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GEOLOGY AND GEOCHEMISTRY OF VOLCANIC DIKES
IN THE PACHECO PASS AREA, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Pavel A. Kosovichev

May 2006

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ABSTRACT

GEOLOGY AND GEOCHEMISTRY OF VOLCANIC DIKES IN THE PACHECO PASS AREA, CALIFORNIA

by Pavel Kosovichev

Late Tertiary volcanic dikes in the Pacheco Pass area of central California range from basalt to rhyolite and are thought to be associated with the northwestward passage of the Mendocino triple junction. This study aims to investigate their magmatic evolution, contact relations, and associated hydrothermal activity.

Field work in a study area north of Pacheco Pass indicates injection and quenching of andesite along two sets of steeply-dipping fractures. Major and trace element data from 15 localities reflect calc-alkaline evolution from a LILE-enriched basaltic source by magma mixing and crustal contamination. These data suggest a genetic link to the northwest-younging volcanics along the California coast. Hydrothermal veins in the study area contain the rare mineral chromian dawsonite and small amounts of Cu, Ag, Ni, and Hg. Petrographic and chemical data suggest localized epithermal deposition and isotopic equilibrium with metamorphic fluids.

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INTRODUCTION

Purpose of Study

The present work is a multifaceted investigation of several related aspects of Tertiary volcanics in the Pacheco Pass area of the California Coast Ranges. The area is significant because it contains a wide compositional array of volcanics that may reflect slab-window magmatism, part of the proposed model of Cenozoic tectonic evolution of coastal California (Furlong, 2004). The goals of this thesis are: (1) to map the geologic features and lithology around Burra Burra Peak in detail and document the contact relations between the Dowdy Ranch Andesite (DRA) and the Franciscan Complex mélangé; (2) to investigate possible genetic relationships between the DRA, the Orestimba dikes, and other volcanics along the northern California coast, using major and trace element data; and (3) to describe the hydrothermal assemblages in the immediate vicinity of Burra Burra Peak (Dowdy Ranch area) and Orestimba Creek.

This investigation more clearly defines the origin and evolution of the volcanics in the Pacheco Pass area of central California, with emphasis on the Orestimba and

Dowdy Ranch volcanic units; it also addresses the nature of associated hydrothermal mineralization.

Geologic Setting

Cenozoic volcanic centers along the central coast of California belong mainly to the post mid-Miocene Northern California Coast Range Volcanics (NCRV) (Dickinson, 1997). The NCRV lie to the east of the San Andreas fault along a 200 km-long north-south belt of the Northern Coast Ranges and become progressively younger in age to the northwest (Fig. 1). These volcanics constitute an important piece of the tectonic record, and they serve as windows into the petrochemical characteristics of the lower crust and upper mantle along the California coast (Wakabayashi, 1996). The rocks adjacent to the volcanic fields are sites of significant hydrothermal alteration and host important mercury and gold deposits, such as those at Clear Lake and Quien Sabe (Barnes, 1997; D. Sorg, 2005, personal commun.).

Tertiary volcanic dikes and plugs in the Pacheco Pass area are intruded into Franciscan rocks and are thought to belong to the NCRV (Metzger et al., 2005). The Diablo Range Volcanics (DRV), as referred to in this text, form a

Figure 1. Radiometric ages and locations (filled triangles) of the NCRV, in relation to major faults (red lines). The area containing the Diablo Range Volcanics (DRV) is shown with a grey outline. Modified from Dickinson (1997) and Whitlock (2002).

subset of the NCRV (Fig. 1) and cover a roughly rectangular area bounded by Eylar Mountain, Mount Hamilton, the Quien Sabe volcanic field, and San Luis Reservoir (Fig. 2). In addition to the larger DRV bodies shown as Tertiary volcanics in Figure 2, many small and little-known dikes and plugs are present within the area outlined in Figure 2.

The central Diablo Range in California (Fig. 2) consists of a northwest-southeast central belt of Jurassic-Cretaceous metamorphic rocks of the Franciscan Complex, flanked by sections of the Coast Range Ophiolite. Cretaceous rocks of the Great Valley Group lie to the east and west of the Franciscan Complex and in most places are tectonically separated from it by the Coast Range fault (Nakata et al., 1993; Wakabayashi, 1999), as well as by Cenozoic strike-slip faults (Fig. 2).

In the Pacheco Pass area, the central Franciscan belt of the Diablo Range is bounded by the NW-trending Ortigalita and Madrone Springs right-lateral strike-slip faults (Fig. 2). The NW-trending Greenville strike-slip fault system extends southward towards the general region of the Orestimba volcanics where several fault splays terminate. The Greenville, Madrone Springs, and Calaveras

Figure 2. Geologic map of the central Diablo Range. Note the northwest trend of lithology, volcanics, and faults. Based on Nakata et al. (1993).

fault systems are active, and may have accommodated over 80 kilometers of displacement in the past 13 million years (Wakabayashi, 1999).

Among the DRV, two units were chosen for detailed study: the andesite of Dowdy Ranch, and the basalt through andesite along Orestimba Creek northwest of Mustang Peak (Fig. 2). They are referred to as the Dowdy Ranch Andesite (DRA) and the Orestimba volcanics. These two units and associated metamorphic rocks are the focus of this thesis. The DRA consists of several large plugs and many associated smaller bodies. The Orestimba volcanics are composed of a few small plugs and dikes located within an area of several square kilometers (Wentworth et al., 1999).

Description of the Mapped Area

The area including the Dowdy Ranch andesite was mapped at a scale of 1:24,000; the mapped area (study area 1 in Fig. 2) occupies rugged, hilly terrain in the Central Diablo Range, California, and it is in the vicinity of Burra Burra Peak (Fig. 2). The area is accessed via State Route 152 and the gravel Kaiser-Aetna road, which connects to numerous rough dirt roads in the field area. Visibility

is good during the dry season (May-October), becoming considerably hampered by fog in early winter.

The topography consists of northeast-trending ridges, separated by deeply incised creek channels flowing into the North Fork of Pacheco Creek. The strong relief is defined by local exposures of resistant andesite and Franciscan meta-sandstone and blueschist. The prominent ridge containing Burra Burra Peak is composed of resistant tectonic blocks of blueschist that divide local drainages and dominate local topography. Ponds and springs appear to be associated with lithologic and structural boundaries, but they also occur on landslide debris.

The quality of bedrock exposure is generally very poor. Landslide debris, soil and vegetation comprise over 90% of the field area, making mapping an arduous task. Traversing the steep and rugged terrain on foot and conducting observations on the outcrop scale is therefore the preferred approach to field investigation.

Previous Work

Preliminary work of variable degree and quality was done by previous workers in the two study areas. The DRA was described as an outlier of the Quien Sabe volcanic

field by McKee (1958). Lower crustal xenoliths within the andesite were identified by Sorg and colleagues in the early 1990s (Nakata et al., 1993). More recently, Metzger et al. (2005) have performed petrographic and microprobe analyses of Al-rich xenoliths hosted by the DRA. Their work includes a petrographic description of the andesite and some major- and trace-element data for the DRV.

Dating of the DRA by Nakata et al. (1993) involved the radiometric Ar-Ar method. Ages of 12.3 to 8.5 Ma were obtained for xenoliths, and one Ar-Ar biotite age of 8.2 ± 2.8 Ma was determined for the DRA host. However, the accuracy of the radiometric biotite date has been questioned due to the significant error margin (Wakabayashi, 1999). Prior to this study, partial trace element analyses had been obtained from five samples in the study areas: four Orestimba volcanics, and one DRA.

The 1:100,000 scale preliminary geologic map of the San Jose quadrangle (Wentworth et al., 1999) shows general outlines of the DRA. A field investigation of hydrothermal rocks in the vicinity of Burra Burra Peak contained evidence of some localized, millimeter-scale veinlets of

malachite associated with blue semi-schist in a prospect pit ~70 m south of Burra Burra Peak (McKee, 1958).

The volcanics around Orestimba Creek were mapped by Sorg, using reconnaissance techniques. Hydrothermal alteration was found in the Franciscan Complex mélange along tributary creeks flowing into Orestimba Creek. The rare carbonates aluminohydrocalcite and chromium-rich dawsonite were identified using X-ray diffraction and microprobe analyses (Dunning, 2000). Ni-rich serpentinite was found on the margins of the aluminohydrocalcite vein. These minerals have been attributed to silica-carbonate alteration, a process closely associated with mercury mineralization (D. Sorg, 2004, personal commun.).

CONTACT RELATIONS AND PETROGRAPHY

Methods

Initial reconnaissance was conducted at the map, outcrop, and microscopic scales, in order to identify the lithologies present in the field area and define map units. During mapping, comprehensive areal coverage was attempted by traversing the terrain on foot systematically, such that lines of traverse were spaced at intervals of outcrop visibility (about 30-40 m). Outcrop locations were mapped with the aid of a compass and hand-held GPS unit.

A draft map of area 1 in Figure 2 on a 1:10,000 scale USGS topographic base was completed using 223 GPS coordinate readings to constrain position. Owing to poor exposure, the final map was compiled by interpreting outcrop patterns. Continuous sets of outcrops of one lithology over a reasonably small area were mapped as one body of rock. The locations of some faults were inferred from clues such as abrupt changes in slope, alignment of ridges, springs, ponds, and tectonic breccia localities. Some generalization was necessary due to the presence of many small-scale features in the Franciscan mélange,

landslides, and the inherently poor exposure. Hence, similar rock types were combined into map units and the final map scale was reduced to 1:24,000.

Landsliding was of particular concern as it complicated mapping significantly. For instance, the region encompassing the east-northeast trending andesite lobe, located in the NE portion of the map area, was thought to represent colluvium (D. Sorg, 2005, personal commun.). However, the main portion of the andesite lobe was mapped as bedrock by Wentworth et al. (1999).

In conjunction with mapping primary lithology, several dozen samples were collected for detailed petrographic study. Thin sections were made of the rocks on the andesite-host rock contact, and identification of primary phases was performed using the Olympus BHT monocular petrographic microscope. Modal percentages of phenocrysts are based on point counts using 1/3 mm step size and a 0.5 mm minimum-diameter phenocryst criterion.

Description of Map Units

The mapped area (area 1 in Fig. 2) contains a wide array of mid-Mesozoic to early Tertiary(?) metasedimentary and metavolcanic rocks, tectonically broken and interleaved

by subduction and known collectively as the Franciscan Complex. Two sub-categories of the Franciscan Complex are present in the field area: the Yolla Bolly terrane, and the tectonic *mélange*. The Yolla Bolly terrane in the map area consists mostly of the lower uncleaved metagraywacke member. The *mélange* of the Eastern belt of the Franciscan Complex consists of a matrix of metagraywacke with many individual tectonic blocks (Wentworth et al., 1999).

The Franciscan Complex in the area is intruded by the late Tertiary DRA (Plate 1). As mentioned previously, the purpose of the mapping is to establish the field relations between the andesite and the Franciscan host rock. Because small-scale variation among the metasedimentary rocks is not of primary concern here, rock units are grouped by lithology as described below.

Yolla Bolly Terrane

Yolla Bolly terrane metamorphic rocks are dominantly quartzofeldspathic graywacke with mudstone, conglomerate, blueschist, chert, and minor greenstone. The chert is dated as Middle-Late Jurassic (Wentworth et al., 1999).

Franciscan Mélange

The matrix of the mélange is a weakly- to strongly-foliated lithic metagraywacke and argillite with variable amounts of pumpellyite and glaucophane (Wentworth et al., 1999). The mélange contains tectonic blocks of conglomerate, greenstone, amphibolite, metachert, and blueschist.

Blueschist

The map unit consists of well-foliated blueschist-facies metamorphic rocks. Preliminary thin-section work reveals blue amphibole, quartz, albite, jadeite, and minor lawsonite, actinolite, and garnet. Exposures are characterized by a distinctive blue color (Fig. 3). Local occurrences of garnet-bearing chlorite schist are spatially associated with the blueschist and are included in this map category.

Metamorphosed Ultramafic Rocks

Ultramafic units typically consist of serpentinite and talc-tremolite schist (Fig. 3). The most prominent exposure of this unit is near the Burra Burra Peak copper

Figure 3. Exposure of ultramafic rock near the prospect just south of Burra Burra Peak, showing the relationship between tremolite schist (patches of pale green), serpentinite (olive green) and blueschist (at lower right). View facing north. The hammer is resting on the serpentinite-blueschist contact. Hammer handle is 21 cm long.

prospect pit (Plate 1), and small exposures of it are scattered in other localities. Rocks in this category contain talc, tremolite, chlorite, and serpentine.

Quartz-Carbonate Seams

In the Franciscan *mélange*, meter-scale metamorphic fissures filled with quartz, calcite, and aragonite are locally abundant along Pacheco Pass (Sasakura, 1983). In the field area, similar fissures are composed of variable proportions of clays, quartz, calcite, and pyrite. In the collected samples, preliminary thin section analysis reveals no well-developed aragonite, and it may be reverted to calcite.

Breccias

Franciscan sedimentary breccias are of clast-supported and matrix-supported types. Clasts typically are very angular and less than 2 cm in diameter; the most common clast lithologies are chert and sandstone. Some breccias are associated with lithologic contacts between blueschist and metasedimentary rocks.

Andesite of Dowdy Ranch

The DRA (Fig. 4) is a gray andesite, which weathers to pinkish tan. The unit contains 17 to 27% plagioclase and pyroxene phenocrysts, the most abundant being plagioclase feldspar. The texture is porphyritic, commonly glomerophyric, and it ranges from intersertal to hyalopilitic. The phenocrysts are predominantly subhedral.

Results

Map-Scale Relationships

The metasedimentary portion of the Franciscan mélange comprises the dominant lithology in the field area, with blueschist-facies metamorphic blocks scattered within the metasedimentary rock matrix (Plate 1). Most blueschist blocks are less than 100 m across and show variable geographic alignment in map view. The blocks may be structurally juxtaposed, making it difficult to distinguish between individual blocks. The blueschist of Burra Burra Peak is thought to be one large block (Wentworth et al., 1999). Several areas to the north, northeast, and south of the peak are mapped as sizable blueschist bodies (Plate 1), but each of these may comprise more than one block. Yolla Bolly metasedimentary rocks are limited to the southeast

Figure 4. Andesite of Dowdy Ranch, exposed northwest of Burra Burra Peak; view facing west. The sub-perpendicular joints seen here are common, as are spheroidal joints. Convex fractures, possibly pseudopillows related to rapid cooling, are visible near the base of the outcrop. The exposure is ~3.5 m high.

corner of the map area, structurally below the Franciscan mélange. The map units are cross-cut by two sets of faults: one trending $\sim N55^{\circ}W$, and one trending $\sim N10^{\circ}E$.

