Major and trace element geochemistry of the Neogene Halloran Hills andesites, San Bernardino County, California: Implications to tectonic evolution of the eastern Mojave

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ABSTRACT

The Halloran Hills, northeast of Baker, CA, were the site of Neogene (12.1 Ma) andesitic volcanism. Field sampling reveals that andesite outcrops consist of both brecciated and non-brecciated flows. Large phenocrysts of altered clinopyroxene are present in most samples. A smaller number contain euhedral, phenocrysts of orthopyroxene. XRF whole rock analyses indicate that Halloran Hills andesites are High-K trachyandesites, emplaced during continental, crustal extension. Two distinct sample populations were noted; High silica ($SiO_2 \approx 62\%$) and Low silica ($SiO_2 \approx 56\%$). Trace element data suggest both High and Low silica andesites are derived from a common source, the former representing a smaller melt fraction.

Cenozoic volcanic rocks in nearby Mesquite Pass and the Cima volcanic field were also examined for this study. The 13 Ma Mesquite Pass volcanics are a suite of alkaline rocks ranging in composition from rhyolite to trachydacite. The Cima volcanics are comprised of older basaltic trachyandesite (7.5 - 3 Ma) and younger trachybasalt (l.5 Ma - Pres.). When combined with data from the Halloran Hills, an extended pattern of alkaline volcanism emerges. It began during the initial stages of Miocene detachment and has continued to the Present, as upwelling asthenosphere occupied the void created by a thinning lithosphere. The compositional variations of the rocks reflect progressively deeper levels of melting, from shallow crustal rhyolite and trachydacite, to lower crustal trachyandesite to mantle trachybasalt. Assuming a stationary heat source for the volcanism, the eastern Mojave has undergone clockwise rotation at an average rate of 5 mm/year during the Neogene. This rotation involved two distinct events; a period of east-west extension, related to detachment, and a younger north-south directed event, a consequence of dextral shear.

Introduction

The Halloran Hills (HH) are 18 kilometers northeast of Baker, California (Fig. 1). They are bounded to the south by the Cima volcanic field and to the east and west respectively, by Shadow Valley and Silurian Valley.

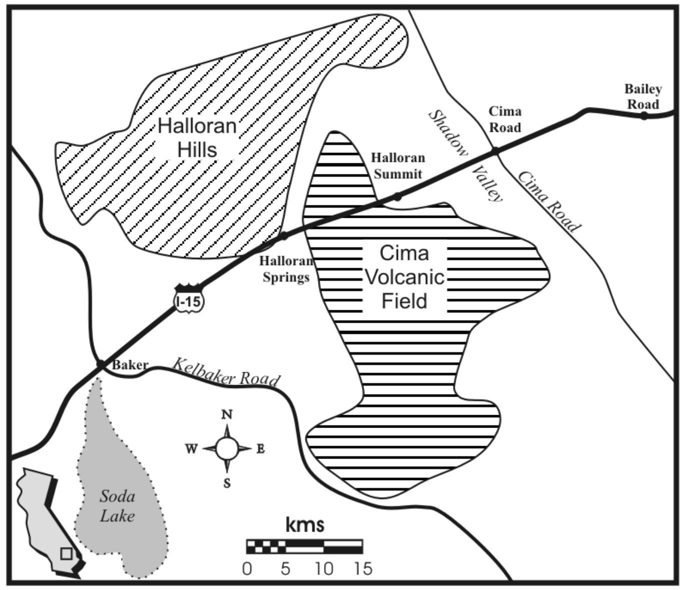

Figure 1. Index map showing the location of the Halloran Hills.

The oldest rocks in the HH are 1.7 Ga metamorphic rocks, informally termed Fenner Gneiss. These have been intruded by Mesozoic granitoids of the Teutonia batholith (Beckerman, et. al., 1982). Teutonia intrusives range in composition from diorite to granite with monzogranites predominating (Wilshire, 2002).

