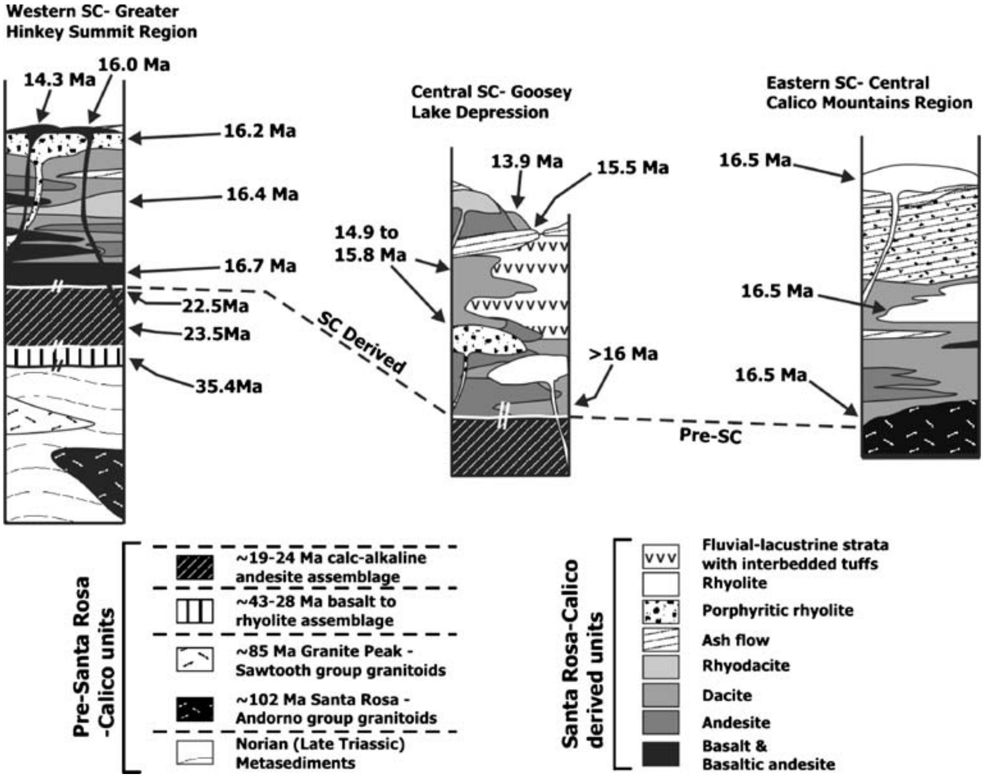


Fig. 3 Generalized stratigraphy of the SC illustrating the complex stratigraphic relationships found across the volcanic field (not to scale). All SC and pre-SC ages, not including the Cretaceous granitoid ages, are based on new $^{40}Ar/^{39}Ar$ determinations from this study and from Brueseke et al. (2003). New $^{40}Ar/^{39}Ar$ data and a summary table of the new ages are provided in "Appendix 1 (Electronic Supplementary Material)". Ages calculated relative to FC-2 Fish Canyon tuff sanidine interlaboratory standard at 28.02 Ma

The silicic units defined and discussed in this study exhibit substantial morphological, petrographic, and geochemical diversity. Most of these units display modal evidence for the incorporation of non-juvenile lithologies or/and complex fluctuations in magma chemistry during their differentiation. We generically refer to this evidence as “disequilibrium” features or textures, which commonly present themselves as sieved and resorbed feldspar crystals, mafic phase rich crystal clots, xenoliths of SC or pre-SC mafic to intermediate volcanic rocks, xenoliths of local granitoid basement, and xenocrysts of Mg-olivine.

Physical diversity of Santa Rosa–Calico silicic units

The following four points summarize the key physical observations of SC silicic units and provide the context for the more detailed discussion that follows. They also serve as a foundation from which the whole rock geochemistry must be interpreted. (1) Numerous eruptive loci are identified, are concentrated along the western and eastern margins of the volcanic field, and are primarily of two types, domes and fissures, (2) no SC-derived, large-volume, areally extensive eruptive units are identified, (3) disequilibrium features indicative of open-system magmatic evolution are ubiquitous and the specific nature of these features is linked to eruption location, and (4) the combined spatial, temporal, and petrographic features suggest that SC silicic activity did not result from catastrophic or periodic eruptions from one large magmatic system.

Western SC

Silicic volcanism in the western SC is characterized by five physically and chemically distinct units: (1) Hinkey Summit–Coal Pit Peak lava flows (hypersthene rhyodacite of LeMasurier 1965; 1968); (2) Western margin lava flows; (3) porphyritic rhyolite intrusive bodies and lava flows; (4) Eightmile Mountain region lava flows (Tr_3; rhyolite of Buckskin Mountain of Vikre 1985b); and (5) flow-banded rhyolite intrusive bodies and lava flows (laminated rhyolite of LeMasurier 1965, 1968). Because of the mid-Miocene epithermal mineralization that affected northern Nevada, we focused our efforts away from those areas where mineralization and alteration is prevalent (e.g. National, Buckskin Mountain, and Spring City areas). The salient field and petrographic characteristics of these units are described below.

Hinkey summit–coal pit peak lava flows

The oldest western SC silicic units are 16.4 Ma rhyodacite–rhyolite lava flows exposed in the vicinity of Hinkey Summit that overlie the basal SC package of mafic and intermediate lava flows (Fig. 2b, Tsc and Fig. 3). In some locations, intermediate lava flows are also found interbedded with these Hinkey–Coal Pit Peak lava flows. These lava flows range from ~15–120 m in thickness and appear to be thickest along the southern margin of the SC (southeast of Hinkey Summit), suggesting a nearby source. These lava flows often form thick, crudely columnar jointed walls and weather to thin plates (Fig. 4a). Flow margin breccias are present at some exposures and upper portions of flows are often flow-banded and vitrophyric. Petrographically, they are characterized by abundant 1–3 mm sanidine crystals in an aphanitic light grey/pink-purple matrix (Fig. 1 of Appendix 2 in Electronic supplementary material). In thin section, plagioclase and sanidine, quartz, clinopyroxene, orthopyroxene, and occasionally biotite are present. Feldspars are often resorbed and sieve-textured and occasional mafic xenoliths are present.

Western margin lava flows

The western margin lava flows are best exposed along the crest of the northern Santa Rosa Range between Granite Peak and Buckskin Mountain (Fig. 2b, Tsc). Based on their physical similarities, LeMasurier (1965, 1968) did not differentiate these lava flows from the Hinkey–Coal pit silicic units. Western margin silicic lava flows are characterized by platy weathering, cliff-forming outcrops and, in some exposures, by brecciated tops. Some exposures of these lava flows were mapped by Vikre (1985b) and grouped into a northward thickening (up to ~100 m), extensive unit (Tr_2; crystal-lithic rhyolite tuff). South of Buckskin Mountain, the western margin flows vary in thickness from ~25–35 m. This region was extensively glaciated during the Pleistocene; thus, this unit may have been much more areally and volumetrically extensive than current exposures indicate. Field relationships coupled with the prior mapping of Vikre (1985b) suggest that this unit was sourced north of Buckskin Mountain. Petrographically, these lava flows are also similar to Hinkey–Coal pit lava flows; plagioclase and sanidine, sparse mafics (clinopyroxene, orthopyroxene, and occasionally biotite), and quartz are present in flows of this unit (Fig. 1 of Appendix 2 in Electronic supplementary material). Resorbed, sieved, and complexly zoned plagioclase is also present.

