1 **Origin of Miocene andesite and dacite in the Goldfield-Superstition volcanic province, central**
2 **Arizona: hybrids of mafic and silicic magma mixing**

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9 **Abstract**

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11 The Miocene Goldfield-Superstition volcanic province (G-SVP), ~8000 km² in central Arizona, is
12 composed largely of silicic pyroclastic rocks and lavas, and smaller volumes of alkalic basalt and
13 intermediate-composition lavas. Volcanism began ~20.5 Ma as sparse rhyolitic and mainly basaltic
14 lavas followed by intermediate lavas, lasting until ~19 Ma. At that time, ~1 m.y. of silicic eruptions
15 began, creating most of the G-SVP. Petrologic studies are available for basalts and some for silicic
16 rocks, but petrologic/geochemical information is sparse for intermediate-composition lavas. These
17 latter, andesites and dacites, are the focus of this study, in which we present the processes and
18 sources responsible for their origins.

19 Goldfield-Superstition andesites and dacites have SiO₂ ~56-70 wt.% and Na₂O+K₂O that
20 qualifies some as *trachy*- andesite and dacite. A prominent petrographic feature is plagioclase-
21 phyric texture (~11-30 vol% plagioclase), where oligoclase-andesine phenocrysts have cores
22 surrounded by corroded, or reacted, zones, mantled by higher An% plagioclase. Where corroded
23 zones are absent, margins are etched, curved, or embayed. Groundmass plagioclase is labradorite,
24 also more calcic than the phenocrysts. Other minerals are quartz (subrounded; embayed),
25 clinopyroxene, amphibole, biotite, and rare titanite and zircon.

26 A salient compositional characteristic that provides insight to andesite-dacite origins with
27 respect to other G-SVP rocks is revealed when using SiO₂ as an index. Namely, abundances of
28 many incompatible elements, mainly HFSE and REE, decrease over the low to high SiO₂ range
29 (i.e., abundances are lower in dacites than in co-eruptive andesites and underlying alkalic basalts).
30 As examples: G-SVP basalts have ~50-70 ppm La, and andesites-dacites have ~59-22 ppm La; for
31 Zr, basalts have ~225-170 ppm, but most andesites-dacites have ~180-50; for Y, basalts >20 ppm,
32 andesites-dacites ~18-9 ppm. To understand these trends of lower HFSE and REE with increasing
33 SiO₂, we modeled fractional crystallization of G-SVP alkalic basalt (~50 wt.% SiO₂; ~9 wt.%
34 MgO), dehydration melting (10-25%) of granodiorite and high-K amphibolite, and basalt-rhyolite
35 magma mixing.

Fractionation and melting each require specific modal percentages of titanite, zircon, and allanite (e.g., $\leq 1\%$), the high ends of ranges for accessory-mineral/liquid partitioning coefficients, continual crystallization of accessory minerals from basalt to dacite (for fractionation), and specific source-melting percentages and low titanite, zircon, and allanite melting proportions (~ 0.02 ; dehydration melting). These requirements are too stringent to be realistic. Moreover, accessory minerals are rare in these lavas, and neither fractionation nor melting accounts for the plagioclase textures observed.

On the other hand, low-HFSE, -REE rhyolites (e.g., La 9-31 ppm; Zr 31-93; Nb 9-17; Y 4-10) containing Na-plagioclase are in the G-SVP and were temporally and spatially available to have mixed with G-SVP basalts. Mixing proportions of 20:80 to 90:10 for different rhyolite:basalt combinations yield hybrid compositions that overlap the G-SVP andesite-dacite compositional fields. Also, basalt invading rhyolite reservoirs containing mush zones can account for Na-plagioclase concentrations of ~ 11 -30 vol% formed after mush disruption and dispersal, plagioclase corroded-cores and higher-An% mantles and groundmass, and subrounded-embayed quartz. The straightforward explanation for G-SVP intermediate lavas, then, is repeated hybridization of basaltic and low-HFSE, -REE rhyolitic magmas during the early stages of G-SVP magmatism.

Key words: andesite origin, dacite origin, corroded plagioclase, basalt fractional crystallization; dehydration melting, basalt-rhyolite magma mixing

1. Introduction

The Miocene Goldfield-Superstition volcanic province (G-SVP) in central Arizona is composed largely of silicic lavas and ash-flow tuffs, and comparatively small amounts of alkalic basalt and intermediate-composition lavas (Fig. 1a). These varied rock types cover $\sim 8000 \text{ km}^2$ (Peterson, 1968). Considering the large area and volume of this volcanic province and its wide range in rock types, there are few detailed petrologic and geochemical studies of the G-SVP. What little studies there are began as reconnaissance nearly 50 years ago (e.g., Sheridan et al., 1970), and in the following decades, geologic information for the G-SVP investigations came largely from MS graduate thesis projects. These provided geologic maps, some rock compositions, and developed the general volcanic stratigraphy. Detailed petrologic studies began only recently with emphasis on the G-SVP basaltic rocks (Fodor and Vetter, 2011; Singer and Fodor, 2013).

In this report, we examine G-SVP intermediate-composition lavas. These lavas, generally andesites and dacites, are stratigraphically above the main occurrence of G-SVP basaltic lavas and below the voluminous silicic ash-flow tuffs and lavas that make up the bulk of the province (e.g., McIntosh and Ferguson, 1998; Ferguson and Trapp, 2001). Our motivation for studying these

andesites and dacites is one that often applies to intermediate-composition lavas in other large and diverse volcanic provinces. Namely, we endeavor to determine whether the andesites and dacites are differentiates of co-existing basalts, partial melts of middle or upper crust, partial melts of lower crust amphibolite or granulite, or are hybrids formed by mafic magmas that mixed with rhyolitic melts or assimilated silicic crust. While our evaluation will benefit understanding the petrogenesis of intermediate lavas in this central Arizona province – which qualifies as a silicic large igneous province (e.g., Bryan and Ferrari, 2013) -- our results will also apply to how andesites and dacites elsewhere can relate to their co-existing mafic and silicic volcanic rocks.

Our approach to studying the G-SVP andesites and dacites was to use petrography, whole-rock major and trace element compositions, and mineral compositions. The study incorporates 19 samples collected from the western portion of the G-SVP, which is the most accessible part of this large province (Fig. 1a). Among our pertinent observations for the compositions of G-SVP intermediate lavas is that, collectively, there are inverse correlation trends between many incompatible trace elements, namely HFSE and REE, and SiO₂. This geochemical relationship makes it challenging to explain the intermediate lavas by igneous processes such as fractional crystallization, with or without assimilation, and partial melting of almost any type of source rock.

2. Geologic Background

The western margin of the G-SVP begins about 40 km east of Phoenix, Arizona, and the province extends eastward about 60 km to Superior, Arizona (Fig. 1a). Physiographically, the province is at the northern portion of the southern Basin and Range, where it meets the transition to the Colorado Plateau (Fig. 1a). While silicic tuffs and lavas are exposed almost continuously across the G-SVP, outcroppings of the stratigraphically lower mafic and intermediate lavas are observed only in the western portion, as that is the most accessible by roads and trails (i.e., much of the G-SVP is wilderness and lacks access).

The first report on the petrography of G-SVP intermediate lavas was by Sheridan et al. (1970), who noted 'melted' and 'pitted' bands in plagioclase phenocrysts of a dacite. Hillier (1978) and Kilbey (1986) mapped and presented compositions for intermediate lavas they called andesite, latite, and dacite. On Arizona Geological Survey geologic maps created in the 1990s, the intermediate-composition rocks are called dacite (e.g., Skotnicki and Ferguson, 1995; Ferguson and Gilbert, 1997). Stratigraphic nomenclature of Ferguson and Trapp (2001) places the intermediate-composition lavas into the *Government Well* formation of the G-SVP.

The ages of the intermediate lavas can only be inferred from ⁴⁰Ar/³⁹Ar dates for sanidines in silicic G-SVP rocks (McIntosh and Ferguson, 1998). The oldest dates for the province are ~20.5 Ma, which are for small-scale rhyolite domes (Dombroski, 2010) that initiated the volcanism of the province (McIntosh and Ferguson, 1998). Alkalic basalt magmatism followed the dome

emplacements (Fodor and Vetter, 2011). The intermediate lavas overlie the basalts, and in turn are overlain by pyroclastic rocks dated ~19 Ma. Therefore, both the mafic and intermediate lavas of the G-SVP were emplaced between about ~20.5 and 19.0 Ma (McIntosh and Ferguson, 1998; Ferguson and Trapp, 2001).

The earliest published isotopic compositions for G-SVP volcanic rocks are by Stuckless and O'Neill (1973), who focused on Sr and O isotopes. One of their samples, 'older dacite', yielded an initial $^{87}\text{Sr}/^{86}\text{Sr}$ whole-rock ratio of 0.7057. This is similar to our one unpublished $^{87}\text{Sr}/^{86}\text{Sr}$ ratio we determined in year-2008 for an andesite BD-3), 0.705064 (Table 1). These ratios are also similar to the few available ratios for G-SVP basaltic lavas (0.7052 – 0.706; Fodor and Vetter, 2011).

Two recent publications in particular bear on this andesite-dacite study. One is the study of G-SVP basaltic rocks by Fodor and Vetter (2011) that identifies primitive alkalic basalt lavas (~11 wt.% MgO) of the *Cottonwood Spring* formation, and slightly more evolved alkalic basalt (~9 wt.%) of the *Weekes Wash* formation. Representative compositions of both *Cottonwood Spring* and *Weekes Wash* basaltic lavas are used for modeling in some sections of this paper.

The other relevant study is the MS thesis of Dombroski (2010). It provides whole-rock and mineral compositions for ~20.5 Ma small-scale rhyolite domes that preceded G-SVP basalts. The dome rhyolites were therefore available to mix with alkalic basalt to create intermediate magmas.

3. Sampling

More than half our samples come from the western portion of the G-SVP known specifically as the Goldfield Mountains (Fig. 1b). This relatively small range is located west of the Apache Trail (state route 88; Fig. 1b), the single highway that cuts through the volcanic province. We identify four subsets of collection sites within this region -- Bulldog Canyon, Saddle Rock, Tomahawk, and Cottonwood -- that we collectively place into a 'northern group' of samples (Fig. 1b). Hillier's (1978) study of intermediate-composition lavas was for sample locations corresponding to our northern group. Because we plot some of his compositional data, we note the Hillier (1978) location in Figure 1b.

Our remaining samples are from east of Apache Trail, in the Superstition Mountains (Fig. 1b). The collection-site subsets are Siphon Draw, Silly Mountain, Dinosaur Mountain, and Peralta Road (Fig. 1b). We place these into a 'southern group', although the Siphon Draw location is between the 'northern' and 'southern' groups (Fig. 1b). All told, our sample sites represent lavas emplacements over ~500 km². Appendix I lists the sample latitudes and longitudes.