Cenozoic stratigraphy is complex, influenced by Miocene detachment faults (Reynolds, 1991; Reynolds and Calzia, 1996) and subsequent dextral shear Reynolds, 1997). Peach Springs Tuff (18.5 Ma) unconformably overlies rocks of the Teutonia batholith (Nielson et. al., 1990). Freshwater carbonates, fine-grained clastics, gravels and andesitic volcanics (12.1 Ma) (Wilshire, 2002) lie above the Peach Springs Tuff. Where the tuff is absent, they are in direct contact with the Mesozoic intrusives. Detached blocks, debris flows and avalanche deposits of Proterozoic to Lower Paleozoic sedimentary rocks are often juxtaposed with the Tertiary units. Brecciated debris has moved westward from the Mountain Pass area to the east (Reynolds and Nance, 1988; Reynolds, 1991). Post-extensional erosion was followed by "glide" blocks moving great distances from source areas in the Avawatz Mountains to the west (Reynolds, 1991).

Following erosion and tilting of the Miocene sedimentary rocks, basaltic volcanism began around 7.5 Ma (Turrin, et. al., 1984). While much of this volcanism occurred in the Cima volcanic field south of the HH, scattered 4.5-5.5 Ma flows are present in the southern Halloran Hills. After a hiatus of 1.5 to 2 million years volcanism recommenced at 1.5 Ma in the southern portion of the Cima field. Erosion has generated Quaternary alluvial deposits ranging from fine-grained sediments in the pluvial basins to coarse grained fanglomerates mantling the resistant ridges created by basalt flows.

The purpose of this research is to reexamine the "pyroxene" andesites of the Halloran Hills. It seeks to provide a more quantitative characterization of the rocks and answer fundamental questions regarding their petrogenesis. Specifically, do the andesites represent a single eruptive event or multiple events? Are the andesites related in time and space to other Cenozoic volcanism in the eastern Mojave? Do these relationships fit into a comprehensive tectonic model?

Sampling and Analytical Procedures

Rocks of andesitic composition outcrop at a number of localities in the Halloran Hills. No detailed geologic map exists, thus, stratigraphic and structural relationships are often uncertain. Two andesite age dates have been reported. One, from a plagioclase separate of a highly altered andesite, yielded an age of 12.8 Ma (Wilshire, 2002). The second, a "fresh" pyroxene andesite, was dated at 12.1 Ma (Wilshire, 2002).

Twenty-two samples of andesite were collected from the Halloran Hills. Samples varied widely in character. Those from the northern portion of the HH were often extensively brecciated. Breccias consisted of andesite clasts in a groundmass of andesitic composition, suggesting autofragmentation of flows. Some breccias samples, however, contained clasts derived from basement rocks. These breccias were extensively altered and silicified, perhaps due to emplacement along faults. Andesite samples from the southern HH were not brecciated.

Color and phenocryst mineralogy also varied. Many samples were medium to dark gray, but a small number from the southeastern HH were red-purple to red-brown. Seriate textured plagioclase was ubiquitous and large, euhedral k-feldspars common. Very large (up to 5 mm), phenocrysts of green to black clinopyroxene were also common. The clinopyroxene was slightly altered and embayed. The "red" andesites contain smaller (1-2 mm), euhedral, phenocrysts of wine-colored orthopyroxene. The orthopyroxene appeared largely unaltered. Biotite and hornblende are rare accessory phases.

Field samples were crushed, sieved and pressed into aluminum mounts for XRF analysis. Major elements were analyzed with software provided by PANanalytical Inc. Trace element analyses utilized "basaltrace" a software routine developed in-house by the Cal Poly Geological Sciences Department.

Geochemistry

Figure 2 is a TAS (Le Bas) diagram for the andesite samples from the HH. The samples span a diverse range of composition from dacite and trachydacite to basaltic trachyandesite, with the overwhelming majority within the trachyandesite field. The Le Bas diagram assigns rock name strictly on the basis of chemistry. No formal relationship to modal mineralogy has been proposed. Informally, however, pyroxene andesite and trachyandesite are likely synonymous. The andesites appear to define two distinct populations; termed High (9 samples) and Low silica (13 samples). The former group is composed of samples with >60 wt% SiO_2, and the latter <58 wt% SiO_2. To facilitate comparison, the CIPW norm was calculated for each group (Table 1), and a spider diagram constructed from minor and trace element data.