Porphyritic rhyolite lava flows and intrusive bodies

The porphyritic rhyolite is best exposed between Hinkey Summit and Buckskin Mountain as abundant shallow intrusive bodies and large flow-dome complexes (Fig. 2b, Tpr and Tsi). These magmas were emplaced/erupted at ~16.2 Ma. This is the most widespread and abundant western SC

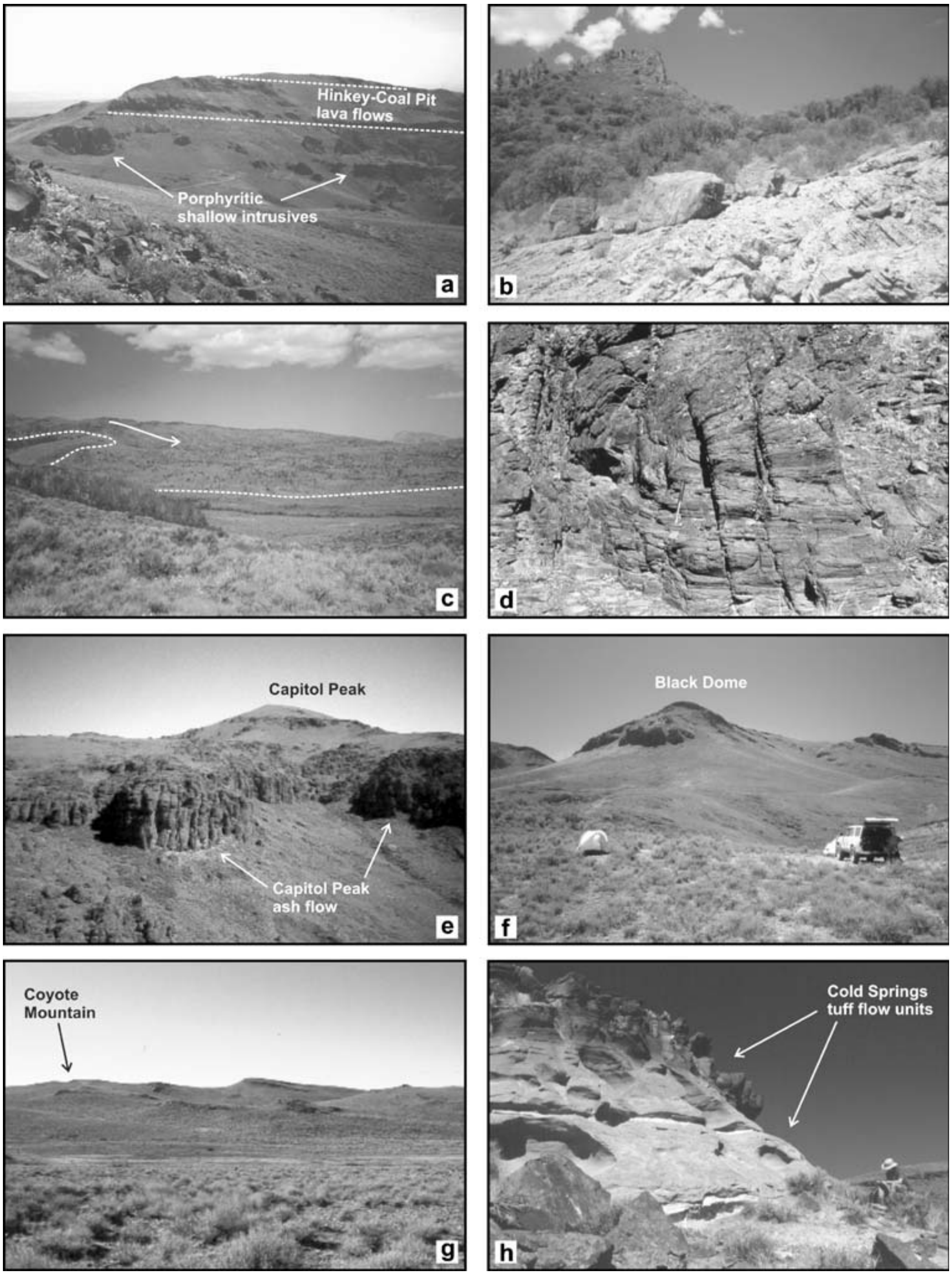


Fig. 4 Photographs of SC silicic units and features. **a** Silicic lava flows and porphyritic dikes exposed at Hinkey Summit. **b** Porphyritic rhyolite neck and near-vent pyroclastic deposits exposed south of Forest Service Road 84 along the western SC margin. **c** Porphyritic rhyolite lava flow along the southern SC margin. **d** Recumbent fold in a lower Calico lava-like ash-flow tuff exposed in the Calico Mountains along the eastern SC margin. **e** Columnar jointing in the Capitol Peak ash-flow tuff and overlying silicic units at Capitol Peak, Calico Mountains. **f** Black Dome in the southeastern SC with inferred outflow dipping to the north. **g** Coyote Mountain surrounded by exposures of the Coyote Mountain ash-flow tuff, dipping away from the vent region. **h** Distal exposure of Cold Springs tuff flow units exposed in the Hardscrabble basin along the southeastern SC margin

silicic unit and the most spectacular exposure is a large hypabyssal body found southeast of Hinkey Summit. Porphyritic rhyolite dikes are concentrated in two north–south trending zones that cut older SC units between Hinkey Summit and an eroded porphyritic rhyolite coulée south of Buckskin Mountain. These dikes range from 6–12 m across and have well exposed vitrophyric margins. Porphyritic rhyolite lava flows are best exposed in coulées located along the southern and western SC margins. A neck and near-vent bedded pyroclastic deposits associated with the western coulée are located south of Buckskin Mountain, and provide the best evidence for local eruption of this unit (Fig. 4b). The eastern margin of this flow forms a prominent ~120 m cliff along the western margin of the Goosey Lake depression and the areal extent of this unit is at least 11 km^2. This areal estimate suggests that at least ~1.3 km^3 of magma erupted from this location. Satellite imagery reveals prominent ogives on the surface of this flow, also suggesting an eastward flow direction. Sedimentary units and tuffaceous sediment exposed under the flow margin suggest the Goosey Lake depression already existed prior to the eruption of this unit. The southern flow-dome complex is also well exposed and areally extensive (at least 15 km^2). Preliminary mapping and thickness estimates suggest that this lava flow represents at least

~1–1.5 km^3 of erupted magma. It erupted along the southern margin of the Goosey Lake depression and field relationships indicate that it flowed into a topographic low (Fig. 4c). The domal vent of this coulée is visible on satellite imagery.

Unlike other SC silicic units, porphyritic rhyolite intrusive bodies and lava flows are amphibole bearing (Figs. 1 and 2a of Appendix 2 in Electronic supplementary material). Additionally, these units are much more crystal rich than any other SC silicic unit; amphibole and plagioclase phenocrysts are present up to 5 mm and biotite phenocrysts are as large as 2 mm (Fig. 1 of Appendix 2 in Electronic supplementary material). This unit lacks clinopyroxene and high-SiO$_2$ varieties lack orthopyroxene. As with other western SC units from the Hinkey Summit region, abundant disequilibrium textures are observed in the porphyritic rhyolite. Resorbed and complexly zoned feldspars are the most common; however, granitoid(?) clots and mafic xenoliths are also present in some samples (Figs. 1 and 2c, d of Appendix 2 Electronic supplementary material).

