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Provenance of the upper-miocene briones formation in the central Diablo Range, California

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PROVENANCE OF THE UPPER-MIOCENE BRIONES FORMATION
IN THE CENTRAL DIABLO RANGE, 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

Guy Felix Chetelat

May 1995

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ABSTRACT

PROVENANCE OF THE UPPER-MIOCENE BRIONES FORMATION IN THE CENTRAL DIABLO RANGE, CALIFORNIA

By Guy F. Chetelat

Sandstone of the upper-Miocene Briones Formation in the southwest Livermore basin and along the western flank of the central Diablo Range was derived primarily from the Sierran volcanic arc, with lesser amounts derived from Coast Range uplands. Most feldspars and unmetamorphosed volcanic rock fragments are attributed to a Sierran source. Most polycrystalline quartz grains, sedimentary rock fragments, and metamorphic rock fragments are attributed to a Coast Range source.

Abundant Sierran detritus shows that Briones sandstone in the study area is related to Sierran-derived units of the Neroly Formation rather than the Coast Range-derived Orinda Formation. The Franciscan Complex of the central Diablo Range was the primary source of Coast Range detritus in the Briones Formation. The mixture of Sierran and Coast Range sediment indicates that the central Diablo Range uplands did not form a barrier to westward dispersal of Sierran sediment during this part of the late Miocene.

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INTRODUCTION

The Briones Formation is a shallow-marine sandstone of late Miocene age in the northern Diablo Range of central California (Figs. 1, 2). The Briones Formation crops out in the Contra Costa basin, in the Livermore basin, and south of the Livermore basin along the western side of the Diablo Range. Outcrops of the Briones Formation in the southwest corner of the Livermore basin and west of the Calaveras fault are the focus of this study (Fig. 2). These outcrops contain a significant record of upper-Miocene sedimentation in the San Pablo embayment (the precursor to the Livermore basin), and are comparatively less studied than exposures to the north in the Contra Costa basin.

The Briones, Cierbo, and Neroly Formations compose the San Pablo Group. The Briones underlies and is, in part, correlative with the fluvial and shallow-marine Neroly Formation to the east and with the fluvial Orinda Formation in the western Contra Costa basin (Creely and others, 1982; Graham and others, 1984).

Upper Miocene deposits in the study area, including the Briones Formation, are underlain by deformed oceanic, trench, and fore-arc material of the Mesozoic Franciscan

▲ Section Studied

▤ Neogene Sedimentary Rocks

Figure 1. Neogene sedimentary basins of the northern Diablo Range. Selected East Bay faults are taken from Aydin and Page (1984).

Figure 2. Distribution of Briones Formation in the Diablo Range east of Milpitas (after Rogers, 1966).

Complex. The Briones Formation in the study area is overlain by fluvial deposits of the Orinda Formation.

From the Mesozoic until 29 Ma, subduction of oceanic lithosphere under California formed a convergent plate boundary with trench and associated volcanic arc (Atwater, 1970; Dickinson and Snyder, 1979). Arrival of the East Pacific spreading ridge at the trench in southern California produced a right-lateral-transform boundary that propagated northward behind the Mendocino triple junction as the spreading ridge reached the trench (Atwater, 1970). The Briones Formation was deposited when central California's coastal margin was changing from a convergent plate boundary to a transform boundary, between 10 and 5 Ma (Graham and others, 1984).

Potential sediment sources for the Briones and related upper Miocene formations were the Sierran-volcanic arc and Coast Ranges. Previous researchers have concluded that the primary sources of Briones sediment were Coast Range uplands located west of the Hayward fault (Bay block) and the Franciscan core of the Diablo Range (Mt. Hamilton block) south of the Livermore basin (Wagner, 1978; Graham and others, 1984). Results from this study are used to evaluate the validity of this conclusion and to address related questions.

Two questions are addressed by this study:

- (1) What were the sources of sediment in the Briones Formation?
- (2) What do the sources of sediment in the Briones Formation reveal about the central California coastal margin during the late Miocene?