4. Petrography

The modal mineralogy for each sample is presented at the bottom of Table 1. It lists phenocrysts of plagioclase, clinopyroxene, amphibole, biotite, and quartz, and accessory minerals titanite and

zircon The mode also includes oxidized (opacitized) silicates believed to be amphibole, and secondary minerals calcite and sericite, each occurring in only a few samples.

4.1 Northern Group Samples

Bulldog Canyon samples have from ~13 to 18 vol% plagioclase phenocrysts, largely subhedral and ~2 to 5 mm in length, of which most have cores surrounded by corroded, or reacted, zones and thin plagioclase overgrowths (Fig. 2a). Subhedral clinopyroxene can be up to 2 mm in size. Amphibole fresh enough to identify is present in only a few samples at <1 vol%, but more amphibole (~3-5 vol%) is present as opacitized grains identified by outlines that are linear or wedge shaped. (The possibility that some opaque grains are opacitized olivine cannot be discounted.) Biotite is rare, identified in only two samples. The groundmasses of *Bulldog Canyon* lavas are glassy but have plagioclase microlites (Fig. 2a).

Cottonwood and *Tomahawk* samples have from ~17 to 30 vol% subhedral to euhedral plagioclase, mainly ~2 to 3 mm, but up to 6 mm. Some phenocrysts are spongy and/or have cores surrounded by corroded, spongy zones, and thin mantles of plagioclase (Fig. 2b, c). Other phenocrysts have curved margins, rarely embayed, or margins that are essentially straight but in detail appear to be etched at boundaries with matrix glass. Only two samples have clinopyroxene phenocrysts, ~2 vol%, but most have micro-clinopyroxene in the groundmasses. Amphibole is present up to 6 vol.%, most of which opacitized but still recognizable by wedge and linear forms (Fig. 2e). Biotite ranges from a trace amount up to ~4 vol%. Almost all samples have traces of subrounded and/or embayed quartz (Fig. 2b). Groundmasses are glassy and contain microlites of plagioclase and Fe-Ti oxides.

Saddle Rock samples have ~17 vol% plagioclase phenocrysts largely subhedral and ~1.5 to 3 mm. Some are spongy throughout (Fig. 2d), and almost every grain has corroded, or reacted, margins. There are traces of biotite and clinopyroxene that are <0.1 mm in size, and nearly 1 vol% oxidized/altered silicate minerals. One sample has >2 vol% calcite that appears to be secondary after plagioclase and clinopyroxene. The groundmasses of these samples are mainly plagioclase laths, devitrification feldspar, Fe-Ti oxides, and glass.

4.2 Southern Group Samples

Peralta Road samples have from ~11 to 26 vol% plagioclase phenocrysts, mainly subhedral to nearly euhedral and ~2 to 5 mm in length (Fig. 2f). Margins on the lath forms vary from straight to slightly curved and irregular, and may be etched or corroded (Fig. 2f). Spongy or corroded zones are less common than in northern group plagioclase, and there are no thin plagioclase rims surrounding the plagioclase grains (i.e., no plagioclase core-mantle relationships). Two samples have clinopyroxene phenocrysts, ~1-2 mm and at ~2 and 6 vol%. Two other samples have from

~0.5 to 3 vol% each of amphibole and biotite, both of which are oxidized to where some amphibole is opaque (identified by wedge and linear forms). Among three samples, subrounded and embayed quartz occurs at 0.2, 3, and 6 vol%. Groundmasses in all four samples are glassy with plagioclase microlites and laths.

Silly Mountain sample has ~28 vol% subhedral to euhedral plagioclase grains, 2-5 mm, that have straight, curved, or irregular margins that in detail may be etched at the contacts with the glassy matrix (Fig. 2g). Biotite and amphibole are present, ranging from nearly fresh to oxidized (opacitized). Traces of subrounded quartz grains and zircon are also present (Fig. 2g). The groundmass is largely glassy, but with a snowflake devitrification texture (Fig. 2g).

Siphon Draw sample has ~21 vol% subhedral plagioclase phenocrysts, ~2-5 mm, with straight and curved margins, and some corroded and surrounded by thin plagioclase rims. Largely the plagioclase grains are mottled under crossed polarized light because they are complex mixtures of albite and orthoclase, as determined by microprobe. Biotite, up to 4 mm, is present, and ~0.2 vol% wedge-shaped titanite (Fig. 2h). Subrounded and embayed quartz grains compose over 3 vol% of this lava. The groundmass appears glassy and contains plagioclase microlites.

Dinosaur Mountain sample has ~21 vol% plagioclase, but it is altered to an Ab-rich feldspar and white mica (sericite). Some of the white mica occurs as phenocrysts, 1-2 mm and ~4 vol%, that likely represent total replacement of feldspar phenocrysts. The alteration of this lava also created ~2.5 vol% calcite. The groundmass appears to be both devitrified and altered glass.

5. Analytical Techniques

Major element compositions were determined by x-ray fluorescence of glass fusion discs largely acquired at the University of North Carolina-Chapel Hill XRF analytical facility, and some at the North Carolina State University XRF lab. Trace element compositions were determined by ICP-MS at Acme Laboratories, Vancouver, BC. Minerals were analyzed by an ARL-SEMQ six wavelength-spectrometer electron microprobe at North Carolina State University. Operating conditions were 15 keV and 0.015 micro-amperes for 10-second peak and background count times. Reference minerals are from the Smithsonian collection for microprobe analyses, plus a synthetic rare earth element standard was used for REE analyses in titanite. The one Sr isotope ratio we report was acquired at the University of North Carolina-Chapel Hill isotope analytical facility.

6. Analytical Results

6.1 Major elements

Major elements compositions are listed in Table 1, and illustrated in a total alkalis vs SiO₂ plot (TAS) in Figure 3, and in SiO₂ variation diagrams in Figure 4. The TAS diagram shows that the samples straddle the line that separates andesite-dacite from trachyandesite-trachydacite. Similarly,

the intermediate-composition lavas examined by Hillier (1978) from locations along the Apache Trail (northern group) have overlapping compositions. An exception to andesite and dacite is the southern-group Dinosaur Mountain sample which plots in the low-SiO₂ rhyolite field. Also shown is the rhyolite glass matrix for a northern group dacites. Table 1 includes Al₂O₃/(Na₂O+K₂O+CaO) (molecular) ratios, and the <1 ratio for most andesites and dacites classifies them as metaluminous.

The TAS diagram makes no distinction between northern and southern group samples. There are, however, some differences that correspond to sampling sites within each group. For example, Bulldog Canyon andesites have the lowest SiO₂ of the northern group, and Saddle Rock samples plot separately from those nearby at Tomahawk-Cottonwood sites. In the southern group, the four Peralta Road samples span a SiO₂ range almost as wide as displayed for all other samples. Single samples, such as Silly Mountain, have high SiO₂, and the Siphon Draw sample has exceptionally high total alkalis -- but this is due to alteration of original plagioclase to Or-feldspar and sericite.

The SiO₂-variation diagrams for the intermediate lavas (Fig. 4) include for comparison two types of G-SVP alkalic basalts (Fodor and Vetter, 2011). One type, *Cottonwood Spring* low-Ti variety, is the more primitive (MgO ~11 wt.%), and the other, *Weekes Wash*, is more evolved (MgO ~ 9 wt.%). Among the intermediate lavas, some notable features in the variation diagrams include the collective inverse correlations between SiO₂ and TiO₂, CaO, Fe₂O₃, MgO, and P₂O₅. The Hillier (1978) samples overlap our samples, supporting that his collection represents our northern group lavas (Fig. 1b). The data for Al₂O₃ are scattered, and collective data for K₂O form a flat to weakly positive correlation with SiO₂. We note in the Al₂O₃, K₂O, and MgO panels where we suspect that alteration enriched or lowered magmatic values (e.g., a Bulldog andesite).

The collective correlation trends formed when plotted against SiO₂, whether inverse as most major elements or slightly positive as for K₂O, appear to be linear extensions from the G-SVP basalt compositions. Among these trends, a distinction to note is that Peralta Road samples have higher TiO₂ and P₂O₅.

6.2 Trace elements

The incompatible element abundances show both inverse and positive correlations with SiO₂ when samples are viewed collectively for each element (Fig. 5). For example, among large-ion lithophile elements (LILE), Sr decreases with increasing SiO₂, and Rb and Ba display flat to rather scattered data fields. But when compared to basalts, Ba and Rb form weakly positive trends with SiO₂ as it increases from basaltic values (e.g., 46-48 wt.%) to ~70 wt.%. There is some within-group variation, such as the relatively high Ba in northern group Tomahawk samples.

The high-field strength and rare earth elements (HFSE; REE) Zr, Nb, Y, Hf, and La all collectively show trends of decreasing abundances with increasing SiO₂. Ta and Th have generally flat trends with SiO₂. For all these elements but Y, the trends begin with values equal to or slightly

highly than the values for G-SVP basalts (Fig. 5). Some distinctions to note include that southern group Peralta Road samples are enriched in Zr, Nb, Ta, Y, and Hf relative to northern group lavas. Even with this relative enrichment, the four Peralta samples demonstrate collective trends that decrease in these elements as SiO₂ increases. The transition metals Sc and Ni each have inverse correlation with SiO₂ that begin with values lower than in G-SVP basalts.

Patterns for chondrite-normalized rare-earth elements are in Figure 6, where each panel includes G-SVP alkalic basalt (both the primitive and more evolved varieties) patterns for comparison. All northern group lavas (panels A, B; Fig. 6) have light-REE (LREE) enriched patterns that are subparallel to and below the patterns for G-SVP basalts. The patterns for lowest total REE abundances are generally for lavas with the highest SiO₂, and they have more pronounced Eu negative anomalies.

Similarly, the Peralta Road lavas (panel C; Fig. 6) of the southern group have REE patterns lower than those for basalts, subparallel to basalts from LREE to middle-REE, and have Eu negative anomalies. Patterns for these lavas appear to converge with the basalt patterns at the heavy-REE (HREE) end of the patterns more than those of the northern group. This is consistent with the comparatively higher HFSE observed in Peralta Road andesites and dacite (Fig. 5). Panel D shows patterns for single-samples of the southern group, all of which are similar in shape and overlap, and represent rather high SiO₂ whole-rock compositions (e.g., ~63-70 wt.%).