Eightmile Mountain lava flows

Eightmile Mountain area lava flows crop out along the northern SC margin, in the vicinity of Eightmile Mountain; the thickest exposures (>190-m thick) are found just east of Eightmile Mountain (Fig. 2b, Tem). This unit was mapped by Vikre (1985b) as the Rhyolite of Buckskin Mountain (Tr$_3$). Satellite imagery and field mapping indicate that this unit extends over ~20 km^2 and may represent 2–4 km^3 of magma. Eightmile mountain lava flows overlie a locally derived package of andesite–dacite lava flows and this stratigraphic relationship suggests that these silicic lava flows are <16 Ma. The best defined vent for this unit is a northeast trending fissure located southeast of Eightmile Mountain. Abundant boulder to pebble sized, pervasively oxidized, frothy tack-welded bombs and highly weathered north–south trending dikes help define this eruptive locus (Fig. 2b of Appendix 2 in Electronic supplementary material). These features and a lack of any domal body or steeply dipping near-vent carapace deposits indicate that Eightmile Mountain lava flows erupted from fissures. Based on topography and stratigraphic relationships, we also believe that another less well exposed vent region is located to the east (Fig. 2b). The near vent facies and overall outcrop patterns associated with Eightmile lava flows are very similar to proximal and distal features exhibited by fissure-fed rhyolite lava flows along the Owyhee front of the western Snake River Plain graben (e.g. Reynolds Creek lava flow(s); Bonnichsen et al. 2004).

Eightmile Mountain lava flows weather to plates, similar to Hinkey–Coal Pit and western margin silicic lava flows. Petrographically, these have an aphanitic, gray to purple/pink flow-banded matrix, often with abundant 1–3 mm sanidines. Partially resorbed plagioclase feldspar is the major phenocryst phase, with trace amounts of oxides, apatite, and zircon (Fig. 1 of Appendix 2 in Electronic supplementary material). Resorbed, sieved, and complexly zoned plagioclase as well as plagioclase+clinopyroxene clots are observed in some Eightmile Mountain area silicic units and when present, are much less abundant compared to other SC silicic units. Highly fractured, euhedral to subhedral Mg-rich olivine xenocrysts are also occasionally present and likely reflect incorporation during magma ascent.

Flow-banded rhyolite lava flows and intrusive bodies

Flow banded rhyolite intrusive bodies and lava flows are best exposed in the vicinity of Hinkey Summit, cross-cut older SC volcanic units, and appear to be time-transgressive (Fig. 2b, Tsc and Fig. 3). In some locations along the western margin of the Goosey Lake depression, these lava flows directly overlie porphyritic rhyolite lava flows. Flow banded lava flows are best exposed along the north side of Forest Service road 084 near where it drops into the Goosey Lake depression and as a large columnar jointed intrusive body located southwest of Hinkey Summit. These lava flows and intrusive bodies are characterized by ubiquitous 1–3 mm laminations that give an open-textured appearance and they also lack phenocrysts. Where exposed as lava flows, they are characterized by a basal vitrophyre and abundant 2–5 cm wide lithophysae. Additionally 1–15 cm rounded obsidian clasts and weathered fragments are present in drainages and on Holocene to recent pediment surfaces across the SC. These obsidian fragments may be physically related to the flow banded-rhyolite bodies (i.e. an eroded obsidian dome). LeMasurier (1965, 1968) suggested that flow banded rhyolite lava flows may be as thick as 120 m; however, we interpret the bulk of what he mapped as flow banded rhyolite in these thick exposures as a fine-grained variety of the porphyritic rhyolite unit. In other locations around Hinkey Summit, ~2–4 m thick white discontinuous dikes are exposed and are all extremely flow-banded and crystal poor. Plagioclase, sanidine, quartz, and biotite are all found in this unit but are rarely observable in hand sample (all <1 mm). Trace amounts of oxide and apatite are also visible in thin section. No disequilibrium features are observed in this unit.

Eastern SC

Silicic volcanism in the eastern SC initiated at ~16.6 Ma (Fig. 3) and is characterized by three physically and chemically distinct units: (1) Calico Mountains area units; (2) Odell Mountain area units; and (3) Coyote Mountain–Zymns Butte–Black Dome area units. Unlike western SC silicic units, stratigraphic relationships and geochronology suggest that the eastern region silicic volcanism ended by 16.4 Ma. The salient field and petrographic characteristics of these units are described below.

Calico Mountains silicic units

The most areally extensive and physically diverse package of eastern SC silicic units are exposed in the Calico Mountains. Calico area units include lava-like ash-flow tuffs, lava flows, and numerous silicic vent deposits (Fig. 2b, Tsc). In the thickest portion of the Calico Mountains pile, these units are interbedded with dacitic and andesitic lava flows and form an ~400 m thick package that unconformably overlies Santa Rosa–Andorno group granitoid. In the lower 200 m of this package, silicic units that crop out are predominantly highly welded, lava-like ash-flow tuffs (Fig. 4d). Where exposed, their basal portions are vitrophyric and lack a brecciated zone. Additionally, some of these units exhibit extreme rheomorphism, lack vesicles, and are xenolith-rich, suggesting their emplacement as pyroclastic flows (Fig. 2e of Appendix 2 in Electronic supplementary material). Sparse 1–3 mm phenocrysts of highly resorbed and sieve-textured potassium feldspar and plagioclase are present and are also commonly shattered, again suggesting a pyroclastic origin. Clinopyroxene and orthopyroxene are also present while oxides, apatite, and zircon are found in trace amounts. Two distinct xenolith varieties are observed: plagioclase±clinopyroxene±orthopyroxene clots, and clasts that resemble local mafic and intermediate lava flows (Fig. 1 of Appendix 2 in Electronic supplementary material).

In the upper 200 m, an ~150-m-thick ash-flow tuff underlies ~50 m of rhyolite lava flows that are exposed at Capitol Peak, the highest peak in the Calico range. The ~150-m-thick Capitol Peak ash-flow tuff is the thickest unit exposed in the northern Calico Mountains and is a distinct cliff-forming unit (Fig. 4e). A vitrophyric base, slight columnar jointing, rheomorphic folding, abundant 2–5 cm brown to green mafic xenoliths, and abundant 1–3 mm rounded potassium feldspar crystals helps to distinguish this unit from other local silicic units. Some of the mafic xenoliths bear 1–3 cm feldspars and physically resemble the plagioclase–phyric variety of Steens Basalt. Stratigraphically above this ash-flow tuff are at least two rhyolite lava flows. Texturally, these units are feldspar and pyroxene rich; potassium feldspar and orthopyroxene are the dominant phenocryst phases. Trace amounts of clinopyroxene, oxide, apatite, zircon, and sparse plagioclase are also present, as are resorbed feldspars. Vents for these units may be located further north in the northern Calico range (King 1984).

Further south in the central and southern Calico Mountains, thicker exposures of rhyolite lava flows are present from just north of where Forest Service road 531 crosses the range (Mahogany Pass) to the north fork of the Little Humboldt River (Fig. 2b). Here, the ~50–100-m-thick Mahogany Pass rhyolite lava flow overlies basaltic andesite and andesite lava flows. An eroded rhyolite dome that is the source of this sanidine-rich porphyritic unit is present just to the north (Hill 7502 on the Capitol Peak 1:24,000 U.S.G.S. quadrangle). At this small topographic high, vertical fins of vitrophyre rim a broadly circular plug-like feature and are spatially associated with abundant 15–20 cm tan feldspar-rich pumice clasts. South of Mahogany Pass in the central and southern Calico range, the Mahogany Pass rhyolite overlies a texturally identical, but compositionally distinct rhyolite lava flow. We interpret this underlying flow to have been erupted from an unidentified vent in the southern Calico range. Although highly dissected by post-emplacement faulting, the field relationships suggest that the central and southern Calico Mountains were characterized by a number of overlapping silicic coulées. Petrographically, the central and southern Calico silicic lava flows are similar and are characterized by phenocrysts of potassium and plagioclase feldspar, oxides, and traces of apatite, zircon, and orthopyroxene (Fig. 1 of Appendix 2 in Electronic supplementary material). In these units, plagioclase feldspars are commonly partially resorbed/rounded and occasional granitoid(?) clots are present.