Map-scale andesite-host relations and locations of analyzed samples are shown in Plate 1. In map view the DRA covers more than 1 km^2 and consists of at least two large, sinuous bodies with many apparently connected lobes of variable size. Smaller plugs and dikes are clustered in close proximity to the larger bodies and are most likely connected at depth. Branching and interconnecting of plugs via smaller conduits can be inferred from map relations and similarity in rock type. Some of the smaller plugs and dikes are scattered over an area of several square kilometers; the smallest of these are less than 5 m in diameter. Some of the plugs persist to the north and east of the area shown in Plate 1. There is no evidence of sill-like bodies.

Petrography of the Volcanic Units

The Orestimba Creek samples (Plate 2) are located to the northwest of the Burra Burra Peak area and consist mostly of olivine-clinopyroxene-hornblende basaltic andesites; original olivine phenocrysts are now mostly

altered (Table 1). The rocks have intergranular to subophitic, pilotaxitic texture (Fig. 5). Although porphyritic in general, the rocks show a transition to continuous grain size gradation. All basaltic andesites in Table 1 lack textural evidence of disequilibrium. Sample PK230A is an andesite located in the same general area as the basaltic andesite (Plate 2). It is distinct from the olivine-phyric rocks in its nesophitic texture. It shows textural disequilibrium in the form of quartz inclusions rimmed by augite, and embayed and fritted plagioclase grains (Fig. 6).

The andesite of Dowdy Ranch has a porphyritic texture, containing 17-27% plagioclase and pyroxene phenocrysts (Table 1), the most abundant being plagioclase feldspar (16-26%), followed by clinopyroxene (~1%). One sample has minor orthopyroxene (<1%). Plagioclase phenocrysts have normal and reverse zoning, with an average core composition of An₅₀ (Stevenson et al., 2002; Metzger et al., 2005). Hornblende, biotite, apatite, zircon, and oxides are common accessory phases. The texture is porphyritic, commonly glomerophyric, and intergranular (Table 1). Trachytic alignment of plagioclase microlites is evident in many specimens.

TABLE 1. SUMMARY OF PETROGRAPHIC DATA

Sample	Location and lithology	Principal Texture	Groundmass Texture	Phenocryst and xenocryst mineralogy and modal percentages	Comments
PK226	Orestimba basaltic andesite	Porphyritic, somewhat seriate; glomerophyric (plagioclase, clinopyroxene)	Intergranular, pilotaxitic; 90% groundmass	Plagioclase- 6% Clinopyroxene- 4% Hornblende- <1% Olivine- <1% (350 point counts)	Small (<0.3 mm) carbonate veinlet present. Olivine mostly altered to iddingsite and serpentine.
PK230A	Orestimba andesite	Porphyritic, somewhat glomerophyric (plagioclase, clinopyroxene)	Diabasic/ nesophitic, trachytic; 87% groundmass	Plagioclase- 9% Clinopyroxene- 2% Quartz xenocrysts- 2% (339 point counts)	Quartz xenocrysts up to 2 mm in diameter present. A few percent oxides in groundmass.

TABLE 1 (continued)

Sample	Location and lithology	Principal Texture	Groundmass Texture	Phenocryst and xenocryst mineralogy and modal percentages	Comments
PK237B	Orestimba basaltic andesite	Porphyritic, somewhat seriate, glomerophyric (plagioclase, clinopyroxene)	Intergranular, pilotaxitic; 91% groundmass	Plagioclase- 6% Clinopyroxene- 2% Hornblende- <1% Olivine- <1% (379 point counts)	Olivine largely altered to iddingsite and serpentine.
PK221B	Orestimba basaltic andesite	Seriate, glomerophyric (olivine, clinopyroxene)	Intergranular to subophitic, pilotaxitic; 85% groundmass	Plagioclase- 9% Clinopyroxene- 5% Olivine- 1% Biotite- <1% Hornblende- <1% (410 point counts)	Minor carbonate and clay replacement. Olivine replaced by chlorite and iddingsite.
PK224	Orestimba basaltic andesite	Porphyritic, somewhat seriate, glomerophyric (olivine, clinopyroxene, hornblende)	Intergranular, pilotaxitic; 86% groundmass	Plagioclase- 11% Clinopyroxene- 2% Hornblende- 1% Olivine- <1% (378 point counts)	Contains thin (~0.1 mm) carbonate veinlet. Olivine replaced by iddingsite and serpentine.

TABLE 1 (continued)

Sample	Location and lithology	Principal Texture	Groundmass Texture	Phenocryst and xenocryst mineralogy and modal percentages	Comments
99EW PP-10	Dowdy Ranch andesite	Porphyritic, glomerophyric (plagioclase)	Intergranular, trachytic 70% groundmass	Plagioclase- 26% Quartz xenocrysts- 2% Clinopyroxene- 1% (500 point counts)	Contains gabbroic xenolith.
91SGPP-54A	Dowdy Ranch andesite	Porphyritic, glomerophyric (plagioclase)	Intergranular, trachytic 79% groundmass	Plagioclase- 16% Quartz xenocrysts- 4% Clinopyroxene- 1% (309 point counts)	Contains gabbroic xenolith.
97EW PP-16A	Dowdy Ranch andesite	Porphyritic, glomerophyric (plagioclase)	Intergranular, trachytic 78% groundmass	Plagioclase- 20% Quartz xenocrysts- 1% Clinopyroxene- 1% Orthopyroxene- 1% (401 point counts)	Contains quartzo-feldspathic and gabbroic xenoliths.

Note: Samples 99EWPP-10, 91SGPP-54A, and 97EWPP-16A collected by Dennis Sorg and Elizabeth White.

Locations of Orestimba volcanic samples are shown on Plate 2.

Figure 5. Photomicrograph of Orestimba basaltic andesite (sample PK224). The glomerophyric texture is evident, commonly involving clumps of clinopyroxene. The large intergrowth on the right contains clinopyroxene, olivine, and hornblende. Field of view is 7 mm x 5.25 mm.

Figure 6. Photomicrograph of Orestimba andesite (sample PK230A). The dominant phenocryst is plagioclase (on the left), commonly with embayed and fritted rims and complex zoning. The quartz xenocryst at lower right is partially replaced by augite along fractures. Field of view is 7 mm x 5.25 mm.

The DRA contains 1-4% glassy and partially resorbed quartz xenocrysts mantled by augite coronas (Fig. 7). Embayed and partially dissolved plagioclase is also evident. More commonly, the plagioclase contains "sponge" or "sieve" textures comprising either fritted rims or cores (Stimac and Pearce, 1992). High-grade aluminous xenoliths and quartz xenocrysts as well as gabbroic xenoliths are common in the andesite.

Properties of the DRA-Franciscan Contact

The nature of the DRA-Franciscan contact is commonly obscured by the limited exposure. A discernible plane between the andesite and host rock is exposed only at localities 1 through 4 in Plate 1. The contact dips at an angle between 46 and 69°, in variable directions.

Mineralogical or textural changes in the host rock are not found more than about 0.5-1 m from the andesite. Visible disruption of foliation in blueschist and recrystallization in sandstone are recorded at distances of 10 to 30 cm from the andesite. The adjacent andesite contains quenched zones up to 0.5 m thick composed of

Figure 7. Photomicrograph of quartz xenocryst with augite rim in DRA (sample PP-54A). Mottled plagioclase grains are visible in the lower left corner and towards the upper right. The field of view is 3.5 mm x 2.6 mm.

partially recrystallized vitrophyre and glassy
autobreccias.

Properties of Contact-Margin Andesite

Contact-margin andesite is of two main textural types: vitrophyre and autolithic breccia. These rocks are heterogeneous, containing alternating bands of vitrophyric and hyalopilitic andesite. The vitrophyre consists of a glass groundmass and ~3% phenocrysts, mainly plagioclase. The groundmass of hyalopilitic andesite contains microlites in addition to glass (Fig. 8). Spherical glassy domains are detached from the layers of vitrophyre and dispersed in the adjacent hyalopilitic andesite (Fig. 8).

The autolithic breccias sampled at localities 2, 3, and 4 (Plate 1) have a matrix of hyalopilitic porphyritic andesite, which has a groundmass of >50% glass and is dark bluish-gray in color. The breccias contain 10-15% autolithic clasts up to ~3 cm in diameter, which range in form from well rounded to highly angular (Fig. 9). In contrast to the banding seen in recrystallized vitrophyre, the breccias contain lenses of glass, most of which are aligned with the flow (Fig. 9). Flow alignment of the hypocrySTALLINE groundmass and autoliths is evident in both

Figure 8. Photomicrograph of a flow containing interlayered vitrophyric andesite (dark gray) and hyalopilitic andesite (light gray). Round glassy domains are visible on the left and near the lower right corner. Cross-polarized light. Field of view is 7 mm x 5.25 mm.

Figure 9. Cut surface of andesitic autobreccia from locality 3 (Plate 1), showing the alignment of glass fragments (dark blue) and clasts from upper center to lower right.

the hand sample and thin section (Figs. 9 and 10). Augite rims are well developed around nearly all inclusions of quartz and glass, and the augite locally replaces the entire domains.

The mineralogy of autoliths inclusions (Table 2) from localities 2, 3, and 4 (corresponding to samples 215/3, 215/2, and 195B, respectively) is based on petrographic description and electron microprobe analyses in Appendix A. The inclusions fall into two main categories based on texture.

Inclusions in the first category (inclusions 1-6 in Table 2) possess a granoblastic texture (Fig. 11) and probably are metasedimentary rocks. Quartz and plagioclase (40-60%) are dominant and constitute the matrix of the granoblastic inclusions. Neoblastic pyroxene, K-feldspar, ilmenite, and sphene form euhedral to subhedral intergrowths within the quartz-plagioclase matrix. Manganese is abundant in some inclusions and forms pyrolusite and related Mn-oxides. Mn-rich opaque minerals, as well as the Ti-bearing phases may form up to 50% of an inclusion.

Inclusions in the second category have a recognizable primary texture and are composed of chert and greywacke in

Figure 10. Photomicrograph of autolithic breccia with flow alignment of the groundmass, phenocrysts, and chlorite-quartz inclusions (greenish-brown). Plane-polarized light. Field of view is 7 mm x 5.25 mm.

TABLE 2. CLAST COMPOSITION OF CONTACT-MARGIN ANDESITIC AUTOBRECCIA OF DOWDY RANCH.

Inclusion type and sample number (Plate 1)	Phase assemblage	Comments
1. Metasedimentary Sample 215/3	Quartz + plagioclase K-feldspar + ilmenite + pyroxene +	Some K-feldspar is found as "armoring" on plagioclase.
2. Metasedimentary(?) Sample 215/3	Anorthite + sphene + pyroxene + quartz + plagioclase	
3. Metasedimentary(?) Sample 215/3	K-feldspar + ilmenite + pyroxene + biotite + quartz + plagioclase	Most pyroxene occurs as fine intergrowths of orthopyroxene and clinopyroxene.
4. Metasedimentary Sample 215/3	Pyroxene + plagioclase + sphene + quartz	
5. Metasedimentary Sample 215/2	Ilmenite + pyrolusite(?) + anorthite + biotite + pyroxene + quartz + plagioclase	Ilmenite occurs as euhedral, bladed crystals intergrown with feldspar.
6. Metasedimentary Sample 215/2	Ilmenite + pyrolusite(?) + pyroxene + plagioclase + quartz	
7. Graywacke Sample 195B	Quartz + chlorite + plagioclase + biotite + ilmenite + K-feldspar (minor)	Plagioclase contains normal zoning.
8. Graywacke Sample 195B	Quartz + chlorite + K-feldspar + biotite(?) + plagioclase + sphene	In most cases, chlorite is replaced by biotite near the margin of an inclusion.
9. Chert Sample 195B	Quartz + K-feldspar + chromite + chlorite (minor) + plagioclase

Figure 11. Photomicrograph of a complex intergrowth in the core of metasedimentary autolith inclusion, containing quartz (colorless), biotite (1), orthopyroxene (2), sphene (3), and ilmenite (fine-grained, opaque). Plane-polarized light. Field of view is 1.4 mm x 1 mm.

early stages of recrystallization (Fig. 12). The texture is similar to that of the Franciscan metasedimentary rocks studied by the author. The dominant minerals are quartz, plagioclase, and chlorite, with lesser amounts of biotite, K-feldspar, sphene, and chromite. In both types of autolithic inclusions, the textural and compositional diversity implies a dominantly quartzofeldspathic protolith and varying degrees of contact metamorphism.

Two-Phase Geothermometry

The mineral assemblages in the recrystallized contact metamorphic inclusions (Table 2) make it possible to estimate temperature using the two-pyroxene and the two-feldspar solvus systems. Based on granoblastic textures and lack of apparent mineral zoning, these inclusions are inferred to have been completely re-equilibrated with the melt. Five calibrations that have been applied to low-pressure (<5 kbar) contact-metamorphic systems were selected (Fonarev and Graphchikov, 1991; Mizuno and Miyano, 1999). Pressures (P) of 500 and 1000 bar were used, assuming near-surface emplacement, as is the case at Quien Sabe (Drinkwater, 1983), and ~2-5 km of surface erosion. Table 3 summarizes the results of temperature calculations

Figure 12. Photomicrograph of a greywacke autolith (lower left) in a matrix of hyalopilitic andesite. The relict sedimentary texture is evident. Cross-polarized light. Field of view is 7 mm x 5.25 mm.