Patterns for primitive-mantle normalizations are in Figure 7, where each panel includes at least one representative G-SVP primitive alkalic basalts for comparison; panel C additionally shows a pattern for the more evolved basalt. Panels A and B show northern group samples, and some of the main features reinforce those in the SiO₂ variation diagrams. Namely, Rb, Ba, and K are higher in the intermediate lavas than in basalts, and many of the other incompatible elements are lower than abundances in basalts. In addition, there are Nb-Ta anomalies more pronounced than in basalts. Also, the andesite and dacite patterns cross over the basalt pattern, or nearly so, at Zr-Hf. Panel B shows the same features for other northern group samples, except for having a less pronounced Zr-Hf overlap with basalt.

In southern group samples, panel C reinforces the characteristic for some Peralta Road samples having comparatively higher HFSE. In particular, the Zr-Hf portion of Peralta patterns cross over the basalt patterns to higher values. Only the most evolved (SiO₂ ~68 wt.%) sample has lower Zr and Hf than basalts. Panel D shows the remaining southern-group lavas, all high in SiO₂ (~63 to 70 wt.%) and LILE and notably lower in HFSE than basalt.

6.3 Mineral and glass compositions

Representative clinopyroxene compositions are listed in Table 2 and illustrated in Figure 8a as Fs-Wo (ferrosilite-wollastonite) endmembers for point analyses. For comparison, clinopyroxene in

two samples of *Weekes Wash* basalt are included. Clinopyroxene in the northern group samples collectively form a trend of increasing Fs and slightly decreasing Wo that extends from the *Weekes Wash* basalt clinopyroxenes. The trend includes two clinopyroxene populations in dacite CW-8 defined by ~10 and 14 mol% Fs (Fig. 8a, encircled compositions; Table 2). The two Peralta Road samples (southern group) that contain clinopyroxene either overlap or extend the Fs-Wo trend to highest Fs and lowest Wo. This latter is unexpected because the high-Fs, low-Wo sample, PR-2, has a whole-rock Mg# of 55.8 (Table 1) similar to that for Bulldog Canyon sample BD-A (northern group), Mg# 58.6, which has clinopyroxene that overlaps *Weekes Wash* basalt clinopyroxene (Fig. 8a). For lavas that have within-clinopyroxene Fs-Wo trends, such as PR-2 (Fig. 8a), zoning is normal. Overall, the clinopyroxenes have relatively high Al₂O₃, ~2.7 to 6.2 wt.%, but Al₂O₃ is ~1 wt.% in the relatively high Fs clinopyroxene of CW-8 (Table 2).

Representative plagioclase compositions are in Table 3 and illustrated in Figures 8b,c as An-Or (anorthite-orthoclase) endmember plots for point analyses. In northern group lavas, plagioclase phenocrysts -- sometimes as cores with respect to having surrounding corroded zones and thin rims (Fig. 2a-c) -- are largely oligoclase and andesine (Fig. 8b). The thin rims around the cores are mainly labradorite but also calcic andesine. Figure 8b shows the rim compositions to be separate from their cores at ~An₄₅ and extending to ~An₆₄. These largely labradorite rims are compositionally equal to their coexisting groundmass laths (generally ~0.1-0.3 mm), which are also mainly labradorite, ~An₅₀₋₆₀, more calcic than the plagioclase cores.

For southern group lavas (Fig. 8c), there are no core-rim relationships and we accordingly identify the plagioclase as phenocrysts and groundmass. Phenocryst compositions are between ~An₂₅ and An₄₈, as in the northern group (Fig. 8b,c). Three samples have groundmass laths more calcic than coexisting phenocrysts (Fig. 8c). The fourth sample, PR-1, has slightly more calcic portions in phenocrysts (~An₃₈₋₅₆) and therefore some phenocrysts and groundmass laths overlap (Fig. 8c). Additionally, some small grains are slightly more sodic (to ~An₃₅₋₄₀). Also notable is that PR-2, the southern group lava with highest MgO (4 wt.%, Table 1), has plagioclase with highest Or relative to An (Fig. 8c).

Representative amphibole compositions are listed in Table 2 and illustrated as individual point analyses in Figure 9 where they represent points inward from opaque rims. In a SiO₂ vs Al₂O₃ expression, amphiboles in the northern group samples show a weak inverse correlation over ~44 to 38 wt.% SiO₂. Some samples have more than one distinct amphibole composition, such as CW-8, where Mg# spans ~65 to 72 (Table 2) and Al₂O₃ is ~9.5 to 12 wt.% (Fig. 9a). Its low-Al₂O₃ variety overlaps with that in sample SM-1, a southern group dacite with amphibole Mg# ~60 (Table 2; Fig. 9a). Figure 9b shows that there are weak correlations between MgO vs TiO₂ and vs FeO. All amphiboles are pargasite except the edenitic low-Al₂O₃ amphibole in high-SiO₂ (67.8 wt.%) dacite SM-1 (Leake et al., 1997).

Representative biotite compositions are listed in Table 2. The compositional variation observed is shown by FeO, ~12 to 17 wt.%, which translates in Mg# 73-57. While this range represents the northern and southern group lavas combined, it can also be represented in single lavas (SR-9, SA-1) as well as in single thin sections (CW-8) (Table 2). That is, a single lava can have more than one composition biotite. The BaO in the biotite ranges from ~0.6 to 1.1 wt.% (Table 2)

Titanite was observed in only one sample, and a composition is in Table 4. The analyses show small amounts of La and Ce.

Glass comprising the matrix of dacite CW-7 is the only glass fresh enough for obtaining microprobe analyses of major elements. The TAS diagram (Fig. 3) shows that it is a rhyolite, as does its composition listed in Table 4.

A composition for white mica, sericite, is in Table 4. This is a secondary mineral in the single rhyolite sample, DM-1, that is almost certainly due to subsolidus hydrothermal fluid interaction with original plagioclase (e.g., Plummer and Puntis, 2009).

7. Discussion

Topics to address for establishing the origins of the G-SVP plagioclase-phyric andesites, trachyandesites, dacites, and trachydacites include identifying: (i) their source materials; (ii) the particular igneous process that they underwent as magmas; (iii) the relationships among these lavas to one another and to the G-SVP alkalic basalts and silicic rocks. All of these concerns require recognizing that prior to emplacement of intermediate composition lavas, small-scale rhyolite domes in Bulldog Canyon and alkalic basalt lavas had already erupted. Their significance lies in providing silicic and basaltic magmas available for interacting prior to eruptions of the andesites and dacites.

7.1 Origins for the andesite and dacite lavas

Annen et al. (2006) provide a thorough review of the various sources for and mechanisms by which intermediate-composition magmas are understood to originate. Those appropriate to consider for the G-SVP lavas are fractional crystallization, assimilation fractional-crystallization, magma mixing, and crustal melting.

7.1.1 Fractional crystallization

Because G-SVP alkalic basalts underlie the intermediate lavas, fractional crystallization of basalt in deep to shallow crustal levels is a possible origin for G-SVP andesites and dacites. While it is impossible to estimate original volumes of basaltic and intermediate lavas due to erosion and faulting, field examinations suggest at least equal volumes and surface areas (e.g., Skotnicki and Ferguson, 1996), leaving it reasonable to consider fractional crystallization relationships. On the

other hand, abundances of most HFS incompatible elements in the andesites and dacites are inconsistent with a straightforward differentiation from parental basalt. Namely, when using SiO₂ as an index of differentiation from ~48 to 70 wt.%, abundances of the REE and most HFSE display decreasing trends with increasing SiO₂ (Figs. 5, 6). While negative correlations with SiO₂ are not unusual for some incompatible elements, such as P₂O₅ and TiO₂, and Sr if plagioclase segregates during differentiation, Zr, La (all REE), Nb, Th, Hf, and Y are generally expected to increase as mafic magmas crystallize their characteristic minerals. On the other hand, K₂O, Ba, and Rb demonstrate incompatibility with respect to basalt minerals by their flat to positive correlations with SiO₂ as extrapolated from abundances in G-SVP basalt through to the most evolved intermediate lavas (Figs. 4, 5).

Assimilation fractional-crystallization (AFC) does not improve chances for trace element abundances relating the andesites and dacites to alkalic basalts by differentiation. This is because as long as there is some parent basalt crystallization in response to latent heat needed to assimilate crust, there will be at least nominal increases in incompatible element abundances in the assimilating basaltic melt. This holds even if the crustal assimilate is largely quartz, which has little to no abundances of incompatible elements to offer.

On the other hand, a way to explain the decrease in HFSE and REE abundances during fractional crystallization from basalt to dacite is by including accessory minerals, such as titanite, zircon, and allanite. Titanite incorporates all REE and HFSE, zircon accepts HREE and HFSE, and allanite partitions Th. To account for the decreasing trend for Sr and for Eu negative anomalies more pronounced in the lavas with highest SiO₂, plagioclase is required to continually crystallize from basalt to dacite. Also, Sc can decrease if clinopyroxene and/or titanite crystallize.

To test this model for accessory minerals, we first applied mass balancing for the major elements of two G-SVP basalt compositions as parental for andesite and dacite. Only the more evolved basalt, *Weekes Wash*, which has SiO₂ ~50 wt.% and MgO ~9 wt.%, gave good results. Table 5 shows that *Weekes Wash* crystallization can produce Bulldog Canyon andesite (SiO₂ ~56 wt.%) and Cottonwood dacite (SiO₂ ~65 wt.%) in the northern group of samples by respectively fractionating 54% and 72% of the *Weekes Wash* assemblage plagioclase, clinopyroxene, olivine, and Ti-magnetite (we did not include accessory minerals in these calculations). The *Weekes Wash* composition is also a good major element fit as parent for southern group lavas, Peralta Road andesite and dacite, by crystal segregation of 63 and 76%, respectively (Table 5).

We then applied the calculated modal minerals (Table 5) and their respective partitioning coefficients, K_{DS}, to Rayleigh fractionation calculations for HFSE, La, Sr, and Sc in the northern group lavas. For these calculations we included small amounts (<1%) of titanite, zircon, and allanite in the crystallization assemblages because these minerals strongly influence HFSE and REE

(and some transition metals) behaviors in melts (e.g., Tiepolo et al., 2002; Bachmann et al., 2005). K_D values for accessory minerals are in Table 5.

Calculations show that by adding from ~0.2 to 1% titanite, ~0.02% zircon, and ~1% allanite to the assemblages, and applying the high ends of ranges published for HFSE and La partitioning coefficients with respect to titanite and zircon (e.g., Bachmann et al., 2005), fractional crystallization yields liquids with HFSE and La abundances generally in line with those observed for northern group andesite and dacite (Table 5). Namely, 'parental' *Weekes Wash* basalt can progressively fractionate liquids that have decreasing HFSE and REE abundances provided that small amounts of accessory minerals are in the crystallizing assemblages. Results, however, are highly sensitive to specific K_D s (generally highest values, and for silicic melts) and specific modal percentages of each accessory mineral per element (Table 5).