Odell Mountain area silicic units

The Odell Mountain area silicic units are best exposed along the east fork of the Quinn River in the vicinity of Odell Mountain, where ~295 m of silicic material crops out Fig. 2b, Tom). Ash-flow tuffs, lava flows, and an eroded rhyolite dome/coulée are exposed in this region. Based on field relationships and geochronology, Odell area silicic volcanism occurred at ~16.6 Ma. At Odell Mountain proper, interbedded lava flows, ash-flow tuffs, and air-fall tuffs are poorly exposed. The uppermost unit is an ~150-m-thick crudely columnar jointed and flow-banded feldspar and quartz-rich lava flow. A sequence of feldspar and orthopyroxene-bearing, highly welded ash-flow tuffs underlie this lava flow. Also abundant in these ash-flow tuffs are 1–3 cm mafic xenoliths, and shattered Mg-rich olivine xenocrysts are present in one of these flows. The lowest exposed stratigraphic units are quartz and potassium feldspar-rich rhyolite lava flows that crop out along the south fork of the Quinn River. In these lava flows, resorbed and sieved feldspars are present and at least some of these lava flows erupted from an eroded dome exposed south of Odell Mountain (Fig. 2b). Oxidized vertical dikes and frothy near vent carapace deposits help define this vent. Field relationships and satellite imagery illustrate that outflow from this source was directed to the north, southeast, and southwest where it was onlapped by Eightmile Mountain area lava flows. To the south, this unit is onlapped by a xenolith-rich Odell Mountain ash-flow tuff and a younger ash-flow tuff derived from the Goosey Lake depression (Cold Springs tuff; Knight et al. 2004).

Coyote Mountain–Zymns Butte area silicic units

The Coyote Mountain–Zymns Butte–Black Dome area lies to the south of the Calico Mountains and at the southeastern end of the prominent central SC fault zone (Fig. 2b, Tct and Tsc). In the vicinity of Coyote Mountain, silicic volcanism was occurring by at least ~16.4 Ma marked by the eruption of the Coyote Mountain tuff from Coyote Mountain. The other well exposed silicic vents in this region are domes; Zymns Butte and Black Dome (Fig. 4f). At and peripheral to Coyote Mountain, the Coyote Mountain ash-flow tuff forms a shallow (~10°) dipping ignimbrite plateau that extends away from the summit in all directions (Fig. 4g). Along the flanks of this vent, block and ash deposits (above ash-flow tuff) and air-fall tuffs (below ash-flow tuff) are locally well exposed, suggesting that Coyote Mountain erupted more than once. The Coyote Mountain ash-flow tuff is a highly welded, rheomorphic, and petrographically monotonous unit (Fig. 3 of Appendix 2 in Electronic supplementary material). Andesite and dacite lava flows underlie the Coyote Mountain sequence. Stratigraphic relationships between Zymns Butte, Black Dome, and the Coyote Mountain ash-flow tuff are difficult to discern, but we suggest that these domes post-date Coyote Mountain activity. Unlike other SC silicic domes, Zymns Butte and Black Dome do not appear to be associated with substantial outflow, although at least one lava flow emanated from Black Dome (Fig. 4f). The Coyote–Zymns–Black area units are potassium feldspar-rich and contain abundant evidence of disequilibrium including xenolithic clots of plagioclase± orthopyroxene±clinopyroxene and abundant resorbed and sieved feldspars.

Goosey Lake depression ash-flow tuffs and air-fall tuffs

The Goosey Lake depression preserves evidence of at least two physically distinct ash-flow tuffs. The most widespread is moderately welded and intermittently exposed across the Goosey Lake depression and along the western SC margin as a ~1 to 5-m-thick simple cooling unit, originally mapped by Vikre (1985b) as Twt (crystal-lithic rhyolite tuff). This unit's most distinguishing characteristic is the presence of 1–2 cm long fiamme in a welded, variably colored matrix (most commonly beige/yellow), and where exposed, its base is vitrophyric. Field relationships suggest that its source was north/northwest of the SC and texturally, this unit resembles distal outflow from the McDermitt volcanic field (Rytuba and McKee 1984). While only cropping out as a single cooling unit, field and chronologic relationships between this unit and those it over/underlies, suggest that it may be outflow of more than one explosive eruption. A very distinct ash-flow tuff, herein named the Cold Springs tuff, is generally observed underlying the above unit and is best exposed in the Goosey Lake Depression (Fig. 4h and Fig. 4 of Appendix 2 in Electronic supplementary material). At Cold Springs Butte, composite exposures of the Cold Springs tuff are at least 50 m thick. Along the southeastern SC margin, Cold Springs tuff flow units are much thinner and likely represent distal facies (Fig. 4h). In the Goosey Lake depression, the basal portion of the Cold Springs tuff is well exposed and overlies lacustrine strata (Fig. 4a of Appendix 2 in Electronic supplementary material). The main body of the ash-flow tuff appears to be composed of at least one ~18 to 30-m-thick, crystal rich compound cooling unit (Fig. 4b of Appendix 2 in Electronic supplementary material). Sparse lithic fragments of welded ash-flow tuff and andesite–dacite lava flows are also found in main body deposits near Cold Springs Butte. While no eruptive loci can be directly linked with this ash-flow tuff, the thickest outcrops and only occurrence of lithic fragments are found near Cold Springs Butte, suggesting that this region may be proximal to source. A roughly oval ~2.5×~3.5 km region visible on aerial imagery is present in the vicinity of Cold Springs Butte and may reflect the presence of a small caldera, the only caldera system within the volcanic field.

Chemical diversity of Santa Rosa–Calico silicic units

Unlike other mid-Miocene Oregon Plateau volcanic fields, SC products display compositional variation from basalt through high-silica rhyolite and span this spectrum with no compositional gaps (Fig. 5 and Table 1 of Appendix 2 in Electronic supplementary material). The entire SC suite mimics a subalkaline differentiation trend (Fig. 5a) and the welded ash-flow(s) exposed in the Goosey Lake depression is the only silicic material that possesses a peralkaline (comenditic) composition (Fig. 5b). This chemical difference supports our field interpretation that this unit may have been derived from the nearby McDermitt volcanic field or a yet identified source. All locally derived silicic units straddle the peraluminous–metaluminous divide, and those from the western SC tend to be more peraluminous

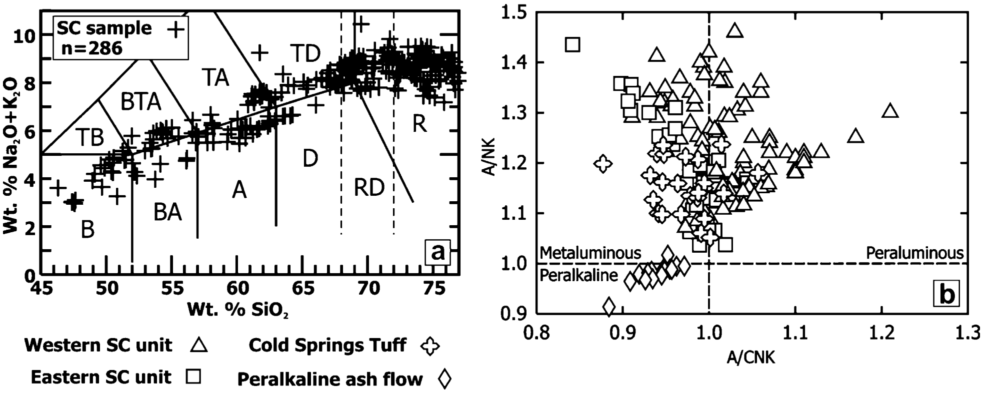


Fig. 5 **a** Total alkalies versus silica diagram (LeBas et al. 1986) illustrating compositional spectrum of sampled SC lava flows, ash-flow tuffs, eruptive loci, and shallow intrusive bodies. *B* Basalt, *TB* trachybasalt, *BA* basaltic andesite, *BTA* basaltic trachyandesite, *A* andesite, *TA* trachyandesite, *D* dacite, *TD* trachydacite, *RD* rhyodacite, *R* rhyolite. **b** Plot of A/NK (molecular Al_2O_3/Na_2O+K_2O) versus A/CNK (molecular $Al_2O_3/CaO+Na_2O+K_2O$)

while those from the eastern SC are only mildly peraluminous (Fig. 5b). Major and trace element data (Figs. 6 and 7) also illustrate that the Cold Springs tuff is chemically unlike other SC silicic units. This supports the field relationships that suggest it erupted from an isolated magmatic system, possibly from the only caldera-forming system within the SC. In order to focus on the main ~16.6–16.2 Ma package of SC-derived silicic activity, the younger (<15.8 Ma) Cold Springs and McDermitt derived ash-flow tuffs are not further discussed in this paper.