TABLE 3. ESTIMATED TEMPERATURES OF MINERAL EQUILIBRATION IN AUTOLITHS
IN SAMPLE 215/3

Thermometric system and equation number		Calculated temperature (°C)		
		500 bar	1000 bar	
1. Two-pyroxene (Wood and Banno, 1973)	$T(K) = \frac{-10202}{\ln(K) - 7.65 \cdot x_{Fe, Opx} + 3.88 \cdot (x_{Fe, Opx})^2 - 4.6}$ $K = \frac{a_{Mg, Cpx}}{a_{Mg, Opx}}$	where	992	992
2. Two-pyroxene (Wells, 1977)	$T(^{\circ}C) = \frac{7341}{-\ln(K) + 3.355 + 2.44 \cdot x_{Fe, Opx}} - 273$	where $K = \frac{a_{Mg, Cpx}}{a_{Mg, Opx}}$	1071	1071
3. Two-pyroxene (Fonarev and Graphchikov, 1982)	$T(K) = \frac{2 \cdot 10^3 \cdot \gamma}{-\beta + \sqrt{\beta^2 - 4 \cdot \alpha \cdot \gamma}}$	where α , β , and γ are parameters based on measured $x_{A, B}$ and experimentally determined $a_{A, B}$.	1188	1188
4. Two-feldspar (Stormer, 1975)	Graphical solution using x_{Ab} in plagioclase and K-feldspar.	---	---	1100
5. Two-feldspar (Powell and Powell, 1977)	$T(^{\circ}C) = \frac{-x_{K, Kfs}^2 [6330 + 0.093 \cdot P + 2 \cdot x_{Na, Kfs} (1340 + 0.019 \cdot P)]}{8.314 \cdot \ln(K_D) + x_{K, Kfs}^2 (-4.63 + 1.54 \cdot x_{Na, Kfs})}$ $\text{where } K_D = \frac{x_{Na, Kfs}}{x_{Na, Pl}}$		1122	1131

using one pair of co-crystallized intergrown pyroxenes and one pair of co-crystallized intergrown feldspars (analyses 1-4 in Appendix A) in sample 215/3 (Plate 1).

Two-Pyroxene Thermometers. The two-pyroxene geothermometer is based on the transfer of Mg^{2+} between coexisting orthopyroxene and clinopyroxene, whose dependence on temperature (T) is governed by chemical activity ($a_{A,B}$) and mole fraction ($x_{A,B}$) of component A in phase B, given by the subscripts.

The thermometers of Wood and Banno (1973) and Wells (1977) are semi-empirical relationships based on the ideal two-site solid-solution model for pyroxenes with thermodynamic parameters inferred from experimental data (equations 1 and 2 in Table 3). The activity coefficients are calculated by assigning formula unit ions to the M1 and M2 sites as outlined by Wood and Banno (1973). Enstatite activity (a_{En}) is given by the expression $x_{\text{Mg}}^{\text{M1}} \cdot x_{\text{Mg}}^{\text{M2}}$, assuming no coupling between M1 and M2 ions (Wood and Banno, 1973). Using analyses 1 and 2 in Appendix A, temperatures of 992°C and 1071°C were obtained using the methods of Wood and Banno (1973), and Wells (1977), respectively (Table 3).

Temperature can also be calculated by using experimentally determined coefficients (α , β , γ) which include P and $x_{A,B}$, rather than by finding the ion distribution coefficient K . Constant parameters for the expected temperature range are then entered into equation 3 in Table 3. This expression gives a temperature of 1188°C using the experimental activity constants for 900-1200°C (Fonarev and Graphchikov, 1982).

Two-Feldspar Thermometers. Two-feldspar thermometers utilize the distribution of Na between coexisting plagioclase and K-feldspar. As with pyroxenes, the ideal solution model is calibrated using experimental data to compensate for non-ideal mixing behavior. The two-feldspar systems of Stormer (1975) and Powell and Powell (1977) give similar temperatures of 1100°C and 1122-1131°C respectively (Table 3), using analyses 3 and 4 in Appendix A. The former is obtained from the determinative curve in Stormer (1975).

Interpretations

Several conclusions can be drawn about the DRA-host rock relationships. Field work confirms earlier

observations that the andesite forms steeply-dipping structures (Nakata et al., 1993) but also shows that it is more abundant and more complex than previously thought. According to an earlier description, the andesite is a "northwest-trending, 1.5 km long by 400 m wide, steeply northwest-dipping dike that intrudes the Franciscan Complex *mélange* on the northeast flank of Burra Burra Peak" (Nakata et al., 1993). In contrast, Plate 1 shows two preferential alignments of the volcanic bodies: one northeast-southwest, and one northwest-southeast. In many instances, andesite bodies appear to coincide with the metasedimentary-blueschist boundary and possibly are truncated against blueschist blocks (Plate 1). Overall, the map pattern points to a network of plugs interconnected by dikes.

The relationship between the DRA and the Franciscan rock is intrusive hypabyssal, except where the contact is faulted (Plate 1). In map view, the andesite is strongly aligned with local faults, suggesting that faults served as magma conduits. If some of the sub-perpendicular faults are antithetic, local extension may have assisted andesite emplacement (Plate 1). The hypocrySTALLINE texture of DRA and the presence of vitrophyre along its margin supports

incomplete crystallization following shallow-level emplacement.

As mentioned earlier, the DRA may be an outlier of the Quien Sabe field. The Quien Sabe volcanics represent a combination of hypabyssal and explosive volcanism, as do the Clear Lake, Sonoma, and Anderson-Coyote Reservoir volcanics (Fig. 1). The Quien Sabe field consists of flows of basalt, dacite, and andesite, interbedded with tuff and laharic breccia. Shallow dikes, plugs, and sills of dacite-rhyolite represent the later hypabyssal volcanic phase (Drinkwater, 1983). In contrast, the DRA consists entirely of hypabyssal intrusive bodies. There are several possible explanations for the lack of an erupted phase in the DRA. Drinkwater (1983) suggested that Diablo Range Volcanics originally were erupted on an area of low relief and subsequently were uplifted and eroded. This study suggests that the DRA represents a network of magma conduits and supports the view that the DRA represents an older, eroded remnant of the Quien Sabe field (Metzger et al., 2005).

The presence of shallow-level, low-aluminum, quartzofeldspathic autoliths in the andesite confirms the magmatic assimilation of Franciscan rocks. The temperature range of

992-1188°C obtained by geothermometry of recrystallized autoliths on the andesite contact is generally consistent with conditions of andesitic magma and reflects temperature equilibration of at least some pyroxene-bearing and K-feldspar-bearing inclusions with the magma. However, the presence of chlorite in non-recrystallized inclusions reflects thermodynamic disequilibrium with magma at ~1100°C and indicates quenching of the andesite along its intrusive margin.

GEOCHEMISTRY OF THE DIABLO RANGE VOLCANICS

Data Collection and Analysis

Six samples of the Diablo Range Volcanics were collected by the author for major and trace element analysis. Sample numbers are shown in Appendix B; two samples are from the Dowdy Ranch Andesite (DRA) dike complex (Plate 1) and four are from separate volcanic dikes in the vicinity of Orestimba Creek (Plate 2). Major and trace elements were determined by X-ray fluorescence and ICP-MS at Washington State University's GeoAnalytical Laboratory. Details of the procedure are presented in Appendix C.

The DRV are similar in their age, composition, and texture, and they are considered to be one volcanic suite (Drinkwater, 1983; Nakata et al., 1993; Stevenson et al., 2002; Metzger et al., 2005). Hence, the major and trace element data for 40 previously analyzed samples of DRV are combined from several sources (Drinkwater et al., 1988; Stevenson et al., 2002; Metzger et al., 2005; Sorg, unpublished data), in addition to the data obtained in this study. The sample coordinates are given in Appendix D.

All chemical data are reported on a volatile-free basis. Major and trace element data are given in weight percent oxide and parts per million, respectively. The available data allow only limited analysis of the relative roles of fractionation and mixing in the DRV. The data for many localities are incomplete and the likely end member compositions cannot be identified to test mixing models. In addition, data on phenocryst content are not available for most DRV, precluding the use of phase diagrams in identifying fractionation trends.

Results

Major Elements

Major element data for samples in this study and from previously studied samples are presented in Appendix B. In order to compare their chemical compositions and identify petrologic trends, the available DRV data were plotted on classification diagrams of Le Bas et al. (1986) and Peccerillo and Taylor (1976). The DRV range from low-silica basalt to rhyolite (Fig. 13) and are classified as subalkaline (E. Metzger, 2005, personal commun.). The Quien Sabe volcanics plot close to the boundary

Figure 13. Petrologic classification of DRV samples, based on alkalis vs. SiO_2 . Data from Sorg (unpublished data), Stevenson et al. (2002), and Metzger et al. (2005), unless otherwise stated. All data are listed in Appendix B. Classification system from LeBas et al. (1986).

between the high-K calc-alkaline and the calc-alkaline series (Fig. 14). The other DRV, including those sampled by the author, show more scatter within both the high-K and calc-alkaline fields; however, they display much the same trend as the Quien Sabe volcanics.

Trace Elements

Multi-element variation diagrams are intended to show normalized element concentrations, and they are useful in comparing basaltic rocks with potential magma sources. For example, basaltic island arc rocks have a characteristic trace element signature, showing enrichments in large-ion-lithophile elements (LILE) in relation to high-field-strength elements (HFSE). If there is no significant crustal assimilation, these characteristics reflect magma generation from a LILE-enriched source (Gill, 1981; Rollinson, 1993).

The trace element abundances of the Orestimba and DRA volcanics, in parts per million, are summarized in Appendix B. Because of their somewhat high silica content, samples of Dowdy Ranch andesite may be inferior to more mafic counterparts for direct comparison of trace element

Figure 14. Classification of DRV based on K_2O and SiO_2 only. Symbols are as for Figure 13. XRF data from Sorg (unpublished data), Stevenson et al. (2002), and Metzger et al. (2005), unless otherwise stated in Figure 13. Classification system from Peccerillo and Taylor (1976).

chemistry. Still, the chondrite-normalized and MORB-normalized spider plots for the DRA are very similar to those for Orestimba basaltic andesites (Fig. 15). All six patterns indicate strong enrichment in LILE (such as Ba, Th, Sr), depletion in HFSE (Nb, Ti, Yb, and others), and a strong negative Nb anomaly. As shown in the MORB-normalized plot, rock to MORB ratios range from 10 to 80 for Rb, Ba, and Th.

Individual element ratios are commonly used as tectonomagmatic discriminators. Ratios of Ba/Ta may be plotted as indicators of arc-type vs. MORB-type magmatism. Ba/Ta ratios greater than 450 show a strong arc affinity (Gill, 1981; Whitlock, 2002). As shown on Figure 16, Ba/Ta ratios are >600 for Dowdy Ranch andesite, and Orestimba basaltic andesites have Ba/Ta ratios of 2000 and higher. These ratios are broadly consistent with the Ba/Ta ratios from volcanic rocks in the Cascades, the NCRV, and in forearc sediments (Whitlock, 2002). In contrast, magmas derived from MORB-type sub-slab asthenosphere, represented by volcanics from the Coast Range and Santa Maria Province of southern California (Whitlock, 2002), have much lower Ba/Ta ratios (Fig. 16).

Figure 15. Multi-element plots of DRA (open circles) and Orestimba volcanics collected by the author. Rock ratio normalization factors are based on Sun (1980) and Pearce (1983).

Figure 16. Ba vs. Ta and Nb vs. Ta plots for Orestimba (filled circles) and Dowdy Ranch volcanics. Scale values are in parts per million. Samples PK221B and PK237B plot as one point on the lower diagram at $Ta=0.47$, $Nb=7.55$. Some relevant trace element ratios are outlined by shaded fields, based on samples plotted by Whitlock (2002).

Ratios of Nb to Ta are used to distinguish between enriched and depleted mantle reservoirs (Rollinson, 1993). Nb and Ta have very similar bulk partition coefficients of ~ 0.01 in clinopyroxene and plagioclase of basaltic melts and low solubility in hydrous fluids. Therefore, their concentrations in basalts and basaltic andesites should correspond to those of the parent source (Whitlock, 2002). It is of note, however, that this scheme does not readily help in distinguishing between MORB-type and arc-type mantle sources, because both would have been depleted by partial melting (Rollinson, 1993). Enriched mantle reservoirs have Nb/Ta ratios on the order of 17-22, whereas most depleted mantle reservoirs have a range of 6-18 (Whitlock, 2002). The DRA and Orestimba samples have Nb/Ta ratios of 12-16, which is consistent with depleted mantle reservoirs, similar to those in the NCRV and Cascade volcanics (Fig. 16).

Ternary trace element diagrams such as the Th-Hf-Ta system can be used for tectonomagmatic discrimination of erupted magmas (Wood, 1980). The diagram shows the relative abundances of HFSE which are insoluble in aqueous fluids, but are sensitive to heterogeneities of mantle sources. Another advantage of this ternary system is its

application to a variety of volcanic compositions, because it is insensitive to element partitioning by fractionation (Wood, 1980; Rollinson, 1993). Samples from the two study areas plot toward the Th apex in Figure 17, showing a strong signature of the magmatic arc-type setting.

Trace element data for the DRV sampled by the author may be compared with those compiled from Drinkwater et al. (1988), Stevenson et al. (2002), Metzger et al. (2005), and Sorg (unpublished data), which are listed in Appendix B. Trace element data for basalts and basaltic andesites from Figure 13 are plotted on chondrite-normalized and MORB-normalized multi-element spidergrams (Fig. 18). Measurements are incomplete for Cs, Rb, U, Ta, Sm, Zr, Pb, Pr, Eu, Dy, Yb, and Lu in some or all samples. Nonetheless, the pattern shows strong enrichment in LILE and depletion in HFSE, and a strong negative Nb anomaly. Rock to MORB ratios are between 20 and 80 for Ba and Th (Fig. 18). The trace element abundances in Figure 18 are essentially the same as those in Figure 15.

Bivariate trace element plots may show whether the observed element behavior is consistent with pure fractionation, pure end member mixing, or a combination of processes. Several highly incompatible elements are

Figure 17. Relative proportions of Hf, Ta, and Th in the Orestimba (filled circles) and Dowdy Ranch volcanics. Note the strong magmatic arc affinity of all samples. Orestimba samples 226, 221B, and 237B plot essentially as one point, the one closest to the Th corner of the plot. Discrimination diagram of Wood (1980).

Figure 18. Multi-element diagrams for DRV basalts or basaltic andesites in Appendix B. Normalization factors after Sun (1980) (top) and Pearce (1983). Symbols are as for Figure 13.

plotted with respect to SiO_2 (Fig. 19). Concentrations of Ba, Th, La, Nd, and Ce (Fig. 19b-f) are expected to increase with increasing SiO_2 , because they are incompatible in major basaltic phases such as plagioclase and pyroxene. In the studied rocks however, they show great scatter and variable behavior. The Orestimba samples show an apparent decrease in incompatible element concentration with increasing SiO_2 (Fig. 19b-f). For instance, Th is incompatible in common basaltic phases (Rollinson, 1993) but its decreasing concentration in the Red Creek and Orestimba dikes does not reflect this property. Samples for the Pacheco Peak and Vaughn Mine localities show no apparent trend in trace element concentration. Of particular note is the wide scatter of trace element concentrations for basaltic samples, indicating either multiple mafic parent magmas, or modest crustal contamination of the basaltic magma or both (Rollinson, 1993).