Trace element abundance ratios that are controlled by accessory minerals can provide additional insights. Figure 10 shows andesite and dacite Zr/Nb either similar to those of *Weekes Wash* basalts or lower in a way that could represent zircon removal. An exception is Saddle Rock lava, for which higher Zr/Nb eliminates likelihood for *Weekes Wash* basalt as parental. Also, the most primitive andesite, Bulldog Canyon, has Zr/Y, Nb/P₂O₅ and Th/Hf higher than in *Weekes Wash* basalt to suggest that fractionation of zircon, titanite, or allanite fractionation were not responsible for the ratio differences between basalt and this andesite. For Peralta southern group lavas, ratios Zr/Y, Nb/P₂O₅, Th/Hf, and Zr/Hf show that if they are basalt fractionation products, they had a parent characteristically different from *Weekes Wash*, and that Th was not influenced by allanite (Th/Hf increases).

Our overall assessment for fractional crystallization relationships between basalt and andesite-dacite is therefore dubious. Because specific conditions are required in the Rayleigh models -- such as the highest published K_D s for the accessory minerals; specific modal percentages for titanite, zircon, and allanite; the need to include allanite to accommodate Th -- and because there are trace element abundance ratios that do not link all G-SVP lavas, fractional crystallization is not convincing to account for G-SVP andesites and dacites. Also, with the exception of titanite in trachydacite SD-5 (Table 4) and trace zircon in dacite SM-1, the required accessory minerals were not observed in the thin sections examined optically and by electron microprobe. Additionally, the mass balancing and Rayleigh fractional crystallization models do not in themselves account for corroded and spongy cores of oligoclase-andesine plagioclase (Fig. 2 a-d), the more calcic plagioclase rims around some cores and as groundmass laths (e.g., labradorite vs oligoclase-andesine), nor for subrounded, sometimes embayed, grain boundaries. Therefore, we explore a second igneous process to account for the G-SVP andesite and dacite trace element abundances and textural aspects.

7.1.2 Dehydration melting

Experimental melting of amphibolites, tonalites, and meta-sediments over recent decades has produced melts that range from SiO₂-rich granitoid compositions to intermediate compositions of 55 to 60 wt.% SiO₂ over ~800-1100°C and from <1 GPa to 2-3 GPa (e.g., Conrad et al., 1988; Beard and Lofgren, 1991; Rushmer, 1991; Skjerlie and Johnston, 1992; Sen and Dunn, 1994; Rapp and Watson, 1995; Gardien et al., 1995, 2000; Patino-Douce and Beard, 1995; Winther, 1996; Singh and Johannes, 1996 a, b; Sisson et al, 2005; Patino-Douch, 2005). Accordingly, we explore dehydration melting of some potential source rock compositions to produce G-SVP intermediate lava compositions. Before this endeavor, however, we ruled out some rock types as candidates, such as meta-sediments. They yield peraluminous melts, and G-SVP lavas are metaluminous. Also, MORB-like amphibolite is eliminated because the high K and Na of G-SVP andesites and dacites (many qualifying as 'trachy'; Fig. 3) require an alkalic source rock (Roberts and Clemens (1993). This leaves two rock types to consider for dehydration melting models: granodioritic (tonalitic) and alkalic basalt (or amphibolite). In both cases, accessory minerals are needed in the source to control HFSE and REE abundances that enter the melts. Both titanite and zircon exist under a wide range of P and T conditions (e.g., Harrison and Watson, 1983; John et al., 2001), where oxidation is particularly important for titanite stability (e.g., Tiepolo et al., 2002) and H₂O for zircon (e.g., Harrison and Watson, 1983; Harrison et al., 2007).

We evaluated 10% and 25% melts of granodiorite, and 15% and 25% melts of relatively high-K amphibolite. For each case, it was assumed that smaller percent melts are dacitic and larger percent melts are andesitic. Also, it is necessary that the trace element abundances in the source rock increase with increasing volume of anatectic melt produced -- meaning that their melting proportions need to be very low compared to those of the source-rock major minerals.

For granodiorite melting, the modal assemblage is 53% plagioclase, 10% each of biotite and orthoclase, 5% amphibole, 20% quartz, 1% ilmenite, 1-2% titanite, and a trace of zircon (0.1%) to accommodate Zr and Hf (modes were normalized after adding varying accessory mineral percentages). Assessing trace elements during melting relies heavily on mineral/liquid partitioning coefficients, K_{DS} , for each element hosted by accessory minerals. K_D values used are the same as for fractional crystallization modeling (Table 5), which are largely from Bachmann et al. (2005), with addition of ilmenite from (Klemme et al., 2006).

For melting proportions in our calculations, we used biotite 0.4 and amphibole 0.2, relatively high proportions because melting experiments identify these hydrous minerals as among the first to be consumed. For plagioclase and orthoclase we used 0.1 for each, quartz 0.159, ilmenite and titanite each 0.02, and zircon 0.001. With our melting proportions, both biotite and amphibole melt out at 25% partial melting. We did not include in our calculations that small amounts of restite

minerals, such as clinopyroxene or orthoclase that may form from melting reactions, believing that their small amounts would have little to no impact on the bulk K_{DS} for HFSE and La.

One other specification of our trace element calculations is circumventing not knowing the original trace element concentrations, C_O , in any model source granodiorite. We accordingly made all original concentrations equal to 1, and then calculated concentrations in liquid, C_L , as batch melts using the equilibrium melting equation inclusive with melting proportions: $C_L/C_O = 1/(D_o + F - FP)$ (where: D_o is bulk K_D ; F is melt fraction; P is bulk melting proportion that accounts for non-modal melting). By this method, a $C_L < 1$ indicates that trace element abundance is lower in the melt product than in the source rock.

To illustrate our results for the elements of concern, we use a C_L/C_O diagram in Figure 11a. Our calculations show that it is possible to produce high-SiO₂ melts (10% batch equilibrium melting) and intermediate-SiO₂ melts (such as andesites; 25% batch melting) with HFSE and La lower in the melt products than in a granodiorite source, owing to HFSE- and REE-bearing accessory minerals. But these results reflect our particular major and accessory mineral modal percentages, melting proportions, and K_{DS} -- all geologically and geochemically reasonable values, but subject to variations and uncertainties (e.g., K_{DS} affected by pressure, H₂O content, technique for determining, as reviewed in Severs et al., 2009). Also, not all of the elements tested differ much in abundances from smaller to greater partial melting (Fig 11a), and they therefore do not identically match the observed trace element trends formed in plots against SiO₂ (Fig. 5).

For amphibolite melting, we used a hypothetical amphibolite with composition based on alkalic basalt SR-8, a *Weekes Wash* representative used in the fractionation model. For 15% melting, we used as the source-rock mode: plagioclase 49%, amphibole 48.5%, ilmenite 1%, titanite 0.4-1.5%, traces of zircon, 0.2 to 0.5%. and to accommodate Th, allanite 1%. Melting proportions are plagioclase 0.45, amphibole 0.5, ilmenite 0.02, titanite each 0.01-0.02, zircon 0.005, and allanite 0.01. For 25% melting, we added 5% clinopyroxene as restite mineral to the mode, including it as another mineral in equilibrium with the 25% partial melt (we then accordingly diluted the other modal minerals). Accessory mineral K_{DS} are as in Table 5 but for trace element partitioning involving amphibolite minerals we used Xiong (2006).

The amphibolite dehydration melting results are plotted in an abbreviated primitive-mantle normalization diagram in Figure 11b that includes the amphibolite source rock (basalt SR-8) and a G-SVP dacite for comparisons. Overall, the HFSE, La, Sr, and Sc in the partial melts are lower in abundances than in the amphibolite source, as they are in actual G-SVP andesite-dacite lavas (Fig. 11b) -- although there are no meaningful differences between the lower and higher percent melting values for most elements, such as Y, Th, and Sc. The normalization plot (Fig. 11b) shows that with our chosen K_{DS} , source mineral-mode, and mineral melting proportions, andesite and dacite

composition melt products can have lower HFSE and REE than their K-enriched amphibolite source.

However, just as we qualified our fractional crystallization modeling, our dehydration melting models for granodiorite and amphibolite do not provide unique solutions for producing G-SVP andesite and dacite compositions. They do show that the approximate abundances and the trends for the HFSE and REE in the andesites and dacites are possible to produce when small amounts of zircon, titanite, and allanite are in a source that undergoes dehydration melting, but the results depend strongly on specific K_{DS} , modal mineralogy, and melting proportions. And even then, abundances of some HFSE in the calculated partial melts do not differ much from lower to higher percentages of source melting. Therefore, we examine magma mixing as a process to account for the major and trace elements of the G-SVP intermediate lavas.

7.1.3 Magma mixing

Another way to produce a suite of intermediate lavas is by mixing mafic and silicic magmas (e.g., Eichelberger, 1978; Kawabata and Shuto, 2005; Kent et al., 2010; Laumonier et al., 2014). There are several petrographic features and some mineral compositions in the G-SVP lavas that are consistent with magma mixing histories. These include the corroded Na-plagioclase cores with Ca-plagioclase rims and associated Ca-plagioclase groundmass laths (note that G-SVP plagioclase textures and higher-Ca margins are identical to plagioclase cores and rims in Figure 1 of Eichelberger (1978), one of the first papers to emphasize basalt-rhyolite mixing to create andesite-dacite hybrids), embayed quartz, rhyolite matrix glass in dacite (Table 4), examples of multiple biotite, amphibole and clinopyroxene compositions within single lavas (Table 2; Figs. 8a, 9), and minerals seemingly out of equilibrium with their host lavas (e.g., Fig. 8a, c and related text). For such mafic-silicic magma mixing to account for the trace element abundance trends observed in the G-SVP (decreasing trends for HFSE and REE with increasing SiO_2), the silicic endmember(s) would have had to be notably low in REE and HFSE abundances and have a relatively large Eu anomaly.

There are such rhyolite candidates in the G-SVP appropriate for a mixing model. These are the rhyolite domes of Bulldog Canyon that underlie the basalts and represent the first magmatism of the province (McIntosh and Ferguson, 1998; Dombroski, 2010). They offer two different rhyolite compositions, each one low in the incompatible elements relevant for our modeling (Table 6). To test a model for mixing basalt with these rhyolite compositions, we calculated hybrid melt compositions for varying proportions of two representative G-SVP alkalic basalt compositions mixing with the two different rhyolite compositions. The fractions tested range from 0.90 to 0.20 rhyolite compositions mixing with from 0.10 to 0.80 basalt compositions. The resulting hybrid major and trace elements are in Table 6.