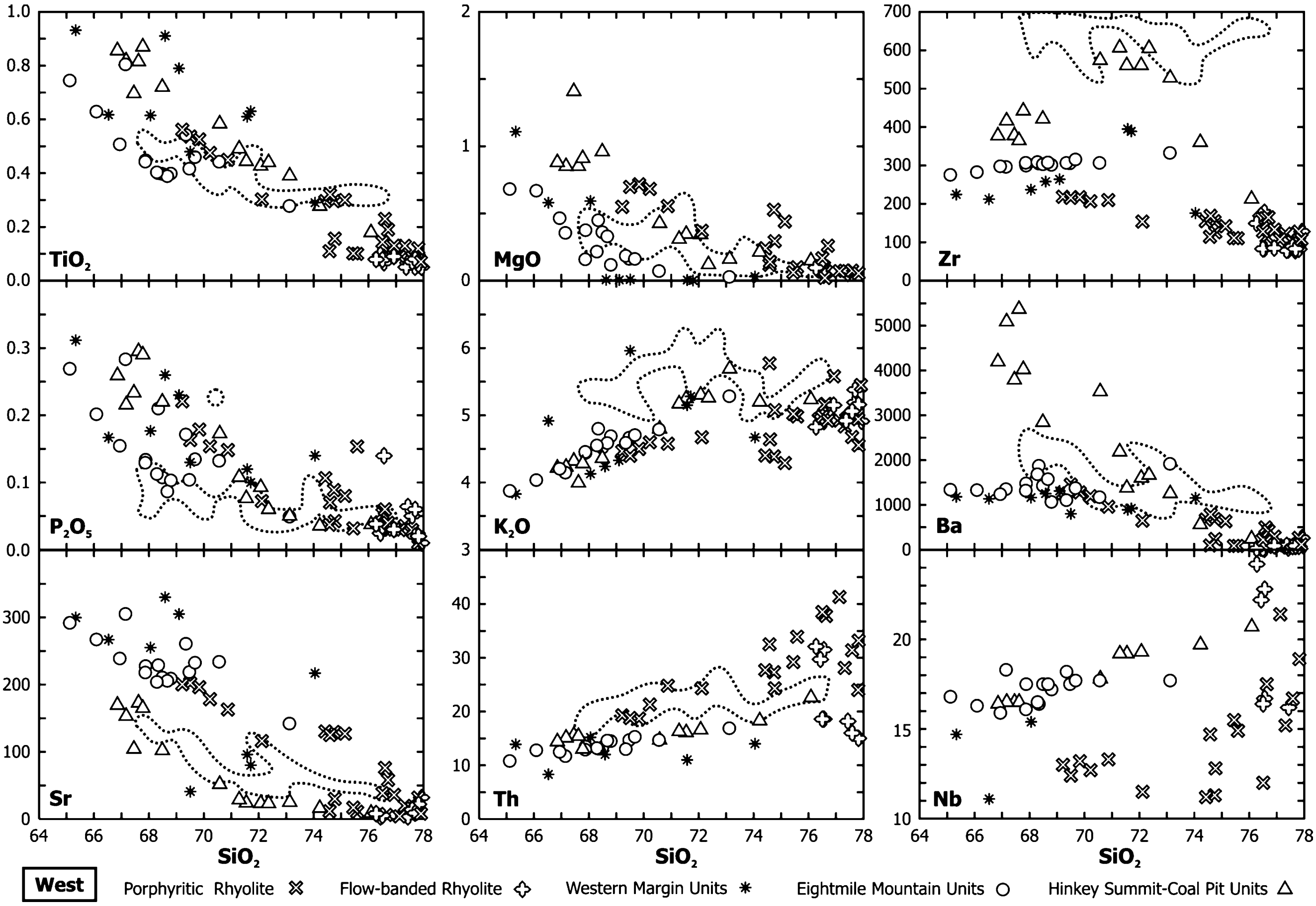


Fig. 6 Major and trace element variations for western SC silicic units (major elements in wt%; trace in ppm). Notice the chemical differences exhibited by each unit. Also shown is the field for the Cold Springs tuff (except Nb), illustrating its chemical dissimilarity to western SC silicic units. Cold Springs tuff Nb data is not included to better illustrate Nb differences among western SC silicic units. However, Cold Springs tuff Nb concentrations range from 33–65 ppm

Chemical diversity of Western SC silicic volcanism

Figure 6 illustrates selected major and trace element characteristics for the western SC silicic units. Within and between units, variations exist as evidenced by obvious data clusters (subgroups) and arrays. Most notable are the between unit sub-parallel data arrays that further highlight the physical, petrographic, and chronologic distinctions discussed previously. Hinkey Summit–Coal Pit Peak lava flows define two distinct clusters between 67–74 wt% SiO_2. These clusters are particularly evident in the Zr versus silica plot. Viewed together, these subgroups define a single array in element–element space and lava flows from both subgroups stratigraphically overlie high-silica Hinkey–Coal Pit lava flows. Furthermore, the high Ba concentrations (up to 5,500 ppm) of the low-silica subgroup and the overall trend of decreasing Ba with increasing SiO_2 for all Hinkey–Coal Pit lava flows are unique within the SC silicic suite. For example, physically similar Western Margin and Eightmile Mountain lava flows are not as enriched in Ba or Zr.

The porphyritic rhyolite intrusive bodies and lava flows also span a wide range in silica content and the most evolved are compositionally similar to flow banded rhyolites. Two chemical subgroups are present within this unit based on silica content: a low silica group (~69–71 wt%) representing the southern SC margin lava flow and a higher silica subgroup (>72 wt%) that represents all other exposures. Within the higher silica subgroup substantial chemical variation is present. This variation is best seen in plots of K_2O, TiO_2, Sr, Th, and Nb versus silica. The samples falling between ~74 and ~75 wt% SiO_2 and the single sample at ~72 wt% SiO_2 represent the large shallow intrusive body exposed southeast of Hinkey Summit. The remaining high-silica samples are from the dikes exposed between Hinkey Summit and Buckskin Mountain and the coulée along the western margin.

Eightmile Mountain region lava flows and near-vent clastogenic deposits range from ~65 to ~74 wt% SiO_2. Scatter is observed in major element concentrations (and Sr) across this silica range, whereas most trace elements define near linear arrays. The overall major and trace element characteristics of these lava flows and near-vent pyroclastic material are most similar to western margin lava flows.

All flow-banded rhyolite intrusive bodies and lava flows are high-silica (>76 wt%) rhyolites. While minor variations are present, this unit defines a cluster in major element space. Within this unit, certain trace elements (e.g., Th and Nb) define two distinct subgroups, yet lava flows and intrusive bodies from these subgroups are texturally indistinguishable. It is interesting to note that obsidian collected from along the southern margin and near the center of the Goosey Lake depression is chemically linked to these subgroups, indicating that at least two physically distinct obsidian bodies were present in the western SC.