Strontium is a large-ion-lithophile element that partitions into plagioclase rather than ferromagnesian phases, and it may therefore reflect the extent of plagioclase fractionation. The plot of Sr vs SiO_2 (Fig. 19a) contains more than one trend. For the Quien Sabe and

Figure 19. Binary variation plots of selected trace elements for data in Appendix B. Symbols are as in Figure 13.

Orestimba-Mustang Peak samples, Sr values decrease from ~1000 ppm at 45% SiO₂ to ~500 ppm at 65% SiO₂. In contrast, Sr values vary little in samples from the Dowdy Ranch, Pacheco Peak, and San Luis Reservoir areas (Fig. 19). The wide scatter reflects the diverse nature of processes involved in magma evolution.

Interpretations

Evidence for Slab Fluid Fluxing

The slab window tectonomagmatic model has been invoked (Snyder et al., 1976; Johnson and O'Neil, 1984; Fox et al., 1985) to explain the northwestward-decreasing age of most NCRV subparallel to the San Andreas fault (Fig. 1). According to this model, the slab window opened where the transform-trench interaction took place due to northward migration of the Mendocino Triple Junction (MTJ), and continuous "removal" of the subducted slab beneath the North American Plate (Fig. 20). The resultant crustal thinning south of the Gorda-Pacific-North American plate junction has resulted in local upwelling of mantle material (Wakabayashi, 1996; Dickinson, 1997; Furlong, 2004).

The geochemistry of volcanic rocks presented in this study stands in contrast to typical slab-window volcanism,

Figure 20. Schematic diagram showing the Late-Cenozoic plate tectonic evolution of California and the time-distance correlation (lower right) of NCRV (triangles) with the migration of the MTJ (shaded area). Modified from Furlong (2004) and Dickinson (1997).

where alkaline OIB-type sub-slab asthenosphere is tapped (Johnston and Thorkelson, 1997; Benoit et al., 2002). DRV samples reported in this study and those reported for other localities have a calc-alkaline affinity (Fig. 14). This is unusual in slab window-derived volcanics, but it is common in arc-type settings (Gill, 1981; Hole et al., 1991). Trace element spider diagrams (Figs. 15, 18) and the Th-Hf-Ta tectonomagmatic discrimination diagram (Fig. 17) show that the mafic and intermediate DRV have an arc chemical signature.

Basaltic andesites from Orestimba Creek and Mustang Peak have strong LILE enrichments, Nb/Ta ratios of 12 to 17, and Ba/Ta ratios above 450; however, there is no petrographic evidence of crustal assimilation in these rocks. All basaltic DRV also have strong HFSE depletions and negative Nb anomalies (Fig. 18). These properties are characteristic of arc-type settings, where slab devolatilization causes a partitioning of HFSE from and LILE into hydrous fluids. This argues in favor of slab fluid fluxing of supra-slab asthenosphere and implies that the relict mantle wedge southeast of the MTJ is a possible magma source, as suggested by Whitlock (2002). Despite the fact that subduction had ceased at that location (Fig. 20),

the mantle wedge may retain the chemical signature of the subducted slab due to earlier fluid fluxing (Whitlock, 2002). The Ba content in the new Orestimba samples is significantly higher than in other NCRV (Fig. 16). This may reflect extensive LILE enrichment of the magma source, and possibly a role for sub-continental lithosphere (J. Miller, 2005, personal commun.).

Based on the available chemical data, the Orestimba and Dowdy Ranch samples are genetically related to each other and to other DRV, but not to the alkaline Coyote-Anderson Reservoir volcanics (Figs. 21-22). At 2.5-3.5 Ma, the Coyote-Anderson Reservoir basalts are alkaline and much younger than other NCRV in their vicinity (Fig. 1) and are thought to have erupted due to localized extension along the Hayward-Calaveras fault system (Dickinson, 1997; Jove and Coleman, 1998; Wakabayashi, 1999). The basalts contain inclusions of spinel lherzolite and have an OIB-like mantle source (Jove, 1992).

The results obtained in this study suggest that the DRV are genetically related to the more northerly NCRV (Whitlock, 2002; Schmitt et al., in press), rather than to the Coyote-Anderson Reservoir basalt. In comparison with more northerly NCRV (Fig. 22), the DRV plot closer to the

Figure 21. NCRV trace element diagrams for basalts and basaltic andesites. Normalization factors based on Sun (1980) and Pearce (1983). Symbols are explained in Figure 22. ICP-MS data from Whitlock (2002).

Figure 22. Classification of some NCRV samples based on K_2O and SiO_2 . XRF data and sample localities from Whitlock (2002). The NCRV localities are shown in Figures 1 and 2. Classification based on Peccerillo and Taylor (1976).

high-K calc-alkaline category. Still, most DRV samples are calc-alkaline (Fig. 14). Like the DRV, the low-silica NCRV (Fig. 21) are enriched in LILE with respect to HFSE.

Ratios of Ba/Ta and Nb/Ta in mafic NCRV are 600-1600 and 11-19 respectively, and the trace element spider plots display a negative Nb anomaly (Fig. 21). The NCRV trace element data are quite similar to those for Orestimba samples (Figs. 15, 18). The main differences lie in the greater overall enrichment in LILE in the DRV.

Evidence of Magma Hybridization

Evidence of lower crustal contamination and magma mixing is critical in evaluating the petrogenesis of arc-type magmas. Andesites in general are viewed as hybrid magmas, rarely formed by direct differentiation of basalt (Eichelberger, 1978). However, pure bimodal mixing appears to be uncommon, and orogenic andesites are more likely to show textural evidence of a combination of mixing, crustal contamination, and fractionation (Gill, 1981).

Textures serving as evidence of chemical disequilibrium between crystals and melt (Eichelberger, 1978; Gill, 1981; Nixon and Pearce, 1987; Stimac and Pearce, 1992), and seen in the DRA and Orestimba andesite

include: (1) "sponge" and "sieve" texture, involving plagioclase with finely fritted or skeletal rims and cores, representing reaction of sodic plagioclase with more calcic melt, or vice versa; (2) simple dissolution and embayment of plagioclase, due to abrupt heating; (3) quartz xenocrysts with augite rims at various stages of growth, representing grain-boundary reactions; and (4) resorption of quartz xenocrysts.

Dissolved, fritted, and embayed plagioclase phenocrysts, and quartz xenocrysts (Fig. 7) serve as textural evidence that magma mixing and crustal assimilation played a significant role in the petrogenesis of intermediate DRV. However, the wide scatter in incompatible element data show that the DRV cannot be related by simple binary mixing. They suggest mixing involving a variety of distinct melts. It is possible that fractional crystallization is superimposed on the mixed melts, and this may further contribute to the observed element scatter, particularly in the trace element data. However, for these magmas, plagioclase fractionation is expected, and several lines of evidence suggest that the role of plagioclase fractionation is relatively modest: (1) Sr values range from 400 to 700 ppm between 47 and 60

weight percent SiO_2 ; (2) for individual sample suites, Sr shows more limited variation, and data trends show slight decrease with SiO_2 , slight increase with SiO_2 , or incoherent scatter; (3) on REE plots, some samples lack Eu anomalies, which would be expected for plagioclase fractionation. In addition, crystal fractionation is inconsistent with significant variation between the Ba/Ta and Nb/Ta ratios of DRA and Orestimba samples (Fig. 16), because these elements have similar partition coefficients in basaltic melts (Whitlock, 2002). These data therefore reflect a high extent of hybridization of DRV by magma mixing and crustal assimilation, and tapping of mantle having variable degrees of LILE enrichment.

HYDROTHERMAL MINERALIZATION

Field Evidence

The areas around Dowdy Ranch, Burra Burra Peak (Plate 1) and Orestimba Creek (Plate 2) contain significant evidence of post Mid-Tertiary hydrothermal fluid flow. Field work by the author in the vicinity of DRA plugs reveals layered chalcedonic sinter (sample 136), as well as light-colored jasperoid, which is locally fractured and has a brecciated appearance (samples 188, 189A). Hydrothermal samples and hydrothermal breccia localities are shown in Plate 1. Hydrolytic-style (samples 7, 211B, 214A) and porous gossan-type altered rocks (sample 191A) are found on or near the margins of DRA. In addition, calcification is found in sheared andesite to the north of Burra Burra Peak (sample 216B). Hydrothermal alteration in the Burra Burra Peak area is limited to narrow fissures and veins.

The Orestimba Creek area contains partial to pervasive replacement of serpentinite and Franciscan metamorphic rock by chalcedonic quartz and carbonate, occurring mostly in shear zones ranging in width from several meters to tens of meters. The altered rocks belong to Franciscan mélangé and

the middle unit of the meta-sandstone member of the Mesozoic Burnt Hills fan sequence; the latter contains well bedded turbidites, ranging from coarse sandstone to mudstone, and locally containing pumpellyite, lawsonite, glaucophane, and jadeite (Morrell, 1978; Wentworth et al., 1999). The altered outcrops are distinguished by a bleached appearance, high carbonate content, and a reddish or tan color due to the presence of Fe-oxides and hydroxides.

The main alteration zone at Orestimba Creek is ~1.5 km long by ~0.3 km wide and trends NE-SW (Wentworth et al., 1999). However, smaller unmapped zones also are present several kilometers to the north and south. The main zone is in close proximity to the basaltic andesite plugs in Orestimba Creek. In addition, chalcedonic veins cross-cut some of the basaltic andesite dikes. Carbonate spring sinter (travertine) is present in Orestimba Creek float.

Analytical Methods

Initial identification of phases and description of texture was performed with reflected and transmitted light microscopy. Additional phase identification and chemical analysis was performed using the microprobe at Stanford

University. Energy Dispersive Spectra (EDS) display a histogram of the number of counts for each X-ray energy level.

Hydrothermal minerals were distinguished from the parent rock assemblage based on textural criteria. The following assumptions were made: (1) key minerals are in equilibrium with the hydrothermal environment, that is, they represent chemical equilibration with the hydrothermal fluid, or direct precipitation from the fluid; (2) the assemblages are in-situ products of formation, and not transported material.

Paragenetic sequences were used to identify temporal stages of mineral deposition and to relate them to a genetic parameter, such as temperature, pressure, or pH. Mineral paragenesis can be inferred from textural relations, such as banding, exsolution, cross-cutting, inclusion, and twinning, among others (Park and MacDiarmid, 1975; Genkin et al., 1986; Misra, 2000). For each study area, a depositional sequence was constructed for every sample, and the resulting sequences were combined into one. This procedure was made possible by the high degree of internal consistency between the sequences of individual samples. After a preliminary sequence was constructed

using 2-3 samples, results for additional samples were reproducible; it was possible to include additional samples with very little change. Although it is possible that the samples analyzed represent more than one hydrothermal system, only one sequence was necessary to describe them in each study area.

Stable oxygen and carbon isotope analyses were performed with the Finnigan MAT 251 Mass Spectrometer at the UC Davis Stable Isotope Lab. Pure carbonate minerals of known composition were extracted from six rock samples by hand, powdered, and analyzed using the common bath method (D. Winter, 2005, personal commun.).

Results

Mineral Chemistry

Epidote. Epidote in all samples is nearly colorless in thin section under plane light. This is consistent with the low Fe content observed in EDS spectrum 34 in Appendix E. Epidote composition varies little, with less than 2 wt% FeO (analyses 5 and 6 in Appendix A). The general chemical formula is $\text{Ca}_{1.5-2}\text{Al}_3\text{Si}_3\text{O}_{13}\text{H}$. These observations point toward a variety of zoisite. In samples 211B, 214A, and 191A from

the Burra Burra Peak area (Plate 1) this phase apparently formed by replacing feldspar (Fig. 23).

Chlorite. Chlorite forms both fine intergrowths and vein filling in the studied samples; it has blue, yellow, grey, or light green pleochroism. The blue, low-Fe variety commonly forms vein filling. Figure 24 is a chemical classification of the chlorite analyses, based on the calculated number of atoms per formula unit in Appendix A, rounded off to the nearest whole number of atoms. The analyzed samples appear to be divided into low-Fe and high-Fe groups (Fig. 24). For example, EDS patterns 2 and 25 in Appendix E show Fe-rich chlorite, whereas patterns 10-12 show Fe-poor chlorite. The low-Fe chlorite in sample 136 has up to 13.1 wt% MnO (analysis 9 in Appendix A). Silicon content generally is low, equivalent to about four or five formula atoms for 18 oxygen atoms (analyses 7-13 in Appendix A).

The Fe:Mg ratio of hydrothermal chlorites increases with increasing temperature, but it also depends on the composition of parent material (Shikazono and Kawahata, 1987). In the field area, the vein-forming low-Fe chlorites commonly occur with low-temperature phases such

Figure 23. Photomicrograph of propylitized andesite (sample 211B). Partial replacement by epidote (1), chlorite (2), sphene (3), and tremolite (4) is evident. Cross-polarized light. Field of view is 7 mm x 5.25 mm.

Figure 24. Classification diagram for hydrothermal chlorites in Appendix A, based on the approximate number of Si atoms and Fe atoms per 18 oxygens in formula unit. Modified from Hey (1954). Samples 7 and 136 are from the Burra Burra Peak area (Plate 1). Sample 227 is from the Orestimba Creek area (Plate 2).

as barite and sphene, so their composition may reflect low-T fluid conditions. By contrast, the high-Fe chlorites showing green to yellow pleochroism commonly occur with epidote and micas.

Clays and Micas. Data on micaceous minerals from Orestimba include microprobe analyses 17, 18, 19, and 20 and EDS spectra 42, 43, 45, 51, and 57 (Appendix E). Analyses 18 and 19 contain mostly Al, Si, and K, whereas analyses 17 and 20 show mostly Al and Si, with minor K. The representative Al-Si analyses have Al:Si ratios of 1:1, suggesting that kaolinite is common. Analysis 18 containing Al, Si, and K is likely muscovite, based on its optical properties. Analysis 18 is inconsistent with phengite, based on its low Fe content of 0.693 wt%. Analysis 19 may be illite, based on its Si:K and Si:Al ratios of 5:1 and 5:3, respectively.

Chromite. Spinel-group minerals from Orestimba and Burra Burra are very similar compositionally, containing Mg, Fe, Al, and Cr, in order of increasing EDS peak intensity in spectra 15 and 47. Analyses 14, 15, and 16

contain 0.552 to 0.642 atoms of Mg per formula unit, indicating a chromite-magnesiochromite solid solution.