Comparing the major element abundances calculated for hybrids to those observed for G-SVP andesites and dacites (Tables 1 and 6) shows enough similarities to suggest that G-SVP lavas of the northern group can be hybrids of G-SVP basalt and rhyolite, although Al_2O_3 is somewhat low in the calculated hybrids. Encouraging is that one rhyolite composition is for a dome that has oligoclase-andesine phenocrysts, An_{28-38} (Dombroski, 2010), thereby making this silicic melt appropriate for providing the Na-plagioclase present in the andesites and dacites (Fig. 8b, c). The other rhyolite has oligoclase, An_{10-18} , and sanidine (Dombroski, 2010), making it less compelling as an endmember because no sanidine was observed in the andesites and dacites.

To further examine these basalt-rhyolite mixes, we superimposed onto the calculated HFSE, La, and Sr abundances (from Table 6) observed lava compositions as fields created from the SiO_2 variation diagrams of Figure 5. The plots (Fig. 12) show that by mixing fractions from 0.20 to 0.90 rhyolite with basalt reproduces trends of decreasing trace element abundances to attend increasing SiO_2 , and that these trends generally overlap the compositional fields for the observed intermediate lava compositions. While calculated MgO is slightly higher and Sr slightly lower than data for the compositional fields (Fig. 12), these small differences can be reconciled if the ~3 to 5 vol% plagioclase in the rhyolite endmembers (Dombroski, 2010) were concentrated to the ~13 to 30 vol% observed in the northern group plagioclase-phyric andesites and dacites. The mechanism we envision is that the rhyolite reservoir(s) had a Na-plagioclase mush zone disrupted and dispersed by invading basalt (e.g., Bachmann and Bergantz, 2004; 2008; Klemetti and Clynne, 2014; Streck, 2014). That is, entry of basalt into a rhyolite reservoir(s) through a basal Na-plagioclase mush zone can account for plagioclase grains dispersing throughout the newly formed basalt-rhyolite hybrid and eventually concentrating to ~13 to 30 vol%. Plagioclase dispersal and subsequent concentration can elevate Al_2O_3 and Sr and lower MgO abundances such that resultant hybrids would compare closer to the compositional fields for actual lava compositions (Table 6; Fig. 12).

Basalt entry into a rhyolite reservoir(s) can also explain corroded, curved, and etched margins of Na-plagioclase in the andesites and dacites as heat from the mafic magma reacted with oligoclase-andesine. Basalt intrusion can also account for depositing calcic-plagioclase rims on some corroded Na-plagioclase phenocrysts, owing to 're-set' of the hybrid melt composition. It can also explain subrounded and embayed quartz, as quartz would have been part of the rhyolite reservoir mineral assemblage. Clinopyroxene compositions in some andesites that are slightly more evolved than clinopyroxene in basalt (Fig. 8a) and amphibole and biotite can be explained as minerals crystallized from the intermediate compositions of hybrids. Multiple compositions for these mafic minerals occurring in single lavas and some mineral compositions seemingly out of equilibrium with host lavas point to multiple events of magmas mixing and hybridizing. Finally, relict olivine from basalt endmembers was not observed in any andesites or dacites, but some of the opacitized grains that we interpret to be amphibole may in fact represent olivine from a basalt endmember of a

hybrid. The opacitization of amphiboles may result from elevated temperatures during magma mixing (e.g., Kawabata and Shuto, 2005; Plechov et al., 2008).

The modeled hybrid compositions and the textural aspects of the actual andesites and dacites demonstrate that G-SVP andesites and dacites are consistent with representing mixes between alkalic basalt and silicic melts that had low HFSE and REE abundances. These silicic melts may be the rhyolite domes (magmas) available to mix with the stratigraphically higher alkalic basalts to yield the andesites and dacites in the northern group (i.e., all rock types are temporally and spatially related). However, while the two selected rhyolite compositions model as reasonable endmembers for the basalt-rhyolite mixes, other similar composition melts were likely available ~19 to 20 Ma to mix with alkalic basalt -- or even the high-SiO₂ dacite-rhyolite compositions of this study (i.e., SM-1; DM-1) may have been endmembers in some mixing. There are enough compositional (mineral and trace element) differences between southern group and northern group lavas to suggest that lavas such as the Peralta Road had basalt and/or rhyolite endmembers other than what we modeled for the northern group (Table 6; Fig. 12). For example, different mol% Or in the oligoclase-andesine phenocrysts (or cores) (Fig. 8b, c) points to various basalt and rhyolite compositions mixing to form hybrids. And distinctions between phenocryst and groundmass plagioclase compositions are generally different between northern and southern group lavas.

One kind of silicic melt for the G-SVP can be ruled out as playing a role in magma mixing to create andesite-dacite. This is any melt produced from the local Proterozoic upper crust because its ⁸⁷Sr/⁸⁶Sr is 0.72 to 1.1 (Stuckless and O'Neill, 1973), greatly different from our single ⁸⁷Sr/⁸⁶Sr, 0.705064 for andesite BD-3.

We recognize that (i) there were likely many mixing events to yield the span of andesite-dacite compositions, (ii) that different basalt-rhyolite compositions were active in the northern and southern groups (e.g., southern group, overall, has higher Zr and Nb), and (iii) that basalt-rhyolite mixing is more complex than simple A+B mixing (e.g., Laumonier et al. (2014) discuss how parameters such as crustal depth, magma H₂O, viscosity, strain rates, and gas pressures influence the mixing process and results). Nonetheless, we are led by all the positive aspects of our magma mixing calculations, our endmember selections for modeling, the possibility for different bodies of low HFSE, REE magmas available for mixing with basalts, and the textural features of the andesites and dacites to favor hybridization as the dominant process for the origin of the G-SVP plagioclase-phyric intermediate lavas.

8. Conclusions

We demonstrated that several igneous processes can account for the major and trace element abundances and patterns of the G-SVP intermediate composition lavas emplaced over 500 km² ~20.5 to 19 Ma. Two processes -- fractional crystallization of basalt and

dehydration melting -- require accessory minerals titanite, zircon, and allanite to control abundances of HFSE and REE to match those in the lavas. For basalt differentiation to andesite and dacite, major element mass balancing is sufficiently good, but trace element calculations to produce G-SVP intermediate-composition lavas have too many restrictions to make this process a reasonable choice. Additionally, these minerals are either rare in G-SVP lavas, or unobserved, and the process cannot account for corroded Na-plagioclase cores, higher An mantles and groundmass laths.

For dehydration melting, titanite, zircon, and allanite must be in the source rocks and only sparingly relinquish their HFSE and REE as melting proceeds. However, besides uncertainties in K_D s for these dehydration models, there are the added variables of modes and melting proportions for the accessory minerals (as well as for the silicate minerals) during source-rock melting. When we add to that how restite minerals from melting reactions and how melting pressures (middle crust for granodiorite to lower crust/upper mantle for amphibolite) affect trace element abundances in melts, and how our models show that for most elements there are little differences in abundances between 10% and 25% melting, we must eliminate dehydration melting as an explanation for G-SVP intermediate lavas.

Basalt-rhyolite mixing requires low HFSE, REE silicic endmember compositions to create hybrid andesites and dacites to replicate the trace element abundances and patterns observed for early stages of the G-SVP. Such Miocene melts were available to mix with basalts. Our calculations show that this mixing, likely occurring as multiple events during G-SVP magmatism between different mafic and silicic melts (e.g., some lavas have multiple populations of mineral compositions), could yield appropriate intermediate-composition hybrids that have appropriate modal percentages of corroded Na-plagioclase with mantles of higher-An plagioclase, and embayed quartz. We conclude that magma mixing is the most straightforward and dominant process to explain the origin of G-SVP intermediate lavas.

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Appendix I

Sample latitudes and longitudes

Northern group

CW-5	33°30' 5.0"N	111°30' 7.4"W
CW-6	33 30 50.1 N	111 30 7.4 W
CW-7	33 30 53.8 N	111 30 22.4 W
CW-8	33 29 26.9 N	111 30 13.0 W
TM-6	33 28 57.6 N	111 28 38.6 W
TM-5	33 29 18.2 N	111 29 22.2 W
BD-A	33 29 19.2 N	111 33 28.7 W
BD-2	33 29 32.1 N	111 32 36.0 W
BD-3	33 29 32.1 N	111 32 36.0 W
NM-1	33 28 17.1 N	111 33 27.9 W
SR-9	33 28 14.5 N	111 31 5.2 W
SA-1	33 28 15.4 N	111 31 3.7 W

Southern group

PR-1	33°22'44.3"N	111°21'11.7"W
PR-2	33 22 51.6 N	111 21 17.0 W
PR-4	33 22 45.3 N	111 21 44.2 W
GR-1	33 23 1.6 N	111 21 6.1 W
SD-5	33 26 32.9 N	111 27 43.9 W
SM-1	33 22 33.9 N	111 29 8.6 W
DM-1	33 22 40.8 N	111 26 43.5 W

Figure Captions

1. (a) Map of Arizona showing the location of the Goldfield-Superstition volcanic province with respect to Phoenix, the southern Basin and Range, and the transition to the Colorado Plateau. (b) A Google Earth image showing the locations of the sampled lavas within northern and southern groupings. Abbreviations are: BD = Bulldog Canyon; SR = Saddle Rock; T = Tomahawk; CW = Cottonwood; H = samples reported by Hillier (1978); SD =

Siphon Draw; SM = Silly Mountain; DM = Dinosaur Mountain; PR = Peralta Road. The namesake Goldfield and Superstition mountains are shown.

2. Photomicrographs with 1 mm scales (yellow). Photos are in crossed polarizers except E and H. (A) Sample BD-A, plagioclase core surrounded by a corroded zone surrounded by a thin rim of plagioclase (note small cpx, lower left, at red line). (B) Sample CW-6, plagioclase core with surrounding corroded zone and plagioclase mantle. Note subrounded quartz grain at bottom center (red line). (C) Sample CW-7, plagioclase cores with surrounding corroded zones and plagioclase mantles. The matrix glass composition is rhyolite; see Table 4. (D) Sample SR-9, subhedral plagioclase grains that are spongy throughout. (E) Sample TM-6, spongy plagioclase phenocrysts, smaller amphibole with opaque rims (at red lines), plus opacitized linear-shaped amphibole in the matrix. (F) Sample PR-2, plagioclase (right-hand side) with thin, seemingly reaction margins (equivalent to ‘corroded’ area in panels A, B, and C, and plagioclase (left-hand side) with somewhat irregular and slightly embayed margins. (G) Sample SM-1, plagioclase with a curved margin and neighboring subrounded quartz grain (top right). (H) Sample SD-5, titanite in dacite.