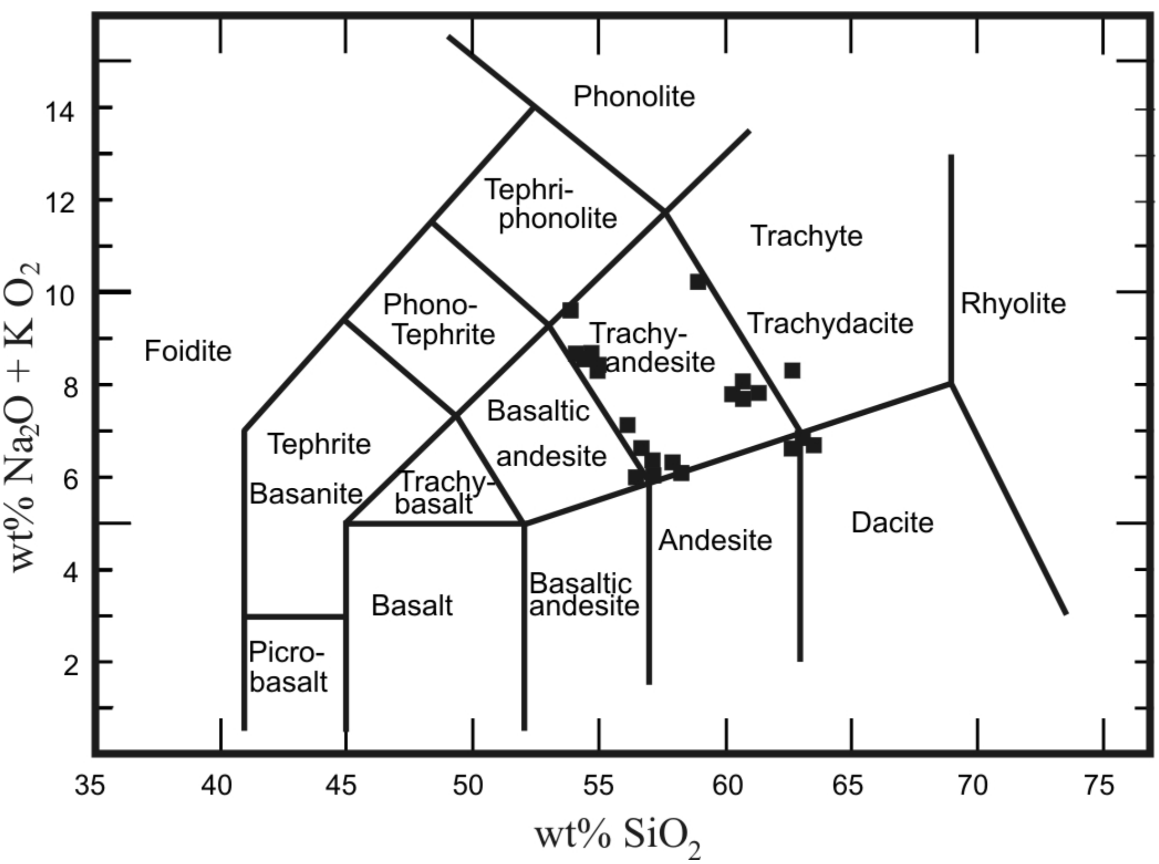

Figure 2. TAS diagram for the Halloran Hills andesites.

Table 1. Halloran Hills Andesites - CIPW Norm									
	Q	***or***	***ab***	***an***	***di***	***hy***	***mt***	***il***	***ap***
High silica	13.27	23.22	30.77	15.51	8.27	3.96	2.49	1.21	1.12
Low silica	2.77	23.32	33.38	17.71	8.83	7.95	2.91	1.78	1.34

Trace Elements (ppm)											
	Rb	**Ba**	**Sr**	**Cr**	**Zr**	**Sc**	**La**	**Ce**	**Nd**	**Sm**	**Y**
High silica	161	1203	1857	50	463	45	21	71	22	2	72
Low silica	163	809	1032	53	412	29	19	61	24	4	67

CIPW normative mineralogy shows little variation between groups, with normative *Q* and *hy* the exceptions. The disparity in normative *Q* results from a 6 wt% difference in average SiO_2 content of the High (62%) and Low (56%) silica andesites. The normative *hy* anomaly is explained by the presence of both orthopyroxene and clinopyroxene phenocrysts in some samples. Samples with modal orthopyroxene would be expected to have significantly greater normative *hy*.