Carbonates. Carbonate samples from both study areas contain some nearly pure calcite. However, most calcite from Orestimba contains detectable Mg^{2+} and Fe^{2+} . A typical analysis of Mg-rich carbonate (analysis 21 for sample 228A) contains a Ca:Mg ratio of about 1, and a Ca:Fe ratio of about 5:1, which is consistent with dolomite. Although most Orestimba dolomites are close to this ratio, some have Ca:Mg ratios much higher than 1, and are here referred to as "low-Mg dolomite". EDS spectra 58 and 60 are indicative of such carbonates. Ankerite is also present (EDS spectrum 48).

Chromian dawsonite $[\text{Na}(\text{Al}_{1-x}\text{Cr}_x)\text{CO}_3(\text{OH})_2]$ is a rare, low-temperature hydrothermal carbonate. Only a few occurrences of chromian dawsonite are documented worldwide. One is the Sana area in Japan, and another is the Orestimba Creek area (Dunning, 2000). At Orestimba, Dunning reported that it is associated with Cr-bearing alumohydrocalcite $[\text{Ca}(\text{Al}_{2-x}\text{Cr}_x)(\text{CO}_3)_2(\text{OH})_4 \cdot 3(\text{H}_2\text{O})]$. The dawsonite from Orestimba Creek consists of fine fibrous crystals packed into radiating spherulites several

millimeters in diameter; it ranges in color from light to dark pink, is highly birefringent, and it effervesces in dilute HCl (Dunning, 2000). These properties match those of the mineral sampled by the author at Orestimba Creek, where it occurs as vein filling up to 3 mm thick in sample 228A (Figs. 25-27).

Chemical analyses of chromian dawsonite given by Dunning (2000) show that this mineral contains ~20% Na₂O, ~25-31% Al₂O₃, and ~12-18% Cr₂O₃ (Table 4). In contrast, the pink vein material in sample 228A analyzed by the author has a much higher content of Al₂O₃ (~57-69%), and MgO (~2-3%); conversely it has Na₂O and Cr₂O₃ concentrations of only ~5-7%, and ~4%, respectively (Table 4). The very high ratios of Al to Cr and Al to Na, are supported by the EDS spectrum (Fig. 27). These data are unexpected, because they also preclude the presence of Cr-bearing alumohydrocalcite, which has ~14-16% CaO, ~19-22% Al₂O₃, ~8-11% Cr₂O₃, and no more than ~3% Na₂O (Dunning, 2000). Therefore, it is likely that the material analyzed by the author is a mixture of Cr-dawsonite and a secondary alteration product.

In acidic conditions, dawsonite [NaAlCO₃(OH)₂] may decompose in the following fashion

Figure 25. Vein material in altered greywacke (sample 228A) in the Orestimba-Hartman Creek area, viewed under reflected light. The pinkish-tan material (1) closely resembles Cr-dawsonite, and the yellowish-orange material (2) is dolomite with Fe-hydroxides. Dark spots of Mg-chromite (3) are visible toward the lower right. Field of view is 2 mm x 2.2 mm.

Figure 26. Photomicrograph of vein material in sample 228A. Radiating clusters of Cr-dawsonite are pervasive, with a parallel tan veinlet (1) of Fe-hydroxide and dolomite. Stringers of opaque nickel sulfide (2) are aligned between the radiating clusters of Cr-dawsonite. The dark brown mineral (3) is Mg-chromite. Plane-polarized light. Field of view is 3.5 mm x 2.6 mm.

Figure 27. Energy-dispersive spectrum of Cr-dawsonite from the Orestimba-Hartman Creek area (Sample 228A).

TABLE 4. CHEMICAL ANALYSES OF CR-BEARING DAWSONITE FROM THE SANA AREA, JAPAN, AND ORESTIMBA CREEK.

Component	Sana area, Japan (Dunning, 2000)	Orestimba Creek (Dunning, 2000)		Orestimba Creek Sample 228A (this study)	
		Light pink	Dark pink	Analysis 1	Analysis 2
Na ₂ O	21.72	19.0	19.6	6.87	4.89
CaO	---	2.7	2.1	0.036	0.052
Al ₂ O ₃	26.65	31.2	25.1	68.98	56.72
Cr ₂ O ₃	16.13	12.4	18.2	3.95	4.4
MgO	---	---	---	1.98	3.31
CO ₂ +H ₂ O by difference	35.50	34.7	35.0	18.18	30.62
Total	100.0	100.0	100.0	100.0	100.0
Note: --- = none reported					

(Loughnan and See, 1967):

Work by Goldbery and Loughnan (1977) shows that both dawsonite and alumohydrocalcite $[\text{CaAl}_2(\text{CO}_3)_2(\text{OH})_4 \cdot 3\text{H}_2\text{O}]$ may readily alter to one of the Al-hydroxides, such as gibbsite or nordstrandite, by means of hydrolysis and dehydration. The observation that nordstrandite $[\text{Al}(\text{OH})_3]$ commonly forms pseudomorphs after dawsonite and alumohydrocalcite (Goldbery and Loughnan, 1977) serves to support this notion, and it helps to explain the apparent enrichment in Al_2O_3 and depletions in Na_2O and CaO in the analyzed vein material at Orestimba.

Alteration in the Burra Burra Peak Area

Microscopic grains of cuprite, sphalerite, chalcopyrite, and Fe-Ni sulfide were found in hydrothermal quartz near andesitic plugs at Dowdy Ranch. These phases are reflected in spectra 13, 18, 19, 22-24, 30, and 32 in Appendix E. In addition, significant Ag peaks were detected in two EDS spectra from sample 136, one of which is shown in spectrum 9.

The mineralogy and textures of selected hydrothermal samples in the Dowdy Ranch-Burra Burra Peak area are listed

in Table 5. Quartz and calcite are collectively the most abundant phases in all samples. The typical alteration assemblage also contains chlorite or biotite, barite, sphene, apatite, and oxides of titanium or manganese. Samples 7, 191A, 211B, and 214A also contain sericite, epidote, albite, and K-feldspar (Table 5). Samples 211B and 214A contain tremolitic amphibole, and zoisite-clinozoisite replacing plagioclase phenocrysts (Fig. 23). Of the sulfides present, pyrite has the highest modal abundance (1-5%) followed by Fe-Ni sulfides (0.5-1%), and chalcopyrite and sphalerite (<0.5%). Quartz veins in samples 136, 188, and 189A contain fluid inclusions with microscopic sylvite (KCl).

Hydrothermal rocks in the Burra Burra Peak area contain textural evidence of replacement of parent rock, especially in altered andesite (samples 191A and 211B in Table 5). This includes phenocryst pseudomorphs, relict foliations, the presence of vermicular intergrowths along cracks, 'islands' of unreplaced rock, and residual resistant minerals such as rutile, zircon, and ilmenite. The association of physiochemically incompatible phases, such as sulfides and carbonates, is also indicative of hydrothermal replacement (Park and MacDiarmid, 1975). The

TABLE 5. MINERALOGY AND TEXTURE OF SELECTED HYDROTHERMAL ASSEMBLAGES IN THE DOWDY RANCH AREA.

Sample	Texture	Minerals detected
7	Preservation of original foliation; deposition of quartz, chlorite, and epidote in relation to cleavage planes and rock fractures. Residual resistant minerals (zircon, rutile) are present. Apparent offset along intersection of fractures.	Quartz> chlorite> epidote> pyrite>> sericite, K-feldspar> biotite> sphene, ilmenite, rutile/anatase, zircon, apatite.
136	Botryoidal texture with cockade structure in chalcedony. Diffusion-related color banding present. Veins contain minor symmetrical banding (quartz-calcite). Offset oblique structures, and residual rutile are present in quartz.	Quartz>> chlorite, barite> calcite> apatite> pyrite> rutile/anatase> cuprite, gypsum.
186B	Vermicular intergrowth of calcite and quartz, with islands of unreplaced calcite in quartz. Some offset present along late-stage intersecting fractures, with non-matching borders of fractures. Chlorite and quartz are deposited in obvious relation to fractures.	Calcite> quartz> biotite> pyrite> chlorite> chromite, bravoite/pentlandite> barite.

TABLE 5 (continued)

Sample	Texture	Minerals detected
188	Hydrothermal breccia with fine intergrowth of mostly quartz, chlorite, and residual resistant minerals (sphene, zircon, rutile). Apparent veining with symmetrical banding, crustification (chlorite on quartz), and inward-coarsening of crystals in veins. Early phase rock present inside later phase veins, and gradational boundaries between vein and host are observed. Obvious offset along intersection of fractures in some instances.	Quartz> chlorite> sphene>> barite> apatite, zircon, rutile> cuprite, chalcopyrite.
189A	Fine-grained breccia with some vermicular intergrowths. Oriented unsupported fragments of host present inside quartz vein. Selective replacement of biotite by calcite and sphene; "islands" of biotite inside matrix of calcite and sphene; gradational biotite-calcite replacement boundary. Residual resistant minerals (sphene, rutile) present. Commonly, there is brecciation and offset along oblique fractures. Symmetrical vein banding, with inward-coarsening of quartz in veins is apparent. Vugs and cavities are abundant, with doubly-terminated chlorite crystals inside quartz-filled vugs.	Quartz> biotite> chlorite> limonite> calcite> pyrite> sphene>> apatite> rutile/anatase, Mn- oxide/hydroxide> chalcopyrite.

TABLE 5 (continued)

Sample	Texture	Minerals detected
191A	Fine-grained intergrowth of acicular grains, with many vugs and cavities. No offset along intersection of fractures.	Quartz, chlorite, hematite> clinozoisite> biotite>> apatite, cuprite, sphalerite.
211B and 214A	Preservation of porphyritic, glomerophyric texture (Fig. 23). Plagioclase and pyroxene pseudomorphs are present, with "islands" of unreplaced plagioclase. Offset oblique veins (filled with minor zeolites or limonite) are present.	Chlorite, tremolite> epidote (mainly clinozoisite after albite), albite> quartz> sphene>> apatite.

extent of replacement ranges from ~10% to >90% of rock volume. In addition, most samples contain quartz and chlorite in open vugs and cavities, due to open-space filling processes. The inward-coarsening of crystals in veins, symmetrical vein banding, crustification of early minerals with later minerals, and cockade structuring of chalcedony (Fig. 28) are also indicative of fracturing in a brittle deformation zone with relatively free fluid circulation (Park and MacDiarmid, 1975).

Alteration in the Orestimba Creek Area

The five samples analyzed belong to the main alteration zone along Orestimba Creek (mapped by Wentworth et al., 1999) spatially associated with the Orestimba volcanics. Samples 227, 228A, and 229 are altered greywacke, sample 233A is a chalcedonic vein hosted by basaltic andesite, whereas sample 236B is pervasively altered and its original texture is indiscernible. The hydrothermal samples from Orestimba have a very high percentage of quartz and carbonates (>95%), with other minerals forming less than ~5% of the rock mode. In addition, the samples contain very little pyrite and biotite. Sphene, clinozoisite, and K-feldspar are absent

Figure 28. Photomicrograph of chalcedonic quartz with cockade structure in sample 136, evidence of dissolution and precipitation along multiple fractures within highly brittle host rock (dark angular fragments). Cross-polarized light. Field of view is 7 mm x 5.25 mm.

(Table 6). In contrast to the accessory minerals with Cu, Zn, Ti, Ni, and Cr in the Burra Burra samples, the Orestimba samples contain minerals rich in Ti, Ni, Mg, and Cr, with minor Hg, Co, and Sr. These elements are shown in spectra 46, 47, 50, 54, and 55 in Appendix E.

The hydrothermal texture of Orestimba samples is characterized by extensive mineralogical replacement of parent rock. Preservation of parent rock texture, vermicular intergrowths of quartz and carbonates, and the presence of residual rutile and ilmenite are consistent with replacement at near-constant volume (Park and MacDiarmid, 1975). Open-space filling is not as evident in the Orestimba samples as in the Burra Burra area samples. This may be attributed to the highly pervasive nature of replacement at Orestimba. Most Orestimba samples contain inward coarsening of vein minerals, symmetrical vein banding, crustification, or comb structures (Table 6). These features are indicative of very shallow-level deposition along brittle fractures, which is also supported by the presence of porous travertine in the general vicinity.

TABLE 6. MINERALOGY AND TEXTURE OF SELECTED HYDROTHERMAL ASSEMBLAGES IN THE ORESTIMBA CREEK AREA.

Sample	Texture	Minerals detected
227	Preservation of clastic sedimentary texture, with offset oblique veining. Inward-coarsening of crystals and symmetrical banding are typical in veins. Apparent deposition of magnetite along clastic grain boundaries, and subsequent replacement of magnetite and pyrite by hematite. Replacement of clastic plagioclase grains by clays is apparent.	Quartz> hematite> calcite> sericite, kaolinite> low-Mg dolomite> rutile> magnetite> chlorite, apatite, pyrite, zircon, epidote.
228A	Apparent preservation of original greywacke foliation, with deposition of vein minerals along cleavage planes and rock fractures. Vermicular intergrowths of carbonates and quartz are present. Discontinuous intersections of fractures are common. Veins contain some offset, inward-coarsening of crystals, and symmetric banding. Replacement of magnetite by limonite is evident.	Quartz> low-Mg dolomite> ankerite> chromian dawsonite> calcite> Mg-chromite> millerite-vaesite> rutile, magnetite, pyrite-bravoite, barite.

TABLE 6 (continued)

Sample	Texture	Minerals detected
229	Brecciated texture with vermicular intergrowth of carbonates and quartz. The original clastic texture with islands of unreplaced host sandstone is evident. Crustification of dolomite-ankerite on limonite, and residual resistant minerals (zircon and rutile) are present.	Calcite> dolomite-ankerite, quartz> pyrophyllite>> strontianite, barite, zircon, rutile, apatite.
233A	Quartz-carbonate vein ~13 mm thick, containing symmetrical banding and inward crystal coarsening. The vein contains rafts of parent basaltic andesite, crustification of siderite and ankerite on limonite, as well as comb structure with dolomite growing into quartz. Residual rutile and zircon are also present.	Quartz> low-Mg dolomite> ankerite, siderite> limonite> rutile>> gypsum/anhydrite, zircon, cobaltoan calcite, mercury.
236B	Contains vermicular intergrowth of carbonates and multiple veining with discontinuous intersection of fractures. Symmetrical banding occurs where carbonate and quartz were deposited along widening fractures. Residual rutile and ilmenite are present.	Low-Mg dolomite> quartz> calcite> pyrite, Fe- oxides/hydroxides> apatite, barite, rutile, ilmenite.