Chemical diversity of Eastern SC silicic volcanism

Eastern SC silicic volcanism is also characterized by a suite of geochemically diverse units (Fig. 7). However, the within unit variability is typically more pronounced than that observed in the western units, whereas the between unit variability is less pronounced. Calico Mountain area units are the most physically diverse in the eastern SC and their major and trace element variations reflect this diversity. Calico units span a wide range in wt% SiO_2, and major and trace element characteristics define at least four subgroups separated by gaps in silica content. Our comprehensive sampling in this area indicates that these subgroups truly represent the available material. Moreover, the subgroups roughly correspond to stratigraphic position, with increasing silica up-section (e.g., Th versus SiO_2). The least evolved samples are the xenolith-rich ash-flow tuffs exposed below the Capitol Peak ash-flow tuff, and their chemical compositions likely reflect the presence of relatively high-MgO xenoliths. The subgroup of samples clustered between 71 and 73 wt% SiO_2 include the lava flows exposed at Mahogany Pass that erupted from a small dome in the central Calico range. At higher silica concentrations (~73 to 76 wt% SiO_2), two subgroups are present: a high Th and Nb, low Sr subgroup similar in chemistry to Odell Mountain units and a cluster of low Th, Nb, and high Sr samples. The two samples that define the high Nb subgroup are the stratigraphically youngest material in the Calico range and their chemical affinity with Odell Mountain units suggests that they are petrogenetically related to Odell Mountain units. The high Sr subgroup includes a dike exposed north of Mahogany Pass and the thick lava flows in the southern Calico range.

Odell Mountain area units are restricted to compositions >73 wt% SiO_2 and are the most evolved eastern SC group. However, at least two distinct subgroups appear to be present. The lower silica subgroup encompasses a mafic-xenolith rich ash-flow tuff and a lava flow that is the lowest stratigraphic unit in the Odell region. The >75 wt% SiO_2 subgroup includes the only exposed Odell area rhyolite dome and the stratigraphically youngest lava flows exposed at Odell Mountain.

Coyote Mountain–Zymns Butte and Black Dome area units exhibit the same range in major and trace element concentrations as those from the Calico Mountains. The least evolved Coyote Mountain area silicic units are dacitic to trachydacitic and underlie the Coyote Mountain ash-flow tuff. The ash-flow tuff itself appears to be chemically zoned, with the array from ~69 to ~75 wt% SiO_2 reflecting

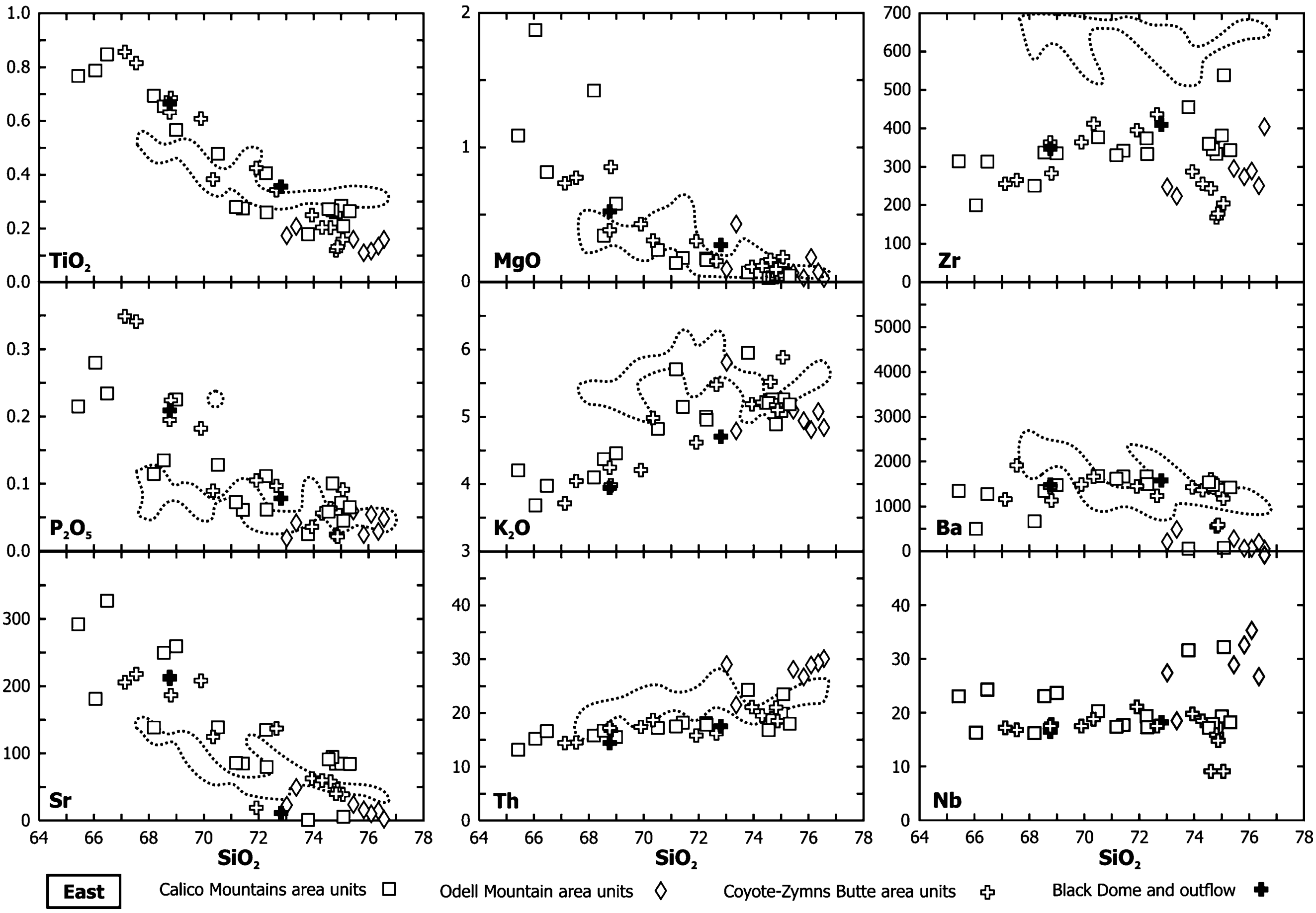


Fig. 7 Major and trace element variations for eastern SC silicic units (major elements in wt%; trace in ppm). Chemically, these units are more similar to each other than western SC units and are chemically distinct from the Cold Springs tuff (same fields as Fig. 6). Like in Fig. 6, Cold Springs tuff Nb data is not included to better illustrate Nb differences among eastern SC silicic units