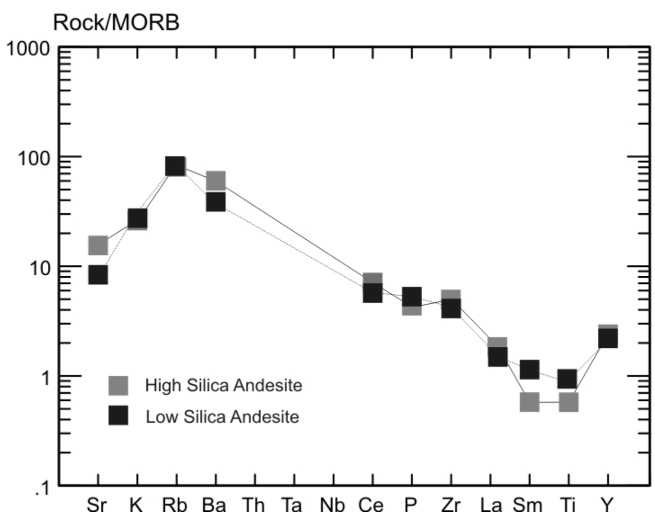

Figure 3. MORB normalized spider diagram for Low and High silica Halloran Hills andesites.

Figure 3 compares trace element data for High and Low silica andesites. Trace elements are normalized against the MORB standard of Pearce (1983). In general, both High and Low silica andesites show similar patterns. This argues for a common source rock or parental magma. However, High silica andesites are enriched in the incompatible elements Sr and Ba and depleted in the compatible elements Sm and Ti relative to Low silica andesites. This is consistent with derivation of High silica andesite from a smaller volume of partial melt and/or greater fractionation from a mafic parent.

The variation in color, texture and phenocryst mineralogy along with grouping of andesites on the TAS diagram suggests two or more episodes of andesitic volcanism. The spider diagram supports this hypothesis.

Andesite Petrogenesis

Gill (1981) argued persuasively for the importance of K_2O, terming it "the significant variable in major element composition between andesites for tectonics". He believed that most andesites are produced at collisional plate boundaries and that K_2O content was a measure of the extent to which continental lithosphere is involved in orogenesis. Low-K andesites are produced by limited interaction with continental lithosphere while High-K andesites indicate that continental crust played a significant role. He further stated that shoshonites were exceedingly rare in convergent settings, implying that the "shoshonite" andesites were not the products of convergence.

Figure 4 is a Gill diagram for the HH andesites. Twenty of the 22 andesite samples plot on the diagram, the remainder containing greater than 5% K_2O. All HH andesites lie within either the High-K or Shoshonite fields. Parker, et. al., (2005) studied the Oligocene Conejos volcanics of southern Colorado. These rocks bear remarkable petrographic and geochemical similarities to the HH andesites. Emplacement of the Conejos Volcanics was related to evolution of the Rio Grande Rift.

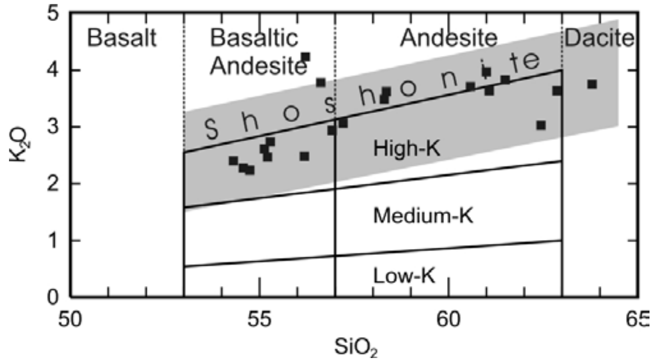

Figure 4. K_2O-SiO_2 diagram for the Halloran Hills andesites (Gill, 1981). Shaded rectangle represents the approximate compositional variation for the Conejos volcanics of Parker, et. al., 2005.