Mineral Parageneses

Burra-Burra Peak Samples. The pattern of deposition in the Burra Burra Peak area can be divided into the early, intermediate, late, and supergene stages (Fig. 29). Quartz, chlorite, biotite, amphibole, and epidote were deposited in the early stages, accompanied by pyrite and chalcopyrite. Quartz, chlorite, sphene, pyrite, sericite, apatite and minor K-feldspar were precipitated in the intermediate stages. Late-stage mineralization is characterized by quartz, calcite, barite, apatite, and gypsum or anhydrite. Supergene enrichment is indicated by the presence of hematite and minor grains of cuprite, both occurring mainly in gossan-like porous samples such as 191A.

Orestimba Creek Samples. The high-temperature assemblage at Orestimba is dominated by quartz, sericite, and kaolinite. It also has minor chlorite, epidote, barite, apatite, rutile, pyrite, and magnetite (Fig. 30). The middle stage occurs at temperatures below 150-175°C, and is typified by quartz, dolomite, low-Mg dolomite, and ankerite, with minor elemental Hg, gypsum or anhydrite, calcite, and other carbonates. The low-temperature stage is characterized by Cr-bearing dawsonite,

Figure 29. Generalized time-temperature paragenetic sequence of hydrothermal mineralization in the Burra Burra Peak area. Temperature conditions shown are approximate, and are based on typical stability ranges of such minerals in hydrothermal environments (Holdaway, 1966; Lindh, 1972; Hemley et al., 1980; Chen and Yang, 1984; Bayliss, 1989; Barnes, 1997; Thompson et al., 1998; Misra, 2000; Frost et al., 2001; Bird and Spieler, 2004; Liebscher and Franz, 2004).

Figure 30. Generalized time-temperature paragenetic grid of hydrothermal mineralization in the Orestimba Creek area. Temperature conditions shown are approximate, and are based on typical stability ranges of such minerals in hydrothermal environments, as for Figure 29.

Mg-chromite and Fe-Ni sulfide (millerite-vaesite), as well as supergene oxidation of Fe sulfides.

Stable Isotope Ratios in Carbonates

Stable Carbon Isotopes. Measured $\delta^{13}\text{C}$ values for carbonates are given in Figure 31 and Table 7. Most samples fall in the narrow range between -4.18‰ and -6.43‰, which is consistent with a volcanic source (Barnes, 1997; Hoefs, 2004). However, because $\delta^{13}\text{C}$ values of hydrothermal carbonates from crustal and mantle reservoirs overlap in the -5‰ to -15‰ range, the data are not diagnostic. Still, the values are comparable to those for silica-carbonate samples in the Knoxville mining district (Fig. 32), where $\delta^{13}\text{C}$ ranges from -6.8‰ to -11.5‰ (Sherlock and Logan, 1995).

Stable Oxygen Isotopes. As shown in Table 7 and Figure 31, $\delta^{18}\text{O}$ values for sample 233A from Dowdy Ranch and sample NA-1 from New Almaden are similar (22.84‰ and 22.6‰, respectively). These values fall within the range of 12.2-28.15‰ for carbonates in the Knoxville Hg district (Fig. 32; Sherlock and Logan, 1995), which is indicative of a metamorphic fluid source (Barnes, 1997). Samples 186B,

Figure 31. Stable isotopic values for hydrothermal carbonate samples. Note that primary igneous and meteoric fluids have $\delta^{18}\text{O}$ values below +10‰ (Barnes, 1997; Hoefs, 2004).

TABLE 7. ISOTOPIC VALUES OF SELECTED SAMPLES

Sample	Location	Mineral	$\delta^{13}\text{C}$ (V-PDB)	$\delta^{18}\text{O}$ (V-SMOW)
186B	Dowdy Ranch (Plate 1)	Calcite	-5.69	13.69
189A	Dowdy Ranch (Plate 1)	Calcite	-10.12	14.01
216B	Dowdy Ranch (Plate 1)	Calcite	-6.43	28.85
233A	Hg-bearing vein in basaltic andesite (Plate 2)	Dolomite	-4.18	22.84
90C	Franciscan metamorphic seam from Dowdy Ranch (Plate 1)	Calcite	-6.06	15.35
NA-1	Hg-bearing silica-carbonate from New Almaden mine (Fig. 32)	Dolomite	-4.48	22.60

Figure 32. Distribution of mercury deposits in the Coast Ranges of California, in relation to major lithologic units, Neogene volcanics, and faults (modified from Grey, 2003, and Pickthorn, 1993).

189A, and 90C have somewhat lower values of 13.69%, 14.01%, and 15.35%, which can result from mixing of meteoric and metamorphic fluids, or by interaction of meteoric water with metamorphic rock (Barnes, 1997). Calcite in sample 216B is isotopically heavier, likely due to deposition at shallow depth and low temperature (Hoefs, 2004), but the high value of 28.85% suggests interaction with a metamorphic reservoir. None of the samples have $\delta^{18}\text{O}$ values similar to those of the Quien Sabe volcanics (Drinkwater, 1983).

Interpretations

Epithermal systems in the Northern California Coast Ranges

Epithermal systems are characterized by temperatures less than 350°C and pressures less than 1 kbar (Pirajno, 1992; Barnes, 1997). In the California Coast Ranges, post-mid Tertiary epithermal mineral deposits are of three main types: silica-carbonate type, hot-spring type, and open-vein type (Table 8). Hg-bearing silica-carbonate is associated with NW-trending structural boundaries, whereas hot spring-type Au-Hg deposits are associated with Neogene volcanism (Fig. 32). There is a general agreement that epithermal Au and Ag deposits in Coastal California are

TABLE 8. SOME CHARACTERISTICS OF MAJOR EPITHERMAL DEPOSITS
IN THE CALIFORNIA COAST RANGES

Deposit type	Common 'gangue' mineral assemblage	Examples
1. Silica- carbonate (Hg, Sb)	Quartz, magnesite, dolomite, calcite- aragonite, chromite, pyrite, hydrocarbons.	Knoxville Hg district; Mayacmas Hg district; New Idria Hg district.
2. Hot-spring type (Au, Ag, As, Hg, Sb)	Silica-opal, adularia, hydrocarbons; clays (part of argillic alteration assemblage).	McLaughlin Au deposit; Sulfur Creek- Cherry Hill District.
3. Open-vein type (Ag, Au, base metal sulfides and sulfosalts)	Quartz, barite, carbonates, magnetite- hematite; adularia, albite, chlorite, epidote (part of propylitic alteration assemblage).	Calistoga mining district; Stayton mining district.
<p>Note: Based on Barnes et al. (1973), Vredenburg (1982), Enderlin (1993), Pickthorn (1993), Sherlock et al. (1993), Sherlock and Logan (1995), Lefebure et al. (1996), Barnes (1997), Thompson et al. (1998), Grey (2003).</p>		

related to hot-spring activity, rather than silica-carbonate alteration (Pickthorn, 1993; Sherlock and Logan, 1995; Barnes, 1997).

Silica-carbonate rock forms by alteration of serpentinite with moderately alkaline ($\text{pH} > 5$), CO_2 -rich fluids at temperatures less than 250°C (Sherlock et al., 1993). Common alteration minerals are listed in Table 8. A simplified two-stage depositional model involves the addition of silica and removal of Fe, Mn, and Mg from the serpentinite. The replacement of lizardite $[\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4]$ by magnesite $[\text{MgCO}_3]$ occurs in the first stage of alteration. The second phase involves the replacement of pre-existing serpentine by opaline silica with only minor magnesite (Barnes, 1997). The deposition of cinnabar generally coincides with that of marcasite and pyrite (Vredenburg, 1982).

Hot-spring deposits typically form from low-temperature ($< 200^\circ\text{C}$), acidic ($\text{pH} \sim 1-3$) fluid (Heinrich et al., 1989; Barnes, 1997). The typical 'gangue' minerals are therefore opaline and crystalline silica, in addition to clays, which form by acid leaching (Table 8). In general, the deposition of quartz and carbonates post-dates hydrolytic alteration, and Au deposition is commonly

accompanied by silica, cinnabar, and other sulfides (Vredenburg, 1982; Rytuba, 1993).

Open-vein type deposits occur at depths exceeding 200 m, at a temperature range of 220-350°C and moderate to low acidity (pH of 4-6) (Pirajno, 1993). Wall rock alteration is typified by an outer zone of propylitization, and the near-vein zone is pervasively silicified (Table 8). Similar Ag-bearing base-metal deposits have formed along traces of the San Andreas fault at depths exceeding 400 m and temperatures of ~250°C. Early stages of deposition are characterized by quartz, pyrite, K-feldspar, calcite, and chlorite. The intermediate stage contains pyrite, sphalerite, galena, chalcopryrite, and chlorite. The late stage contains quartz, pyrite, sphalerite, fluorite, and kaolinite (McLaughlin et al., 1985).

Evidence of Epithermal Deposition

Mineralization at Orestimba is consistent with that of a typical silica-carbonate epithermal deposit, but "silica-carbonate" alteration refers specifically to a serpentinite host. Because the host rock at Orestimba evidently was not serpentinite, Sorg (personal commun.) suggested that the term "quartz-carbonate" alteration would be more

appropriate. The system at Orestimba is dominated by quartz and carbonate phases (Table 6) and is enriched in Mg, Fe, Ni, and Cr. This type of alteration is also consistent with the estimated temperature (~50 to 150°C). Mineral paragenesis at Orestimba is in agreement with the model of early deposition of Fe-bearing and Mg-bearing carbonates, followed by silica flooding with decreased carbonate precipitation. Isotopic evidence supports a metamorphic fluid source similar to that of the New Almaden silica-carbonate Hg deposit.

Hydrothermally altered samples from the Dowdy Ranch-Burra Burra Peak area contain low-temperature phases, as well as textural evidence of replacement and of deposition in open fractures and cavities. Mineral paragenesis in the early stages is characterized by intergrowths of epidote, biotite or tremolite, chlorite, sphene, and K-feldspar, reflecting hydrolytic alteration by moderate-temperature, alkaline (high K^+/H^+) fluids (propylitic alteration) (Pirajno, 1992). Alkali metasomatism is also evident from the numerous KCl-bearing inclusions inside quartz veins. Barite, apatite, calcite, and gypsum indicate decreasing temperatures during the middle stage of mineralization. Overall, the conditions of Cu-Zn-Ag deposition inferred

from samples in Table 5 most closely resemble those of an open vein-type epithermal environment. This does not imply, however, that all Cu deposition in the area is epithermal.

At Dowdy Ranch, veins containing Cu and Ni (samples 186B and 189A) have $\delta^{18}\text{O}$ values close to that of the analyzed Franciscan quartz-carbonate metamorphic seam (Table 7). However, the combined textural evidence and the presence of low-temperature phases (chalcedony, gypsum, barite, etc) shows that the metal deposition is unlikely to be the product of Mesozoic subduction-related regional metamorphism. Rather, these features indicate that a younger low-temperature event overprinted earlier subduction-related deposition (D. Sorg, 2005, personal commun.). The mechanism of the more recent fluid transport is not well constrained: it may be driven by either Neogene faulting or emplacement of the DRV. In either scenario, the re-mobilization of the Franciscan metamorphic components is apparent. This view is supported by the fact that all hydrothermal carbonates reflect an isotopically heavy metamorphic fluid source.

Hydrothermal systems at Burra Burra and Orestimba are both partly epithermal and therefore have several features

in common. In both areas, much of the hydrothermal alteration is controlled by fractures, and some of it clearly post-dates DRV volcanism, because some of the volcanic rocks are altered. Still, less than 5% of the exposed volcanics are altered, suggesting that most alteration is pre-volcanic or early syn-volcanic. The two study areas have many depositional phases and textures in common (Tables 5 and 6). Both study areas contain isotopically "heavy" assemblages with coexisting Fe-Ni sulfide and Mg-chromite (Samples 186B and 228A). This may be related to significant tapping of a serpentinite source, which would commonly be enriched in these elements (D. Sorg, 2005, personal commun.). If this is the case, it reflects another similarity between the hydrothermal mineralization at Orestimba and that at Burra Burra.

SUMMARY

The primary goals of this thesis were to study the DRA and Orestimba volcanics in order to (1) identify their contact relations, (2) investigate a possible genetic link between the studied volcanics and other DRV, and (3) describe hydrothermal mineralization in the Dowdy Ranch and Orestimba Creek areas. The following conclusions were drawn:

1. The DRA dike complex has an intrusive hypabyssal relationship with the host Franciscan Complex; the andesite was injected and quenched along steeply-dipping conduits trending NW and NE.
2. The DRV sampled by the author and others have a calc-alkaline affinity and an arc-type chemical signature, as do other NCRV. The likely magma source for the DRV is LILE-enriched mantle such as mantle wedge lithosphere, or the sub-continental lithosphere. The DRV reflect evolution by a combination of magma mixing, minor fractionation, and crustal assimilation.

3. The study areas of Orestimba Creek and Dowdy Ranch contain evidence of post Mid-Tertiary epithermal replacement of metasedimentary and volcanic rocks by hydrolytic and quartz-carbonate mineral assemblages. The hydrothermal activity has resulted in re-mobilization of a metamorphic fluid source, causing deposition of base metals and the rare chromian dawsonite.

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APPENDIX: METHODS AND DATA

Appendix A: Mineral Analysis

Methods

The JEOL JXA-733 Superprobe at Stanford University is a fully-automated 5-spectrometer unit, equipped with a Be-window SiLi energy-dispersive detector. The instrument has a detection limit of 30-300 ppm for elements heavier than Na, and a spatial resolution of 1-3 μm for quantitative analysis. Standard operating conditions are 15 keV beam accelerating voltage and 15-17 nA sample current.

Samples were cut into standard 30 μm thin sections, which were polished smooth and coated with a 30 nm carbon coat prior to loading into the microprobe vacuum chamber. The sample image was then displayed on the screen at up to 40,000 magnification, and areas of interest were analyzed. An EDS spectrum was obtained by a digital camera and then formatted separately using computer software. Quantitative analysis was performed by comparing x-ray intensities of the sample with those of natural and synthetic standards from the Stanford collection. Corrections were made automatically, using the Citzaf software from California

Institute of Technology. The results are displayed as weight percent oxide and formula unit atoms.