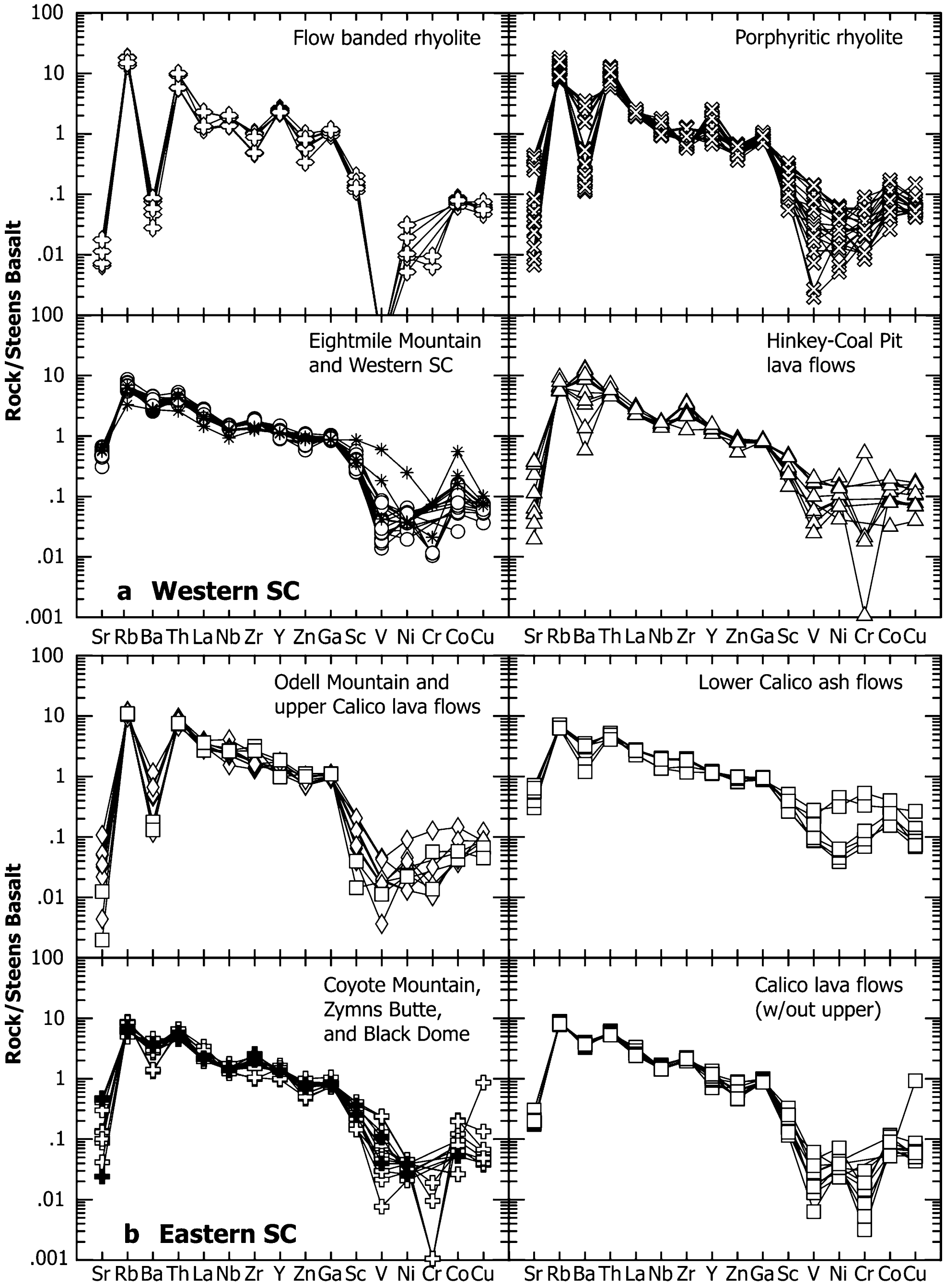
this up-section zonation. At ~74 to ~75 wt% SiO_2, two subgroups of Coyote Mountain samples are present (high and low Nb) that represent the upper portion of the ash-flow tuff (high Nb) and under/overlying welded fall and block and ash deposits (low Nb). Additionally, Zymns Butte falls within the high-silica and high Nb group cluster. Two samples that were collected from Black Dome and its inferred outflow fall within the array defined by Coyote–Zymns units.

In order to summarize and further interpret the geochemical characteristics discussed above, Fig. 8 illustrates multi-element plots for the western and eastern silicic units. All concentrations are normalized to an average Steens Basalt composition since this provides the best estimate for the mafic component involved in SC magmatism.

The western SC porphyritic and flow banded rhyolites exhibit broadly similar trace element patterns characterized by pronounced depletions in Sr and Ba as compared to other western SC units (Fig. 8a), and pronounced depletion in V as compared to all SC silicic units. As previously noted, the porphyritic rhyolite exhibits considerable within-unit variability. Hinkey–Coal Pit, western margin, and Eightmile Mountain units exhibit similar overall patterns that are distinct from those exhibited by the flow banded and porphyritic rhyolites. However, Fig. 8a illustrates that the Hinkey–Coal Pit lava flows possess greater Sr, Ba and Zr diversity including pronounced Zr and Ba enrichment and Sr depletion relative to Eightmile Mountain and western margin lava flows. This supports the temporal and spatial relationships that preclude a direct petrogenetic link between Eightmile Mountain and Hinkey–Coal Pit lava flows.

Eastern SC units are illustrated in Fig. 8b. The trace element patterns further substantiate the similarities between the uppermost lava flows in the Calico Mountains and Odell Mountain area units. The patterns defined by the main group of Calico lava flows are nearly identical to those from Coyote Mountain area units. The lower Calico ash-flow tuffs exhibit trace element characteristics unique among all SC silicic units. The transition metal abundances highlight this point, and reflect the modal abundance of mafic xenoliths in these units (e.g. greater xenolith content coupled with higher transition metal concentrations). Ignoring these highly

Fig. 8 Multi-element diagrams illustrating the chemical variation of units from the **a** Western SC and **b** Eastern SC



contaminated lower Calico ash-flow tuffs, the overall trace element characteristics exhibited by the eastern units are more similar to each other than is the case in the western SC.

Implications of chemical heterogeneity

Previous work restricted to the western SC attempted to constrain the petrogenetic processes responsible for the local silicic magmatism. For example, LeMasurier (1965, 1968) concluded that the bulk chemical variability was due to different degrees of fractional crystallization of a basaltic parental magma. However, Mellott (1987) found isotopic heterogeneities within and between western SC silicic units, with the Hinkey–Coal Pit and western margin lava flows yielding initial Sr isotopic compositions between 0.7046 and 0.7058. Larger ranges and more radiogenic values ($^{87}Sr/^{86}Sr_i=0.7048$ to 0.7076) characterize the porphyritic and flow banded rhyolite units. Mellott (1987) invoked one or more of the following processes to explain these data: (1) mixing between chemically and isotopically heterogeneous mantle and crustal melts, (2) partial melting of isotopically evolved pre-Miocene crust (e.g. local granitoid or meta-sedimentary rocks), and (3) open system fractional crystallization (AFC) of a more mafic parent. Later recognition by Stuck (1993) that the local Cretaceous granitoid basement is comprised of at least two chemically and isotopically distinct components (^{87}Sr/^{86}Sr$_{@16.5\ \mathrm{Ma}}$=0.7048 to 0.7058, Santa Rosa–Andorno group; 0.7061 to >0.7071, Granite Peak–Sawtooth group; 0.7095 to >0.7426, cross cutting aplite dikes) supports some of Mellott's conclusions. Locally erupted Steens Basalt lava flows and shallow intrusive bodies are characterized by ^{87}Sr/^{86}Sr$_i$ values less than 0.7045 (Hart and Carlson 1985; Carlson and Hart 1987; Mellott 1987; Brueseke and Hart, unpublished data). Preliminary isotopic data from the units discussed in this study indicate an isotopic similarity to both granitoid groups (^{87}Sr/^{86}Sr$_i$>0.7045; Brueseke and Hart, unpublished data) and this observation coupled with the earlier isotopic results of Mellott (1987) suggest that simple crystal fractionation of a more mafic parental magma is not solely responsible for the chemical diversity exhibited by SC silicic units. Compositionally similar silicic melts were documented by Petcovic and Grunder (2003) in a study of silicic melt generation in the Wallowa Mountains of Oregon. There, rhyodacitic and high-Si rhyolite melts were generated via the emplacement of Columbia River Basalt Group dikes into Cretaceous hornblende–biotite granodiorite to tonalite wallrock (Petcovic and Grunder 2003). Additionally, crystal clots present in some SC silicic units are mineralogically similar (Fig. 2c, d of Appendix 2 in Electronic supplementary material) to the plagioclase feldspar, clinopyroxene, orthopyroxene, and oxide restite that formed as a consequence of melting granitoid upper crust (Petcovic and Grunder 2003). Bonnichsen et al. (2007) have proposed a similar model of crustal melting driven by mafic upwelling to explain the genesis of the ~12–10 Ma voluminous silicic lava flows and welded tuffs that crop out across the central Snake River Plain, ID. We suggest that a similar process is likely responsible for the generation of most SC silicic units, initiated and driven by upwelling Steens Basalt magmas.