While it is unlikely the Halloran Hills andesites are a consequence of continental rifting, certain parallels exist. The High-K andesites and shoshonites of both the Halloran Hills and Rio Grande Rift were produced from a continental lithospheric source. Furthermore, the Conejos volcanics are a product of extension, as are the HH andesites. In the latter case, detachment rather than rifting is the driving mechanism.

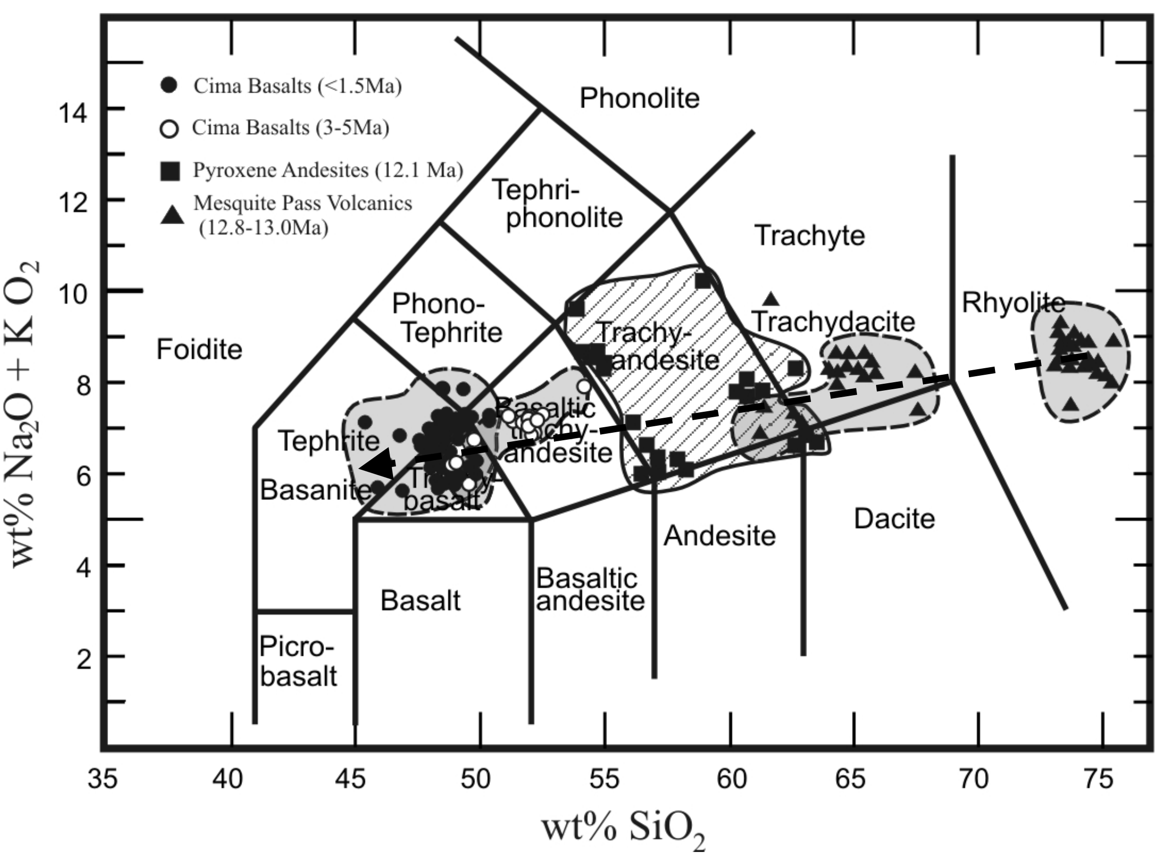

Figure 5. TAS diagram for the eastern Mojave volcanics. Dashed line approximates the path of magma evolution.