Quantitative Analyses

Sample	215/3				215/3				215/3			
Mineral Lithology Analysis	Clinopyroxene Metamorphic autolith 1				Orthopyroxene Metamorphic autolith 2				Ca-feldspar Metamorphic autolith 3			
	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (2)	Percent oxide	Formula cations (2)	Percent oxide	Formula cations (2)
SiO ₂	50.167	1.957	52.350	1.983	54.972	2.512	65.966	2.996				
TiO ₂	0.448	0.013	0.267	0.008	0.062	0.002	0.000	0.000				
Al ₂ O ₃	1.140	0.052	0.878	0.039	27.595	1.486	18.758	1.004				
FeO	15.542	0.507	21.527	0.682	0.318	0.012	0.093	0.004				
MnO	0.171	0.006	0.588	0.019	0.057	0.002	0.000	0.000				
Cr ₂ O ₃	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000				
MgO	8.133	0.473	21.970	1.241	0.011	0.001	0.000	0.000				
CaO	23.714	0.991	0.430	0.017	9.762	0.478	0.377	0.018				
Na ₂ O	0.086	0.007	0.011	0.001	5.358	0.475	4.912	0.433				
K ₂ O	0.000	0.000	0.001	0.000	0.422	0.025	9.146	0.530				
Total	99.403	10.007 [†]	98.026	9.990 [†]	98.558	12.993 [†]	99.252	12.984 [†]				

Note: (1) based on 6 oxygens; (2) based on 8 oxygens

† = total is sum of cations and oxygen atoms

Sample	7		211B		136		136	
Mineral Lithology	Epidote Altered greywacke 5		Epidote Altered andesite 6		Chlorite Jasperoid 7		Chlorite Jasperoid 8	
Analysis	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (2)	Percent oxide	Formula cations (2)
SiO ₂	37.571	3.295	36.648	3.283	28.045	3.909	28.071	3.901
TiO ₂	0.315	0.021	0.000	0.000	0.000	0.000	0.000	0.000
Al ₂ O ₃	31.362	3.206	29.911	3.158	17.070	2.804	17.240	2.824
FeO	0.238	0.017	1.574	0.118	18.937	2.207	18.996	2.208
MnO	0.000	0.000	0.094	0.007	0.209	0.025	0.290	0.034
Cr ₂ O ₃	0.137	0.009	0.000	0.000	0.000	0.000	0.000	0.000
MgO	0.000	0.000	0.023	0.003	17.917	3.723	17.850	3.698
CaO	17.222	1.600	16.338	1.568	0.111	0.017	0.115	0.017
Na ₂ O	0.014	0.002	0.013	0.002	0.042	0.011	0.034	0.009
K ₂ O	0.003	0.000	0.008	0.001	0.001	0.000	0.009	0.002
Total	86.861	21.150 [†]	84.609	21.140 [†]	82.331	30.695 [†]	82.605	30.693 [†]

Note: (1) based on 13 oxygens; (2) based on 18 oxygens

† = total is sum of cations and oxygen atoms

Sample	136				136				136				7			
Mineral Lithology	Chlorite Jasperoid				Chlorite Jasperoid				Chlorite Jasperoid				Chlorite Altered greywacke			
Analysis	9				10				11				12			
	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (1)
SiO ₂	24.056	3.789	29.833	4.037	29.833	4.037	38.122	5.099	38.122	5.099	21.991	3.725	21.991	3.725	0.000	0.000
TiO ₂	0.189	0.022	0.000	0.000	0.000	0.000	0.014	0.001	0.014	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Al ₂ O ₃	14.384	2.67	17.640	2.809	17.640	2.809	12.258	1.932	12.258	1.932	9.813	1.959	9.813	1.959	0.000	0.000
FeO	12.879	1.697	17.858	2.018	17.858	2.018	13.797	1.543	13.797	1.543	41.379	5.861	41.379	5.861	0.008	0.008
MnO	13.161	1.756	0.247	0.028	0.247	0.028	5.375	0.609	5.375	0.609	0.053	0.008	0.053	0.008	0.000	0.000
Cr ₂ O ₃	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MgO	12.032	2.825	17.649	3.555	17.649	3.555	13.486	2.689	13.486	2.689	5.907	1.491	5.907	1.491	0.147	0.147
CaO	0.387	0.065	0.647	0.094	0.647	0.094	0.350	0.050	0.350	0.050	0.809	0.147	0.809	0.147	0.041	0.041
Na ₂ O	0.117	0.036	0.099	0.026	0.099	0.026	0.050	0.013	0.050	0.013	0.125	0.041	0.125	0.041	0.170	0.170
K ₂ O	0.102	0.02	0.198	0.034	0.198	0.034	0.031	0.005	0.031	0.005	0.785	0.170	0.785	0.170	31.402 [†]	31.402 [†]
Total	77.307	30.88 [†]	84.171	30.601 [†]	84.171	30.601 [†]	83.483	29.941 [†]	83.483	29.941 [†]	80.863	31.402 [†]	80.863	31.402 [†]		

Note: (1) based on 18 oxygens

† = total is sum of cations and oxygen atoms

Sample	227		186B		186B		228A	
Mineral Lithology Analysis	Chlorite Altered greywacke 13		Chromite Quartz- carbonate vein 14		Chromite Quartz- carbonate vein 15		Chromite Altered greywacke 16	
	Percent oxide	Formula cations (1)	Percent oxide	Formula cations (2)	Percent oxide	Formula cations (2)	Percent oxide	Formula cations (2)
SiO ₂	35.127	4.366	0.028	0.001	0.054	0.002	0.077	0.002
TiO ₂	0.208	0.019	0.000	0.000	0.000	0.000	0.028	0.001
Al ₂ O ₃	29.963	4.389	25.217	0.923	28.711	1.074	32.256	1.144
FeO	11.082	1.152	17.093	0.444	17.660	0.469	14.702	0.370
MnO	0.014	0.001	0.344	0.009	0.277	0.007	0.258	0.007
Cr ₂ O ₃	0.000	0.000	42.421	1.042	36.016	0.904	35.256	0.839
MgO	5.743	1.064	12.878	0.596	11.657	0.552	14.302	0.642
CaO	1.349	0.180	0.000	0.000	0.000	0.000	0.001	0.000
Na ₂ O	2.065	0.498	0.035	0.002	0.034	0.002	0.042	0.002
K ₂ O	0.015	0.002	0.000	0.000	0.000	0.000	0.000	0.000
Total	85.568	29.671 [†]	98.016	7.018 [†]	94.408	7.010 [†]	96.922	7.007 [†]

Note: (1) based on 18 oxygens; (2) based on 4 oxygens

† = total is sum of cations and oxygen atoms

Sample	229	227	227	227	228A
Mineral Lithology Analysis	Kaolinite Altered greywacke 17	Mica Altered greywacke 18	Illite? Altered greywacke 19	Kaolinite Altered greywacke 20	
	Percent oxide	Percent oxide	Percent oxide	Percent oxide	Formula cations (1)
	Formula cations (1)	Formula cations (2)	Formula cations (2)	Formula cations (2)	Formula cations (1)
SiO ₂	44.784	2.550	3.307	51.715	3.825
TiO ₂	0.891	0.038	0.028	0.194	0.011
Al ₂ O ₃	37.677	2.528	3.174	26.543	2.316
FeO	0.164	0.008	0.041	1.792	0.111
MnO	0.009	0.000	0.000	0.000	0.000
Cr ₂ O ₃	0.000	0.000	0.000	0.009	0.000
MgO	0.123	0.010	0.067	3.174	0.35
CaO	0.051	0.003	0.003	0.080	0.006
Na ₂ O	0.002	0.000	0.100	0.080	0.008
K ₂ O	0.278	0.020	0.816	7.826	0.011
Total	83.977	14.157 [†]	95.649	91.413	0.743
			19.536 [†]	19.373 [†]	84.370
					14.216 [†]

Note: (1) based on 9 oxygens; (2) based on 12 oxygens

† = total is sum of cations and oxygen atoms

Sample	228A	
Mineral Lithology	Dolomite Altered greywacke	
Analysis	21	
	Percent oxide	Formula cations (1)
SiO ₂	0.000	0.000
TiO ₂	0.000	0.000
Al ₂ O ₃	0.396	0.042
FeO	7.604	0.577
MnO	0.143	0.011
Cr ₂ O ₃	0.000	0.000
MgO	18.360	2.483
CaO	29.320	2.849
Na ₂ O	0.189	0.033
K ₂ O	0.000	0.000
Total	56.012	11.995 [†]

Note: (1) based on 6 oxygens

† = total is sum of cations and oxygen atoms

Appendix B: Geochemical Analyses

Major Element Data for DRV Sampled by Author

Sample	PK221B	PK226	PK230A	PK237B	Ndra1/2	Ndra2
	Ore-stimba Creek	Ore-stimba Creek	Ore-stimba Creek	Ore-stimba Creek	DRA	DRA
Sample Location	37°11' 59"N, 121°22' 49"W	37°12' 06"N, 121°22' 51"W	37°12' 54"N, 121°23' 12"W	37°12' 21"N, 121°22' 20"W	37°06' 33"N, 121°21' 24"W	37°06' 48"N, 121°21' 34"W
SiO ₂	53.70	54.50	58.01	54.39	63.44	62.38
TiO ₂	0.793	0.830	0.889	0.819	0.805	0.881
Al ₂ O ₃	15.01	15.73	17.02	15.51	17.37	17.83
Fe ₂ O ₃	7.40	7.16	6.11	7.27	5.24	4.20
MnO	0.150	0.144	0.085	0.128	0.051	0.058
MgO	10.12	7.55	4.57	8.30	1.56	2.59
CaO	8.56	9.35	8.09	9.18	5.51	6.09
Na ₂ O	2.49	2.84	3.41	2.64	3.91	3.93
K ₂ O	1.45	1.55	1.53	1.43	1.92	1.83
P ₂ O ₅	0.331	0.349	0.276	0.343	0.202	0.215
Total	100.00	100.00	100.00	100.00	100.00	100.00

Trace Element Data for DRV Sampled by Author

	PK221B	PK226	PK230A	PK237B	Ndra 1/2	Ndra 2
Zn	64	61	56	57	55	54
Cu	42	47	35	46	16	20
Ga	14	15	15	14	16	19
V	182	189	138	181	97	112
Cr	471	418	236	441	119	125
Ni	202	162	91	183	16	16
La	28.09	29.42	25.86	28.01	31.92	20.91
Ce	49.65	51.88	39.34	49.44	38.14	36.60
Pr	5.51	5.85	4.86	5.55	6.95	4.52
Nd	21.97	23.25	19.59	22.20	28.31	18.52
Sm	4.84	5.08	4.51	4.84	6.77	4.45
Eu	1.38	1.43	1.35	1.38	1.76	1.33
Gd	4.23	4.24	4.51	4.09	7.00	4.21
Tb	0.63	0.64	0.71	0.62	1.14	0.71
Dy	3.73	3.80	4.25	3.61	6.97	4.25
Ho	0.74	0.76	0.90	0.72	1.43	0.86
Er	1.95	1.95	2.42	1.87	3.81	2.22
Tm	0.27	0.29	0.33	0.27	0.55	0.33
Yb	1.76	1.78	2.03	1.70	3.48	2.02
Lu	0.27	0.28	0.33	0.27	0.56	0.32
Ba	1070	1502	1255	1329	621	591
Th	10.73	11.14	7.20	10.61	6.64	6.66
Nb	7.55	7.75	8.28	7.54	9.98	10.66
Y	19.33	19.74	32.11	19.59	40.40	22.31
Hf	3.00	3.16	3.11	2.95	3.38	3.49
Ta	0.47	0.48	0.61	0.47	0.82	0.83
U	3.57	3.71	2.67	3.52	2.60	2.65
Pb	10.54	9.05	8.55	7.69	13.32	13.33
Rb	39.2	35.1	28.3	24.7	55.8	55.4
Cs	3.27	4.87	6.66	4.47	6.92	3.27
Sr	668	741	594	771	456	461
Sc	29.6	30.6	22.9	30.4	19.2	22.4
Zr	111	114	123	113	128	136

Major Element Data for Selected DRV

Samplelet	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
MP-2	45	1.13	16.3	7.72	0.13	4.45	10.7	3.53	1.36	0.42
MC-47	47.1	0.7	13.4	7.6	0.14	8.77	7.22	2.22	1.27	0.29
BH-4B	48.8	1.45	15.8	9.43	0.16	8.62	11.1	2.98	0.85	0.4
PV-26	49.7	1.36	12.1	10.1	0.17	12.7	8.89	0	1.25	0
TS-1	52.9	0.91	14.1	7.86	0.13	8.43	9.51	2.83	1.53	0.29
PP-7	52.7	0.9	13.8	8.91	0.13	9.2	8.65	2.16	1.43	0.26
PP-35	54.3	1.16	17.1	7.04	0.11	5.7	7.95	3.26	1.36	0.26
PV	54.7	0.81	14.2	9.48	0.16	7.23	8.82	2.5	1.58	0.27
TS-12	59.3	0.85	15.1	5.52	0.07	4.12	6.22	3.29	2.01	0.32
QS-19	59.4	0.81	15.1	5.78	0.07	6.08	5.39	3.18	2.34	0.25
TS-15	59.7	0.7	16.1	5.22	0.08	3.73	5.14	3.35	2.06	0.2
TS-16	60	0.88	16.8	4.75	0.07	3.06	6.54	3.75	1.81	0.2
JE-21	60	0.98	17.5	4.11	0.02	1.41	4.73	3.73	2.85	0.19
PP-5	60.1	0.81	17	5.17	0.03	1.65	5.34	3.86	1.83	0.21
MC-7	60.3	0.41	14.5	3.7	0.06	3.31	4.26	3.62	2.31	0.14
PP-8	60.6	0.66	16.2	5.62	0.07	3.7	5.35	3.38	1.93	0.19
PP-13	60.9	0.67	15.7	5.12	0.05	3.83	5.43	3.3	1.84	0.19
PP-12	61.5	0.69	15.8	5.46	0.09	4.24	6.07	3.42	1.81	0.2
JE-22	60	0.88	16.8	4.75	0.07	3.04	6.53	3.7	1.8	0.2
PV-22	62.4	0.85	16.8	8.83	0.06	3.49	1.66	1.69	2.54	0.23
MS-02	65.12	0.461	15.43	3.58	0.075	4.06	4.38	3.74	2.79	0.163
MS-03	65.64	0.459	15.41	3.54	0.069	4.01	4.28	3.57	2.65	0.157
MC-01	65.54	0.452	15.69	3.44	0.069	3.63	4.31	3.89	2.6	0.158
MS-01	65.7	0.458	15.38	3.68	0.075	3.87	4.12	3.67	2.8	0.16

(continued)

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
MC-F	57.06	0.972	17.26	5.95	0.124	4.45	8.36	3.93	1.47	0.226
EM-3	61.24	0.546	15.69	4.23	0.077	6.26	4.59	3.91	3.05	0.18
KMP-01	54.07	0.826	15.19	7.96	0.141	8.16	8.97	2.67	1.33	0.347
KMP-02	53.09	0.8	14.87	7.67	0.161	9.98	8.83	2.55	2.55	0.338
81JD029 [†]	64	0.71	18.7	2.54	0.04	0.87	5.03	5.4	2.36	0.24
81JD278 [†]	51.49	0.8	17.57	6.27	0.12	8.05	11.19	3.21	0.77	0.25
81JD013 [†]	56.35	0.87	14.2	6.69	0.12	8.28	7.48	2.92	2.4	0.39
81JD078 [†]	62.44	0.8	16.68	4.32	0.08	4.17	5.41	3.3	2.3	0.29
81JD202 [†]	59.62	0.74	16.68	4.23	0.08	4.55	7.47	4.13	2.08	0.24
86JD001 [†]	61.67	0.75	15.49	4.69	0.08	4.49	7.36	3.26	1.88	0.2
81JD279 [†]	62.34	0.72	15.56	5.31	0.09	3.81	6.23	3.25	2.27	0.2
86JD002 [†]	67.74	0.73	16.92	4.43	0.06	2.24	4.24	3.98	2.28	0.16
81JD217 [†]	64.81	0.63	17.16	3.19	0.04	1.74	4.6	4.88	2.64	0.17
81JD172 [†]	64.47	0.66	17.04	3.78	0.07	1.6	4.15	5.33	2.48	0.26
84Sg03	67.47	0.51	17.17	2.36	0.03	1.49	3.25	4.55	2.93	0.14
86JD006 [†]	75.4	0.19	14.52	0.9	0.03	0.21	1.33	3.13	4.28	0.02

Note: Data from Sorg (unpublished data), Stevenson et al. (2002), and Metzger et al. (2005).