3. A total alkalis vs SiO_2 (TAS) diagram showing that the studied samples straddle the andesite-dacite and trachyandesite-trachydacite line. The sample from Dinosaur Mountain is a low- SiO_2 rhyolite. Small dots are for samples from a MS thesis by Hillier (1978). One composition for the glass matrix of a dacite is rhyolite, as determined by microprobe. Base diagram is after LeBas et al. (1986).

4. Major element abundances in SiO_2 variation diagrams (in wt.%), with two types of G-SVP alkalic basalt (Fodor and Vetter, 2011) included for comparison (small open circles, *Cottonwood Spring*, low-Ti variety; diamonds, *Weekes Wash*). Each panel includes data for andesites and dacites studied in an MS thesis by Hillier (1978). Suspected altered values are noted.

5. Trace element abundances (ppm) in SiO_2 (wt.%) variation diagrams, with G-SVP alkalic basalts (Fodor and Vetter, 2011) included for comparison.

6. Chondrite-normalized rare-earth element patterns for the andesites and dacites plotted with G-SVP alkalic basalts, SR-11 and SR-8 (in thicker lines) for comparison, expressed in

four panels according to sample sites in the northern and southern groupings. (SR-11 is *Cottonwood Spring*, low-Ti variety basalt; SR-8 is *Weekes Wash* basalt; Fodor and Vetter, 2011.)

7. Primitive-mantle normalized patterns for the andesites and dacites plotted with G-SVP alkalic basalts SR-11 and SR-8 (in thicker lines) (from Fodor and Vetter, 2011) for comparison, expressed in four panels according to sample sites in the northern and southern groupings.

8. (a) Clinopyroxene composition for individual point analyses expressed as Fs and Wo endmembers. Northern and southern groups combined, and compared to representative clinopyroxene in *Weekes Wash* basalt (Fodor and Vetter, 2011). Two green encircling fields are used for CW-8 to amplify the two populations. (b and c). Plagioclase compositions for individual point analyses expressed as An and Or endmembers; northern and southern group samples separated. A boundary line in panel (b) approximates the compositional distinction between plagioclase phenocrysts, which are cores if rimmed, and the more calcic rims (mantles) and groundmass laths (note that the rims and groundmass have slightly enlarged symbols, and that groundmass laths have open symbols).

9. (a and b) Amphibole compositions for individual point analyses as Al_2O_3 , SiO_2 , FeO, TiO_2 , and MgO abundances. Northern and southern group samples are combined in each panel.

10. Trace element abundance ratios to compare among G-SVP alkalic basalt (*Weekes Wash* variety; Fodor and Vetter, 2011) and andesites and dacites. These ratios can be influenced by titanite, zircon, and allanite segregation from melts, and therefore some ratios, such as Zr/Nb, can decrease from basalt to dacite. However, the differences in some ratios among the lavas are not unequivocally due to accessory-mineral segregation and therefore do not support fractionation relationships among most of the lavas.

11. (a) A plot for trace element abundances in dehydration melts from granodiorite. Because actual abundances cannot be fairly estimated for the granodiorite source rock, we use original concentrations, C_0 , as 1, and then calculate by equilibrium batch melting the abundances in the melt produced, C_1 . With accessory minerals titanite and zircon in the source, the HFSE and La are lower in the melts than in the source ($C_1/C_0 < 1$), and increase with greater melting, from 10% to 25%. This generally simulates the observed trace element abundances, where

higher SiO₂ lavas (representing smaller % source melting) have the lowest abundances -- and overall, due to presence of accessory minerals, calculated melts have less HFSE and REE than the source granodiorite. (b) This shows the same concept as panel (a), except that alkalic basalt (amphibolite) is the source rock (containing titanite, zircon, allanite) for which we can assign a composition, thereby enabling primitive-mantle normalizations for source rock and the partial melts (15% and 25%). The source is G-SVP basalt SR-8 from Fodor and Vetter (2011). Note that the calculated HFSE and REE are lower than in the source and compare well to the pattern for northern group dacite CW-6. However, there is little to no distinction between the patterns representing 15% and 25% melting. In both (panels a and b), melting proportions and appropriate partitioning coefficients were applied to the calculations (e.g., see Table 5 and text).

12. Abundances calculated for trace elements by mixing two types of alkalic basalt (small circles for *Cottonwood Springs* basalts, using representative SR-11 in calculations; small diamonds for *Weekes Wash* basalts, using SR-8; Fodor and Vetter, 2011) with two types of rhyolite composition domes (data from Table 6; simple A+B mixing calculations not listed, but all compositions used are from northern group location). Symbols for mixes are: rhyolites SR-5 (triangles) and TB-01 (circles) (compositions in Table 6) mixing with basalt SR-11 (closed circles and triangles) and with basalt SR-8 (open circles and triangles). Trend lines are through data points for the four mixing possibilities. Proportions of rhyolite endmembers in the mixes are from 90% to 20% (Table 6). For comparison of the calculated hybrid trace element abundances to the observed trace element abundances in the lavas, hybrid data and trend lines are superimposed on compositional fields for lava trace element abundances (as plotted in Figure 5). Blue fields are for southern group Peralta Road lavas, higher in some HFSE than other lavas; red field for all other lavas. The generally good overlaps for all trace elements support basalt-rhyolite mixing as a viable way to create the observed trace element abundances in G-SVP andesites and dacites.

Table 1. Whole-rock compositions (wt.% and ppm) of andesites and dacites in the Goldfield-Superstition volcanic province, central Arizona, organized as Northern and Southern groups (see Fig. 1b). Modal minerals are listed at bottom in volume %.

	Bulldog Canyon			Northern Group Saddle Rock			Cottonwood			Tomahawk			Southern Group Peralta Road				Siphon Draw	Silly Mountain	Dinosaur Mountain
	BD-A	BD-2	NM-1	BD-3	SR-9	SA-1	CW-5	CW-7	CW-6	TM-5	TM-6	CW-8	PR-2	PR-1	PR-4	GR-1	SD-5	SM-1	DM-1
SiO ₂	56.26	56.68	58.09	58.15	62.36	62.56	61.34	64.58	65.71	62.41	63.23	63.94	59.80	64.40	65.30	68.29	63.78	67.77	70.07
TiO ₂	0.90	0.97	0.83	0.84	0.82	0.76	0.77	0.66	0.60	0.70	0.72	0.86	1.25	0.92	0.87	0.65	0.67	0.55	0.54
Al ₂ O ₃	17.13	19.07	15.69	16.33	16.71	16.72	17.63	16.89	17.06	16.65	16.05	15.82	15.31	16.47	16.42	15.50	16.47	15.74	14.97
Fe ₂ O ₃	6.88	7.48	6.67	6.74	5.89	5.54	5.51	4.74	4.37	5.31	5.45	5.30	7.14	5.05	5.01	4.01	3.92	3.78	3.03
MnO	0.11	0.06	0.05	0.08	0.05	0.06	0.06	0.09	0.08	0.06	0.09	0.08	0.10	0.08	0.08	0.05	0.05	0.05	0.12
MgO	4.42	1.98	4.32	4.21	2.91	4.03	2.53	1.24	0.82	1.85	3.07	2.69	4.10	1.69	1.24	0.86	1.24	1.09	1.03
CaO	7.01	5.98	6.97	6.87	4.67	3.95	5.02	4.04	3.94	4.63	2.85	4.52	6.31	4.23	2.93	2.03	1.23	3.17	2.66
Na ₂ O	4.26	3.45	3.16	3.78	3.43	4.25	4.53	4.16	4.35	4.74	5.09	4.08	3.45	4.06	4.05	5.30	3.77	3.95	3.92
K ₂ O	2.63	3.94	2.46	2.53	2.53	2.42	2.79	2.67	2.70	2.76	2.48	2.98	2.60	3.37	3.45	3.44	6.72	3.30	4.88
P ₂ O ₅	0.51	0.57	0.43	0.41	0.34	0.37	0.31	0.30	0.37	0.24	0.26	0.40	0.54	0.37	0.37	0.32	0.27	0.25	0.19
Total	100.11	100.18	98.67	99.94	99.71	100.66	100.48	99.36	99.99	99.35	99.29	100.67	100.60	100.63	99.72	100.47	98.12	99.65	101.41
LOI	1.68	1.39	1.36	2.69	2.35	2.77	1.35	0.65	0.47	1.58	2.14	1.31	2.51	1.70	1.57	0.83	1.32	0.71	3.18
Mg#	58.6	36.8	58.8	57.9	52.1	61.6	50.2	36.5	29.3	43.4	55.4	52.7	55.8	42.5	35.3	32.0	41.1	38.9	42.8
Al/(Na+K+Ca)	0.76	0.92	0.76	0.76	0.99	0.99	0.90	0.99	0.99	0.87	0.99	0.87	0.77	0.91	1.04	0.96	1.05	0.99	0.90
Rb	30.1	38	39	50	33	20.1	31.4	37	36.6	39	31	36.5	33.8	64.3	53.3	59.5	135	47.6	121.7
Ba	1107	1437	1090	1170	1216	965	1053	1067	1038	1789	1589	1552	875	995	1422	1093	1658	1059	866
Sr	984	1303	1023	1126	921	635	715	681	701	848	896	858	643	587	569	480	236	593	345
Zr	163	190	155.6	158	173	162	120	89	79	106.5	101.5	136	232	266	168	97.1	87	54	48
Nb	16.9	18.4	13.6	16.2	12.1	11.1	11.8	9.3	10.6	12.3	13.0	17.4	26.6	24.5	22.6	21.6	20.2	10.7	14.4
Hf	3.59	5.06	3.8	3.75	3.82	3.6	2.98	2.42	2.11	2.95	2.87	3.51	4.94	6.11	3.52	2.33	2.18	1.52	1.41
Y	15.4	17.8	18.0	17.6	9.0	10.5	10.9	12.3	14.1	13.4	12.2	13.0	18.3	16.7	16.5	13.4	11.2	9.8	10.0
Th	6.7	8.1	8.1	8.7	5.7	3.7	4.5	4.1	4.2	5.6	4.8	6.8	5.5	7.7	5.6	6.7	5.1	5.7	6.8
Ta	0.80	1.10	0.80	0.90	0.70	0.60	0.70	0.70	0.70	0.70	0.70	1.00	1.40	1.50	1.30	1.30	1.20	0.70	1.10
U	1.5	2.3	2.0	2.2	1.7	1.0	1.4	1.2	1.2	1.3	1.7	1.9	1.1	2.1	1.6	2.3	1.8	1.6	1.7
Sc	13.5	16.8	15.6	18.4	11.0	9.2	7.6	6.7	5.3	10.6	11.5	8.5	15.4	7.4	6.4	5.3	5.2	5.2	3.7
Ni	88	160	112	130	52	33	26	31	25	56	86	36	92	27	5	10	5	15	10