Recent work by Tarman, et. al., (2002) on the petrology and geochemistry of the Mesquite Pass volcanics, 15 kilometers northeast of the Halloran Hills, has documented a suite of rhyolitic to trachydacitic rocks characterized by high alkali content. Samples yielded Ar/Ar ages of 12.8 to 13.0 Ma (Tarman, et. al., 2002).

Field mapping has shown that the Mesquite Pass volcanics were emplaced at the apex of the breakaway zone for the 12.2 Ma (Davis, 1992) Kingston Range detachment fault.

Jessey, et. al., (2007) undertook an extensive sampling program in the Cima volcanic field, south of the Halloran Hills. This research demonstrated that the Cima volcanics underwent significant compositional changes from early mugearites (basaltic trachyandesite) emplaced from 7.5 to 3 Ma, to hawaiites (trachybasalt) extruded from 1.5 Ma to the Present.

Figure 5 summarizes the geochemical trends for eastern Mojave volcanics. Clearly, alkali enrichment characterizes the entire spectrum of Cenozoic rocks. The 13 Ma Mesquite Pass volcanics are of rhyolitic to trachydacitic composition, followed by the Halloran Hills trachyandesite at 12 Ma. Basaltic trachyandesite (mugearite) and trachybasalt (hawaiite) of the Cima volcanic field represent the most recent periods of alkali magmatism.

Discussion and Conclusions

Cenozoic volcanism in the eastern Mojave has evolved over time. The earliest volcanic rocks were rhyolites and trachydacites, followed closely (less than 1 million years) by a period of trachyandesitic magmatism. After a gap of three to five million years, basaltic trachyandesite (mugearite) and trachybasalt (hawaiite) were erupted. The older basalts (7.5-3 Ma) were dominantly mugearites; and the most recent activity (<1.5 Ma) hawaiite. This defines a trend of decreasing silica content (75% to 48%) accompanied by a modest decrease in total alkalis (about 2%).

Greg Davis (1992) speculated that volcanic rocks outcropping in the Mesquite Pass area might be related to the Kingston Range detachment fault. Ar/Ar geochronology has demonstrated that ages for the Mesquite Pass volcanics are compatible with the hypothesized age (≈12 Ma) for detachment. The heat source generating the melts is problematic. One theory suggests that frictional energy associated with large scale crustal dislocations. A second model postulates crustal extension and thinning that results in upwelling of asthenospheric mantle; the heat from the mantle generating partial melts (Tarman, et. al., 2001).

The high-K andesites of the Halloran Hills have chemical similarities to rocks from the Rio Grande rift (Conejos Volcanics, Parker, et. al., 2005). It is proposed that the Halloran Hills andesites, like those of the Rio Grande rift, are a product of crustal extension. Their postulated age (12.1 Ma) is close to that for the Kingston Range detachment, and they lie in close proximity to the Mesquite Pass volcanics. As extension thinned the crust, deeper partial melts generated from more mafic portions of the lower crust were able to reach the surface. As these magmas rose they interacted with the crust, digesting upper crustal rocks and increasing alkali content while adding crustal contaminants.

The most recent episode of basaltic volcanism began at 7.5 Ma. It resulted in the early mugearites followed by the more recent (<1.5 Ma) hawaiites. The role of extension in the emplacement of Cima basalts is more enigmatic. Emplacement begins after a hiatus of 3-4 million years and is coincident with a transformation from extension to dextral shear (Reynolds, 1996). Perhaps, shearing generated faults that penetrated the thinned lithospheric crust enabling mantle-derived magmas to ascend to the surface.

Farmer, et. al., (1995) stated that the locus of volcanism in the eastern Mojave has moved little during the past 12 million years and that there is no relationship to a mantle hot spot. However, if one assumes a genetic relationship between the volcanics of the Cima field, Halloran Hills and Mesquite Pass then a fixed heat source is more likely. If so, a pattern of clockwise rotation or northeastward migration relative to a fixed heat source at a rate of approximately 5 mm/yr would result. Furthermore, this motion appears to have two distinct components; an older phase (13 - 10 Ma) of dominantly east-west motion, and a younger (7.5 Ma - Present) period of nearly north-south movement; the former related to detachment and the latter, dextral shear.

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