[†] = Sample locations are given in Appendix D.

[‡] = Data from Drinkwater et al. (1988).

Trace Element Data for Selected DRV

Sample	Ba	Ce	Co	Cr	Ga	La	Nb	Nd	Ni	Pb	Sr	Th	V	Y	Yb	Zn
MP-2	648	47	35	143	18	29	18	29	80	-	1040	8	171	21	2	54
MC-47	1200	51	42	370	15	31	5	27	230	-	740	12	190	18	2	71
BH-4B	581	38	43	349	18	23	10	28	120	8	524	5	224	23	3	58
PV-26	695	40	59	500	19	25	17	27	368	9	462	5	193	16	2	78
TS-1	547	36	40	458	17	22	4	25	180	10	518	6	193	19	2	58
PP-7	580	32	48	560	18	21	6	20	257	11	442	5	189	16	2	79
PP-35	720	38	33	190	19	23	10	23	110	-	560	7	180	32	2	61
TS-12	990	50	23	286	18	34	12	31	114	-	626	9	125	19	2	56
QS-19	1240	43	29	370	20	26	5	24	180	18	544	8	92	18	2	72
TS-15	754	37	18	89	19	24	9	19	27	-	452	7	84	17	2	55
TS-16	580	49	32	197	18	34	16	31	86	-	598	7	183	26	3	66
PP-5	880	45	17	180	19	27	9	23	31	-	430	8	120	27	3	72
MC-7	671	33	15	182	17	21	7	16	34	-	707	9	61	13	2	42
PP-8	699	39	20	199	18	28	4	22	43	15	487	6	85	14	2	55
PP-13	631	37	18	146	18	23	8	20	35	0	432	6	95	15	2	55
PP-12	629	36	19	160	18	23	9	19	38	-	449	6	105	15	2	59
PV-22	591	44	25	135	19	24	13	23	91	6	262	7	176	12	2	130
MS-02	834	39	-	175	18	17	10.7	-	30	22	606	9	60	16	-	50
MS-03	801	47	-	192	19	22	10.3	-	30	20	661	10	55	13	-	54
MC-01	819	34	-	179	19	34	11.2	-	34	27	656	8	56	16	-	54
MS-01	918	34	-	177	18	19	10.1	-	32	20	630	11	63	17	-	52
MC-F	753	21	-	134	16	14	12.8	-	64	18	597	4	112	21	-	83

(continued)

Sample	Ba	Ce	Co	Cr	Ga	La	Nb	Nd	Ni	Pb	Sr	Th	V	Y	Yb	Zn
EM-3	915	31	-	235	19	20	7.8	-	109	22	605	14	89	11	-	46
KMP-01	1234	44	-	491	14	27	10.9	-	202	7	798	13	196	22	-	71
KMP-02	1317	43	-	524	15	42	9.7	-	218	6	726	14	192	21	-	66

Note: Data from Sorg (unpublished data), Stevenson et al. (2002), Metzger et al. (2005).

"-" indicates that no data are available.

Appendix C: Geochemistry of Volcanic Rocks

Initial Sample Preparation

Samples were broken with a hammer to centimeter-scale pieces. Fragments with no xenoliths, weathering, or surface contamination were selected. A silicon carbide grinding wheel was then used to lightly abrade the impacted surfaces, in order to remove Fe contamination from the hammer. Subsequent review of samples confirmed the removal of all visible iron. Abraded chips were thoroughly cleaned with soap and water to remove any adhering dust particles deposited by abrasion. Samples were then dried in air and weighed. Bulk mass of resulting raw samples ranged between 30 and 50 grams.

X-Ray Fluorescence

Final sample preparation, which was performed at the GeoAnalytical Laboratory of Washington State University, involved low-dilution fused bead preparation. Rock chips were ground, weighed, and fused twice using 3.5 g of rock powder with 7.0 g of dilithium tetraborate (LiB_4O_7) flux. To remove surface residue, the glass beads were finely polished with 600 grit silicon carbide. Details of this procedure can be found in Johnson et al. (1999).

Concentrations of 27 major and trace elements were measured with a Rigaku 3370 automated XRF spectrometer. The equipment was run at a constant 50 kV and 50 mA on a rhodium target, with a 25 mm mask for all elements. Concentrations were determined by comparing the obtained X-ray peak intensities with those of nine USGS standards, and were automatically corrected for interference. Precision was periodically monitored using two internal standards. For unknown samples, accuracy was estimated by analyzing the scatter of data points with respect to element calibration curves. Significant precision loss occurs at element concentrations below 10-20 ppm. In addition, precision and accuracy for some elements can be quite low. Variations as high as approximately 5 ppm, 30 ppm, 10 ppm, and 200 ppm can be expected for Sc, V, Nb, and Ba, respectively. Hence, ICP-MS data for the complete suite of trace elements are preferred. For details on XRF operating conditions, instrument calibration, accuracy, and precision, see Johnson et al. (1999).

ICP-MS

Preparation performed at the GeoAnalytical Laboratory of Washington State University involved fusion/dissolution

of the sample. First, the sample-flux mixture was fused at 1000°C for 30 minutes. Next, 250 mg of the resulting pellet was powdered and dissolved in acid, followed by final dilution of the sample to 1:240 of its initial concentration. Sample preparation details are available in Knaack et al. (1994).

A 250 Sciex Elan ICP-MS instrument containing a quadrupole mass spectrometer was used. The liquid sample was ionized and fed through a two-stage ion extraction interface with a peristaltic pump and automatic sampler at 1.0 ml/min into 1500-watt argon plasma at 7000°C. Ten runs of 0.5 seconds per element were made, for a total of 5 seconds per element. Element intensity values were corrected for chemical interferences and instrument drift using internal standards. Concentrations of elements in unknown samples were computed based on calibration curves constructed from six standard samples. The calculation assumes that unknowns and standards have isotopic ratios similar to those of the crustal average. Analytical precision is given by standard re-runs, and accuracy is estimated by calculating the scatter of individual standards from the calibration curve. For concentration

calculations and details on reproducibility and accuracy,
refer to Knaack et al. (1994).

Appendix D: DRV Sample Description and Location

Sample	Description	Locality	Sample Coordinates
MP-2	Basalt	Mustang Peak	37° 11' 08"N, 121° 21' 34"W
MC-47	Basalt	Orestimba Creek	37° 11' 53"N, 121° 22' 52"W
BH-4B	Basalt	San Luis Reservoir	?
PV-26	Basalt	Llanada	?
TS-1	Basaltic Andesite	Vaughn Mine	36° 58' 28"N, 121° 16' 30"W
PP-7	Basalt	Pacheco Peak	?
PP-35	Basaltic Andesite	El Toro Ranch	37° 05' 43"N, 121° 18' 41"W
PV	Basaltic Andesite	Panoche Valley	?
TS-12	Andesite	Vaughn Mine	36° 59' 28"N, 121° 20' 00"W
QS-19	Andesite	Quien Sabe	?
TS-15	Andesite	Vaughn Mine	36° 58' 53"N, 121° 17' 57"W
TS-16	Basalt	Vaughn Mine	36° 58' 21"N, 121° 16' 47"W
JE-21	Andesite	Silver Creek	?
PP-5	Andesite	Dowdy Ranch	37° 07' 04"N, 121° 21' 42"W
MC-7	Andesite	Red Creek	37° 14' 41"N, 121° 24' 51"W
PP-8	Andesite	Pacheco Peak	?
PP-13	Andesite	Pacheco Peak	37° 00' 24"N, 121° 17' 13"W
PP-12	Andesite	Pacheco Peak	37° 00' 28"N, 121° 17' 12"W
JE-22	Andesite	Silver Creek	?
PV-22	Andesite	Griswold Creek	?
MS-02	Dacite	Robinson Creek	37° 15' 25"N, 121° 24' 26"W
MS-03	Dacite	Robinson Creek	37° 15' 31"N, 121° 24' 13"W

(continued)

Sample	Description	Locality	Sample Coordinates
MC-01	Dacite	Red Creek	37° 14' 36"N, 121° 24' 50"W
MS-01	Dacite	Robinson Creek	37° 15' 21"N, 121° 24' 36"W
MC-F	Basaltic Andesite	Orestimba Creek	37° 12' 54"N, 121° 23' 10"W
EM-3	Trachyandesite	Eylar Mtn	?
KMP-01	Basaltic Andesite	Orestimba Creek	37° 12' 17"N, 121° 22' 21"W
KMP-02	Basaltic Andesite	Orestimba Creek	37° 12' 10"N, 121° 22' 24"W
81JD029	Trachydacite	Quien Sabe	?
81JD278	Basalt	Quien Sabe	?
81JD013	Basaltic Andesite	Quien Sabe	?
81JD078	Andesite	Quien Sabe	?
81JD202	Andesite	Quien Sabe	?
86JD001	Andesite	Quien Sabe	?
81JD279	Andesite	Quien Sabe	?
86JD002	Trachydacite	Quien Sabe	?
81JD217	Trachydacite	Quien Sabe	?
81JD172	Trachydacite	Quien Sabe	?
84Sg03	Dacite	Quien Sabe	?
86JD006	Rhyolite	Quien Sabe	?

Note: Data from Sorg (unpublished data), Drinkwater et al. (1988), Stevenson et al. (2002), Metzger et al. (2005).

Appendix E: Energy Dispersive Spectra of Selected Minerals

25. ED Chlorite Sample 189 04.20.2005

26. ED Chlorite Sample 189 04.20.2005

33. ED Amphibole Sample 211B 05.19.2005

34. ED Epidote Sample 211B 05.19.2005

55. ED Quartz+mercury Sample 233A 05.19.2005

56. ED Quartz + Gypsum/ Anhydrite Sample 233A 05.19.2005

59. ED

Sample 236B

04.20.2005

60. ED

Low-Mg dolomite

Sample 236B

04.20.2005

PLATE 1.

GEOLOGIC MAP OF THE BURRA BURRA PEAK AREA, PACHECO PEAK QUADRANGLE, SANTA CLARA COUNTY, CALIFORNIA

by Pavel Kosovichev

2005

EXPLANATION FOR GEOLOGIC MAP

SURFICIAL DEPOSITS

- Quaternary
- Qal** Alluvium
 - Landslide body. Approximate boundary shown by broken line; flow direction shown by arrow.

VOLCANIC ROCKS

- Upper Tertiary
- Dra** ANDESITE OF DOWDY RANCH - Plagioclase-pyroxene intrusive andesite and minor dacite. Massive, strongly jointed.

BASEMENT ROCKS

- Cretaceous to Lower Tertiary (?)
- Yolla Bolly Terrane Metasedimentary Rocks** - Quartzofeldspathic graywacke, conglomerate, shale.
 - Fms** FRANCISCAN MELANGE METASEDIMENTARY ROCKS - Lithic graywacke, conglomerate, shale, chert.
 - BLUESCHIST** - Blue amphibole-albite-jadeite schist and foliated greywacke. Minor chlorite schist, mica schist, and quartzite.
 - ULTRAMAFIC ROCKS** - Serpentinite and tremolite schist.

SYMBOLS

- ===== Road (unpaved)
- Trail
- Contact - Dashed where located approximately; dotted where concealed.
- Fault, based on preliminary mapping by D.Sorg. Dashed where located approximately; dotted where concealed.
- Thrust fault, based on preliminary mapping by D.Sorg. Dotted where concealed.
- Fault, inferred from topography and lithology.

Pit

Blueschist-facies metamorphic block, not to scale.

Seam of carbonate mineralization.

Andesitic dike, not to scale.

Tectonic breccia locality.

Locality discussed in text.

Hydrothermal breccia locality.

Sample locality.

Unmapped.

km

PEAK

M=14.813°

.988°

Scale 1:24,000.

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

This reproduction is the best copy available.

UMI[®]

Contour Interval: 40 ft.

121° 23' 00" W

1 km

1 mi

PLATE 2.

121° 23' 00" W

121° 21' 00" W

1 km

1 mi

PLATE 2.

PLATE 2.

GEOLOGIC SAMPLE MAP OF THE ORESTIMBA CREEK AREA
QUADRANGLE, STANISLAUS COUNTY, CALIFOR

by Pavel Kosovichev

2005

Base map from Mustang Peak Quadrangle, 7.5 Minute Topographic Series, 1995. U.S. Department of the Int

121° 23' 00" W

1 km

1 mi

121° 21' 00" W

PLATE 2.

LOGIC SAMPLE MAP OF THE ORESTIMBA CREEK AREA, MUSTANG PEAK
QUADRANGLE, STANISLAUS COUNTY, CALIFORNIA

by Pavel Kosovichev

2005

map from Mustang Peak Quadrangle, 7.5 Minute Topographic Series, 1995. U.S. Department of the Interior, Geological Survey. Scale 1:24,000.