Differing degrees of partial melting of local granitoid basement may explain the high Ba concentrations found in the Hinkey Summit–Coal Pit Peak lava flows (Fig. 6) and post melt-generation fractional crystallization could potentially account for some of the trace element variations illustrated in Fig. 8 (e.g. pronounced negative Sr, Ba, and V anomalies for the flow banded and porphyritic rhyolites and Odell and upper Calico lava flows). However, the abundant disequilibrium textures present within SC silicic units and the overall trace element diversity within and between units demonstrate that complex magmatic processes (e.g. heterogeneous parental magmas, crustal assimilation, magma mixing) have contributed to the observed chemical variations. This physical evidence also points to some level of location specific open system behavior. For example, xenolithic granitoid clots (anatectic restite or/and bulk granitoid) are most abundant in those western SC units with eruptive loci in the vicinity of Hinkey Summit (Fig. 2) where the massive granitoid core of the Santa Rosa Range looms only kilometers away. In contrast, in areas predominated by thick mafic to intermediate flow packages (e.g., Eightmile Mountain, Odell Mountain, Calico Mountains; Fig. 2), the silicic units preserve a more variable lithic assemblage including Mg-olivine xenocrysts and basalt–andesite xenoliths. Further Sr, Nd, and Pb isotope work currently in progress should better define how the observed chemical and isotopic differences between and within units vary as a result of crustal melting and/or melting combined with other petrogenetic processes including interaction with local pre- and mid-Miocene crust and contemporaneously produced less-evolved magmas.

Discussion and conclusions

New field mapping, ^{40}Ar/^{9}Ar geochronology, and chemical analyses, coupled with prior reconnaissance studies combine to produce the first comprehensive picture of silicic volcanism in the Santa Rosa–Calico volcanic field. In the western SC, at least five physically and chemically distinct silicic units are present and crop out along a north-northwest trending zone that extends from Hinkey Summit to the National Mining district. Conservatively, one laterally heterogeneous, evolving magmatic system can be invoked for the western SC; however, we prefer an interpretation that calls on multiple physically isolated systems. The central SC is dominated by locally and regionally derived ash-flow tuffs, sedimentary basin deposits, and lava flows that were deposited/emplaced into an actively subsiding structural basin. Included in this area is the only local evidence of explosive, caldera forming eruptions and outflow products (Cold Springs tuff). This unit possesses a unique geochemical fingerprint (Figs. 6 and 7), suggesting derivation from an isolated and younger magmatic system. The physical and chemical characteristics of lava flows and ash-flow tuffs from the eastern SC indicate that they were derived from separate loci along the eastern margin of the field. However, their overall chemical similarity and broadly coeval emplacement suggest a commonality in petrogenetic processes. We therefore suggest that eastern SC silicic activity owes its origin to the tapping of a single crustal magma chamber (or related sill-like bodies) along N–S trending faults during the initiation of SC volcanism. A similar style of volcanism was proposed to explain ignimbrites of the Sierra Madre Occidental that are spatially and temporally associated with coeval extensional tectonism (Aguirre-Díaz and Labarthe-Hernández 2003). These authors also observed rhyolite domes directly overlying lag-breccia and ignimbrites aligned along major faults. This situation may be present in the Calico range where pyroclastic units (the lower ash-flow tuffs) are generally overlain by effusive products (the middle to upper rhyolite domes and flows). Disruption by faulting and/or mafic magma injection could have provided the trigger for localized eruption, leading to the presence of the discrete eastern SC eruptive loci. In this scenario, the minor chemical variations present may reflect heterogeneous magmatic processes affecting localized portions of the larger eastern system. The Eightmile Mountain lava flows of the western SC were also derived from fissural vents and resemble the areally extensive lava flows that erupted along the Owyhee Front at the initiation of western Snake River Plain graben formation (Bonnichsen et al. 2004). Similar broad compositional variation and styles of volcanism are also present at the 10.4 Ma Duck Butte Eruptive Center (north of Steens Mountain). Here, rhyodacite vents are present parallel to basin and range faults and local eruptive units drape and were cut by faults active during volcanism (Johnson and Grunder 2000).

The only locally derived silicic unit that appears to have had a caldera origin is the Cold Springs tuff, the youngest unit recognized in this study. Its apparent eruption from a small caldera in the central SC may reflect a cessation in localized extension (e.g. a cessation in regional rifting) during the waning stages of SC silicic activity prior to Cold Springs tuff volcanism at ~15.4 to 15.6 Ma. Prior workers have suggested that the Goosey Lake depression formed due to magmatic subsidence related to local, large-scale caldera forming volcanism and attributed the abundant eruptive loci that "ring" the Goosey Lake depression to post-caldera resurgence along ring faults (Ekren et al. 1984; Vikre 1985a, b; McCormack 1996). However, the data from this study do not support this interpretation for the main SC silicic eruptive products. The paucity of caldera-forming volcanism in the SC is interpreted to be a direct function of its location within the Northern Nevada rift, where active extension created an environment that frequently disrupted developing crustal magma bodies.

The interplay between volcanism and focused extensional tectonism suggested for the SC may help to better understand the origin of Miocene silicic volcanism on the adjacent Owyhee Plateau (Fig. 1b). The silicic products exposed in this region are often attributed to caldera forming volcanism related to the "Owyhee–Humboldt eruptive center" (originally defined as "a basalt-filled structural basin"; Bonnichsen 1985). However, little is known about the chemical diversity and eruptive sources of these areally extensive units, except for those that erupted from the Juniper Mountain eruptive center, which are lava flows and not caldera-derived (Manley and McIntosh 2002). Across the Owyhee Plateau, numerous, small silicic eruptive centers and shallow intrusive bodies are present and must reflect multiple eruptive loci (Fig. 1b). Additionally, no field-based geologic evidence exists to suggest the presence of caldera-related volcanic systems (Coats 1968; Ekren et al. 1984; Manley and McIntosh 2002). The multiple and abundant loci, diverse eruptive styles, and crustal response to upwelling mafic magmas documented in the SC suggest that the southern Owyhee Plateau may have been characterized by similar features, rather than a large caldera system like those depicted across the eastern Snake River Plain.

In summary, the various lines of evidence presented in this paper point to generation and evolution of Santa Rosa–Calico silicic magmas through a complex set of processes involving mantle- and crustal-derived melts and heterogeneous open system differentiation in physically isolated upper crustal magma bodies. At the root of these complexities are two fundamental aspects of the regional tectonomagmatic development; (1) active mid-Miocene extension, and (2) crustal modification and addition via the voluminous Steens–Columbia River magmatic event. Santa Rosa–Calico silicic volcanism was characterized by numerous eruptive loci distributed along roughly north–south trending alignments. These alignments are likely lithospheric, similar to the Northern Nevada rift and Oregon–Idaho graben, and their presence coupled with the field relationships present in the central SC indicates that regional mid-Miocene rifting was occurring locally. Furthermore, new age data demonstrate that the silicic activity was coeval with regional Steens flood basalt volcanism. Because of its location in a zone of focused extensional tectonism and its spatial and temporal association with continuous upwelling mafic magma, the styles and chemical characteristics of Santa Rosa–Calico silicic volcanism illustrate the important interplay between tectonism and volcanism, and distinguish the Santa Rosa–Calico volcanic field from other mid-Miocene northwestern USA volcanic fields.

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