La	48.0	49.4	55.6	59.0	43.5	25.5	23.9	22.2	27.1	34.0	39.5	37.8	41.6	31.4	30.7	36.9	28.6	23.9	27.4
Ce	89.21	111.23	113.39	119.67	80.86	49.21	46.9	43.17	46.74	69.06	78.0	71.16	80.53	62.35	56.89	64.77	54.3	42.21	51.6
Pr	10.2	12.2	12.2	12.7	10.6	6.0	5.5	5.1	6.3	7.7	8.8	8.2	9.5	7.0	7.0	7.0	5.7	5.1	5.2
Nd	42.5	50.2	45.8	50.8	41.1	24.7	21.2	20.3	24.9	28.7	31.0	33.5	38.5	28.7	28.5	27.0	23.4	19.1	18.3
Sm	6.4	7.0	6.4	6.7	5.5	3.9	3.6	3.6	4.9	4.6	5.4	5.0	5.7	5.0	4.8	4.6	3.5	3.3	2.9
Eu	1.4	1.9	1.9	2.0	2.0	0.8	0.8	0.8	1.0	1.4	1.6	0.9	1.4	0.9	1.1	0.8	0.7	0.7	0.6
Gd	4.4	5.7	5.6	5.4	5.8	2.8	3.1	3.3	4.1	3.6	3.8	4.3	5.1	4.3	4.0	3.7	2.8	2.7	2.4
Tb	0.5	0.6	0.5	0.4	0.5	0.4	0.4	0.4	0.6	0.2	0.2	0.5	0.7	0.6	0.5	0.4	0.4	0.3	0.3
Dy	3.4	3.1	3.1	3.5	3.4	2.4	2.7	2.7	3.0	2.4	2.6	2.9	3.7	3.5	3.5	2.8	2.4	2.0	2.2
Ho	0.6	0.6	0.6	0.6	0.7	0.4	0.5	0.4	0.6	0.4	0.5	0.5	0.7	0.6	0.6	0.9	0.4	0.4	0.3
Er	1.8	2.0	1.8	1.9	2.3	1.3	1.5	1.5	1.7	1.5	1.3	1.5	1.9	2.1	1.9	1.5	1.2	1.0	1.1
Tm	0.2	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Yb	1.6	2.2	1.6	1.5	1.8	1.3	1.4	1.5	1.7	1.3	1.2	1.3	1.9	1.9	1.9	1.4	1.3	1.0	1.1
Lu	0.2	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2
87Sr/86Sr (init) 0.705064																			
Modal mineral percentages (excludes groundmass)																			
plag	19.2	14.6	13.2	18.6	17.2	17.9	26.1	30.8	18.2	24.0	17.2	22.6	26.4	22.4	11.3	22.2	21.6	27.9	20.6
cpx	2.9	2.8	1.4	4.2	0.2	0.1				1.2		2.8	5.9	1.7			0.2		
amph	0.4	0.3					1.7	5.3	3.5	6.0	3.9	5.8			1.0	3.0		1.5	
biot	0.1	0.3			0.3	0.1	3.9	1.2	2.7	3.0	0.2	1.5			2.0	0.5	4.5	4.1	
quartz								0.2	0.1	0.1	0.2	0.1		0.2	3.1	6.2	3.0	0.2	0.4
oxidized silic.	5.5	4.5	2.9	4.1	0.9	0.7											0.2	0.2	0.3
sericite																			3.8
access. mins																	0.2 titan	tr zirc	
secd. calcite				0.1		2.7													2.4

notes: Al/(Na+K+Ca) is molar; mineral mode references: oxidized silicates are opacitized amphibole and possibly olivine; secd calcite is secondary calcite
Mg# = mol (Mg/(Mg+Fe2))*100

Table 2. Representative average compositions (wt.%) determined by electron microprobe for clinopyroxene, amphibole, and biotite phenocrysts in andesite and dacite lavas of the Goldfield-Superstition volcanic province, central Arizona.

<u>Clinopyroxene</u>										
	northern group					southern group				
	BD-A	BD-3	<u>CW-8</u>		TM-5	PR-2	PR-1			
SiO ₂	51.3	49.9	52.9	51.6	50.1	51.5	51.9			
TiO ₂	0.55	0.88	0.14	0.58	0.93	1.0	0.38			
Al ₂ O ₃	4.6	6.2	1.0	3.2	5.6	2.7	3.0			
Cr ₂ O ₃	0.28	0.24	0.01	0.32	0.21	0.05	0.18			
FeO	5.7	6.7	9.4	6.0	7.1	11.3	7.3			
MnO	0.27	0.17	0.61	0.16	0.13	0.40	0.53			
MgO	16.3	15.0	14.5	16.4	15.4	15.9	16.0			
CaO	20.8	20.6	20.4	20.1	20.5	16.9	21.0			
Na ₂ O	<u>0.31</u>	<u>0.66</u>	<u>0.43</u>	<u>0.38</u>	<u>0.40</u>	<u>0.46</u>	<u>0.38</u>			
Total	100.11	100.35	99.39	98.74	100.37	100.21	100.67			
<i>Mg#</i>	83.6	80.0	73.3	83.0	79.5	71.5	79.6			
Fs	9.3	11.2	15.3	9.8	11.7	18.4	11.6			
Wo	43.3	44.1	42.6	42.3	43.2	35.4	42.9			

<u>Amphibole</u>										
	northern group					southern group				
	BD-A	CW-7	<u>CW-8</u>			TM-6	TM-5	SM-1		
SiO ₂	42.6	40.0	42.7	45.2	43.0	42.4	43.7	44.5		
TiO ₂	2.7	2.8	3.1	2.4	3.1	2.4	2.5	1.7		
Al ₂ O ₃	12.7	12.4	10.9	10.1	11.8	12.7	13.2	9.3		
FeO	11.8	11.9	13.0	12.5	10.8	10.5	10.8	15.6		
MnO	0.16	0.10	0.18	0.26	0.15	0.14	0.12	0.20		
MgO	13.6	14.3	13.5	14.8	15.3	14.6	14.6	13.1		
CaO	10.7	14.8	12.5	12.2	12.1	11.3	11.3	11.1		
Na ₂ O	2.7	2.5	2.5	2.5	2.6	2.8	2.9	2.1		
K ₂ O	<u>0.67</u>	<u>0.42</u>	<u>0.88</u>	<u>0.87</u>	<u>0.71</u>	<u>0.74</u>	<u>0.63</u>	<u>0.72</u>		
Total	97.63	99.22	99.26	100.83	99.56	97.58	99.75	98.32		
<i>Mg#</i>	67.3	68.2	65.1	67.9	71.6	71.3	70.7	60.0		

<u>Biotite</u>										
	northern group							southern group		
	BD-2	CW-8	SR-9	SA-1	TM-5	CW-7	<u>CW-8</u>	SM-1	SD-5	
SiO ₂	37.1	37.9	37.4	37.6	38.1	37.8	37.3	37.9	37.9	37.6
TiO ₂	4.6	4.5	4.6	4.9	3.5	4.0	4.0	4.6	4.1	4.1
Al ₂ O ₃	13.5	14.2	13.7	14.1	14.2	14.7	14.2	14.2	14.4	13.9
FeO	17.1	11.7	17.2	12.4	18.1	17.0	15.3	11.7	17.5	17.3
MnO	0.23	0.11	0.23	0.09	0.21	0.13	0.13	0.11	0.05	0.15
MgO	13.8	17.6	13.3	16.6	13.5	13.8	15.6	17.1	14.6	13.9
CaO	0.01	0.04	0.02	0.01	0.04	0.02	0.04	0.04	0.01	0.13
Na ₂ O	0.67	0.64	0.63	0.53	0.53	0.43	0.63	0.64	0.25	0.18
K ₂ O	8.8	9.0	8.9	8.8	9.1	9.0	8.7	9.0	8.7	8.8
BaO	<u>0.83</u>	<u>1.0</u>	<u>1.4</u>	-	<u>0.62</u>	<u>0.58</u>	<u>1.1</u>	<u>1.0</u>	-	-
Total	96.64	96.69	97.38	95.03	97.90	97.46	96.70	96.29	97.61	96.06
<i>Mg#</i>	59.0	72.8	58.0	70.5	57.1	59.1	64.5	72.3	59.8	58.9

Each analysis is the average of 10 to 20 analytical points per grain; see Figures 8 and 9

Table 3. Representative average compositions (wt.%) determined by electron microprobe for plagioclase phenocrysts (some as cores and rims around cores) and groundmass laths in andesite and dacite lavas, Goldfield-Superstition volcanic province, central Arizona.

Northern group

	BD-A			CW-8		CW-7		
	core	rim	gndms	pheno	gndms	core	rim	gndms
SiO ₂	59.4	52.2	52.2	59.3	54.8	58.8	51.3	52.6
Al ₂ O ₃	25.0	29.9	28.9	25.7	28.1	25.0	30.4	29.7
FeO	0.29	0.66	0.93	0.30	0.67	0.18	0.63	0.63
CaO	6.2	11.8	11.0	7.5	10.3	6.2	12.6	12.3
Na ₂ O	7.3	4.5	4.9	6.7	5.3	7.4	4.2	4.5
K ₂ O	<u>0.98</u>	<u>0.30</u>	<u>0.30</u>	<u>0.77</u>	<u>0.36</u>	<u>0.80</u>	<u>0.21</u>	<u>0.25</u>
Total	99.17	99.36	98.23	100.10	99.53	98.48	99.34	99.98
<i>An</i>	29.7	57.9	54.2	36.1	50.4	29.8	61.5	59.1
<i>Or</i>	7.1	2.2	2.2	5.6	2.7	5.8	1.5	1.8

	SR-9		SA-1		TM-5		TM-6
	core	rim	core	rim	core	gndms	core
SiO ₂	59.8	53.7	61.2	58.2	59.6	54.4	60.2
Al ₂ O ₃	24.9	28.1	23.8	25.9	25.3	28.6	24.2
FeO	0.40	1.0	0.43	0.88	0.30	0.57	0.13
CaO	7.2	10.9	6.9	9.0	6.6	9.6	5.6
Na ₂ O	7.3	5.4	7.0	6.3	7.7	6.0	8.3
K ₂ O	<u>1.1</u>	<u>0.38</u>	<u>1.2</u>	<u>0.34</u>	<u>0.78</u>	<u>0.38</u>	<u>0.67</u>
Total	100.70	99.48	100.53	100.62	100.28	99.55	99.10
<i>An</i>	32.7	51.3	32.3	43.1	30.4	45.7	25.9
<i>Or</i>	7.5	2.7	8.5	2.5	5.4	2.7	4.7

Southern group

	PR-2		PR-1		PR-4		GR-1
	pheno	gndms	pheno	gndms	pheno	gndms	pheno
SiO ₂	57.9	53.8	56.0	54.5	60.4	57.5	61.6
Al ₂ O ₃	26.0	28.5	26.9	28.1	24.8	26.3	24.2
FeO	0.73	0.99	0.75	0.59	0.19	0.30	0.20
CaO	8.7	10.8	9.6	9.9	5.7	7.7	5.3
Na ₂ O	5.8	4.8	5.6	5.2	8.0	6.8	8.0
K ₂ O	<u>1.2</u>	<u>0.56</u>	<u>0.67</u>	<u>0.58</u>	<u>0.92</u>	<u>0.60</u>	<u>0.80</u>
Total	100.33	99.55	99.52	98.87	100.01	99.20	100.10
<i>An</i>	41.5	53.2	46.3	49.1	26.5	36.9	25.3
<i>Or</i>	8.6	4.2	4.9	4.3	6.4	4.3	5.8

	SM-1		SD-5	
	pheno	gndms	mixed Ab-Or	pheno
SiO ₂	60.0	57.3	66.2	63.6
Al ₂ O ₃	25.1	26.4	21.0	18.9
FeO	0.22	0.35	0.02	0.09
CaO	6.4	7.6	0.93	0.04
Na ₂ O	7.6	6.9	11.4	0.25
K ₂ O	<u>0.71</u>	<u>0.51</u>	<u>0.18</u>	<u>16.2</u>
Total	100.03	99.06	99.73	99.08
<i>An</i>	30.2	36.5	4.3	0.2
<i>Or</i>	5.1	3.7	1.2	98.0
			<i>Ab</i>	94.5
				1.8

core = core of corroded and/or rimmed plagioclase; rim = rim surrounding corroded core (thin plagioclase margin); pheno = phenocryst with no corrosion or rim; gndms = groundmass lath
Each column is the average of from 8 to 12 analytical points except some groundmass grains can be averages of 6 to 8.

Table 4. Average compositions (wt.%) by electron microprobe for titanite in trachydacite SD-5, matrix glass of dacite CW-7, and white mica in rhyolite DM-1, Goldfield-Superstition volcanic province, central Arizona

	Titanite	Matrix glass	White mica (sericite)
SiO ₂	30.5	71.5	52.4
TiO ₂	34.4	0.27	<0.01
Al ₂ O ₃	1.1	13.2	30.0
FeO	2.0	0.88	2.8
MnO	0.33	--	0.04
MgO	0.08	0.15	2.0
CaO	26.1	1.4	0.14
Na ₂ O	--	3.7	0.07
K ₂ O	0.02	4.1	9.8
BaO	--	--	0.25
La ₂ O ₃	0.41	--	--
Ce ₂ O ₃	<u>0.98</u>	<u>--</u>	<u>--</u>
Total	95.82	95.20	97.46

average of 8 analytical points for titanite; 21 points for glass;
10 points for sericite

Table 5. Mass balancing and Rayleigh fractionation models to demonstrate that alkalic basalt SR-8, representing the *Weekes Wash* formation in the Goldfield-Superstition volcanic province, central Arizona, can produce major and trace elements as observed in representative andesites and dacites (SiO₂ provided in parentheses). Trace element calculations require small amounts of titanite and zircon (and allanite for Th).

Observed parent basalt		Calculated parent basalts for			
		<i>northern group</i>		<i>southern group</i>	
SR-8		Bulldog	Cottonwood	Peralta	Peralta
<i>Weekes Wash</i>		Canyon		Road	Road
(G-SVP)		<i>andesite</i>	<i>dacite</i>	<i>andesite</i>	<i>dacite</i>
		BD-A	CW-6	PR-2	GR-1
	SiO ₂ wt. %	(56.3%)	(65.7%)	(59.8%)	(68.3%)
SiO ₂	50.95	50.74*	50.99	50.99	50.94
TiO ₂	1.05	1.00	1.00	1.12	1.02
Al ₂ O ₃	14.91	14.76	14.91	14.92	14.86
FeO	8.44	8.29	8.4	8.47	8.44
MnO	0.10	0.12	0.12	0.12	0.11
MgO	9.04	8.98	9.06	9.07	9.05
CaO	11.31	11.32	11.33	11.34	11.33
Na ₂ O	2.14	2.75	2.39	2.35	2.57
K ₂ O	1.17	1.25	0.81	1.02	0.84
Minerals** crystallized from parent basalt, in %					
Olv		4.4	6.7	5.8	6.4
Cpx		26.0	29.7	25.3	30.6
Plg		18.7	28.7	26.5	31.9
Mt		4.6	6.7	5.1	6.9
<i>Sum of crystals</i>		53.7	71.8	62.7	75.8
residual liquid (lavas)		46.4	28.2	37.3	24.3
Σr^2		0.47	0.20	0.08	0.26

Rayleigh fractionation results (ppm) after applying modal percentages for *northern group* mass balancing calculations (above) showing the percentages of accessory minerals (titanite, zircon, allanite)*** and partitioning coefficients used in the Rayleigh calculations to achieve the calculated daughter ppm

	parent (ppm)	<i>calculated</i> daughter ppm	<i>calculated</i> daughter ppm	**** $K_D^{tnt/liq}$	$K_D^{zrc/liq}$	$K_D^{cpx/liq}$	$K_D^{all/liq}$
	<u>SR-8</u>	<u>BD-A</u> (% tnt, zrc)	<u>CW-6</u> (% tnt, zrc)				
La	50	46 (0.5)	23 (1.0)	113			
Nb	17	16.5 (0.4)	9 (0.8)	129			
Y	31	16 (0.2)	11 (0.4)	250		1	
Sr	1040	954 (0.3)	743 (0.3)	0.37			
Zr	170	160 (0.05)	88 (0.1)		1000		
Hf	3	2.7 (0.015)	2 (0.025)		3500		
Th	4.85	6 (0.7) ^{allanite}	4.2 (1.2) ^{allanite}				61
Sc	22.4	8 (0.3)	12 (0.5)	5.9		3	

* = the mass balancing expresses the hypothetical parent basalt required to produce the daughter andesites and dacites by subtracting the listed percentages of the minerals from the hypothetical basalt ($\Sigma r^2 < 0.5$ indicates a good mathematical fit).

Mass balancing method based on Bryan et al. (1969).

** = mineral compositions are for *Weekes Wash* basalt (Fodor and Vetter, 2011)

*** = allanite substituted for titanite in Th calculations; zircon substituted for titanite in Zr and Hf calculations.

**** = Partitioning coefficients for accessory minerals that have the main influence on the listed trace elements are from: Bachmann et al. (2005) for La, Nb, Sr, Sc, and 0.4 of Y value; Herrmann (2002) for Th; Severs et al (2009) for Sc. Plagioclase/liq $K_D = 3$.

Table 6. Compositions for andesites and dacites calculated by mixing two Goldfield-Superstition volcanic province basalt types with two rhyolite dome types. Selected examples are for different proportions of rhyolite and basalt in the mixes. The first four columns present the endmember compositions. Major elements in wt.%; trace elements in ppm.

G-SVP Endmembers to Mix					Hybrid Calculations							
<i>Endmember Compositions</i>					<i>Mix Rhyolite TB-01 with</i>				<i>Mix Rhyolite SR-5A with</i>			
Basalts		Rhyolites			10%	60%	10%	75%	30%	65%	40%	80%
SR-11	SR-8	TB-01	SR-5A		<i>SR-11</i>	<i>SR-11</i>	<i>SR-8</i>	<i>SR-8</i>	<i>SR-11</i>	<i>SR-11</i>	<i>SR-8</i>	<i>SR-8</i>
SiO ₂	46.30	50.95	71.85	77.69	69.30	56.52	69.76	56.18	68.27	57.29	66.99	56.30
TiO ₂	1.14	1.05	0.15	0.06	0.25	0.74	0.24	0.83	0.38	0.76	0.46	0.85
Al ₂ O ₃	14.19	14.91	16.22	13.34	15.84	14.92	15.91	15.19	13.6	13.89	13.97	14.60
Fe ₂ O ₃ [‡]	10.03	9.36	1.57	0.60	2.42	6.64	2.35	7.14	3.43	6.73	4.10	7.61
MgO	11.20	9.04	0.49	0.12	1.56	6.92	1.35	6.90	3.44	7.32	3.69	7.26
CaO	12.30	11.31	2.76	0.33	3.71	8.48	3.62	9.17	3.92	8.11	4.72	9.11
Na ₂ O	4.41	2.14	3.17	5.8	3.29	3.91	3.07	2.40	5.38	4.90	4.34	2.87
K ₂ O	0.65	1.17	2.93	2.19	2.70	1.56	2.75	1.61	1.73	1.19	1.78	1.37
P ₂ O ₅	0.79	0.69	0.07	0.02	0.14	0.50	0.13	0.54	0.25	0.52	0.29	0.56
Rb	8	17	72	57	66	34	67	31	42	25	41	25
Ba	1030	975	1412	540	1374	1183	1368	1084	687	859	714	888
Sr	1285	1040	142	77	256	828	232	816	439	862	462	847
Zr	193	172	93	38	103	153	101	152	85	139	92	145
Nb	25	17	8.9	16.6	10.5	18.6	9.7	15	19.1	22.1	16.8	16.9
Hf	3.4	3	2.7	4.2	2.8	3.1	2.7	2.9	2.5	2.9	2.4	2.8
Y	27	31	5.7	7.2	7.8	18.5	8.2	24.7	13.1	20.1	16.7	26.2
La	67	49.3	28.5	11.8	32.4	51.6	30.6	44	28.4	47.7	26.8	41.8
Th	8.3	4.8	4.1	7.8	4.5	6.6	4.2	4.6	7.9	8.1	6.6	5.4
Sc	11	22	1	2.2	2	7	3.1	17	4.7	7.7	10	18
Ni	206	240	2.3	4.2	23	125	26	181	64	135	99	193

Endmember data sources: basalts, Fodor and Vetter (2011); rhyolite domes, Dombroski (2010), with re-analyzed trace elements by ICP-MS

* = FeO for basalts (Fodor and Vetter, 2011) converted to Fe₂O₃ by 1.11 factor

Figure 1a

Figure 1b

Figure 2

Figure 3

Figure 4

Figure 5a

Figure 5b

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12