Answers to these questions are sought by first determining composition of Briones sandstones through quantitative microscopic analysis. Provenance then is determined by matching grains with rock types in source areas and by comparison with sandstones of known provenance. Relative contribution of sand from different source areas then is estimated by comparing numbers of grains attributed to each province.

PREVIOUS WORK

Previous Briones research included mapping, determination of fossils, and interpretation of regional correlation, provenance, and tectonics. Mapping by Crittenden (1951), Hall (1958), Christie (1985), and Coyle (1985) showed that the Briones Formation crops out along the western side of the Diablo Range south of the Livermore basin. Paleontological studies by Trask (1922) and Hall (1958) showed that the Briones Formation was deposited in a predominantly shallow-marine setting during the late Miocene. Creely and others (1982) and Graham and others (1984) correlated the Briones Formation, in part, with the Orinda Formation of the Contra Costa basin, a unit rich in Franciscan detritus. Wagner (1978) and Graham and others (1984) concluded that units of the Neroly Formation that are rich in andesitic detritus derived from the Sierran arc are, in part, coeval with the upper part of the Briones Formation.

Previous studies of Briones provenance were limited in the number of samples and/or thin-sections examined and by reliance on field identification of clast types. Based on hand-specimen descriptions, Wagner (1978) stated that the Briones was derived from two major Coast Range sources: a western highland (also the source of the Orinda Formation) and the Diablo Range south of the

Livermore basin. Based on pebble counts, Christie (1985) inferred local sources in the Diablo Range for three conglomerates in the lower Briones of the Maguire Peaks area. Based on five thin sections (and field observations), Graham and others (1984) concluded that the Briones was related genetically to the Orinda Formation and shared the same Coast Range source located west of the Hayward fault.

Based in part on Franciscan detritus in the Orinda Formation, Creely and others (1982) and Graham and others (1984) postulated the existence of a late Miocene upland (Bay block) west of the Hayward fault that shed Franciscan sediment eastward into Orinda and Briones depositional environments. Graham and others (1984) argued further that the western upland (Bay block) was related to the onset of transform faulting along the Hayward fault trend.

In summary, previous work on the provenance of the Briones has been concentrated in the Contra Costa basin, has been limited in scope, and has led to the general conclusion that most sediment in the Briones had Coast Range sources. Exposures of the Briones Formation in the southwestern Livermore basin and west-central Diablo Range have been relatively unstudied.

STRATIGRAPHY

San Pablo Group

The Briones Formation is part of the San Pablo Group, which is composed, from lower to higher, of the Briones, Cierbo, and Neroly formations of late Miocene age (Creely and others, 1982). The Cierbo generally is included in the Neroly Formation because of difficulty in differentiating between these two formations (Wagner, 1978; Graham and others, 1984). Sandstones and conglomerates of Apperson Ridge, mapped by Hall (1958) as Cierbo Formation, are included in the lower Briones Formation in this study. Although the Briones contains the oldest beds of the San Pablo Group, it is in part coeval with the Neroly Formation (Graham and others, 1984). Generally, the Briones Formation occurs west of the Neroly Formation. Neroly sandstones commonly are bluish in color, which distinguishes them from gray Briones sandstone (Graham and others, 1984).

Briones Formation

Stratigraphic Sections Studied. Five relatively intact sections with good exposures were chosen for detailed study: (1) the Calaveras road-cut east of Milpitas, (2) the Mission Peak area northeast of Milpitas, and three exposures southeast of Sunol at (3) Maguire

Peaks, (4) Welch Creek and (5) Apperson Ridge (Figs. 1, 2; Appendix A).

In the study area, the Briones Formation ranges in thickness from a minimum of 200 m in the west to a maximum of 1,500 m in the east (Crittenden, 1951; Hall, 1958; this study). The sections measured for this study are described in Appendix A and Figures 3 through 7. Stratigraphic location of samples was determined by measurement of distance from contacts and distinctive beds using a tape and compass, pacing, or calculations from maps.

The Briones is composed mostly of sandstone, with conglomerate and shale beds in the lower part. Hall (1958) divided the Briones into three members, a lower member of fine-grained sandstone and interbedded silty claystone, a middle member of lithic and bioclastic sandstone, and an upper member of fine-grained sandstone; his convention is followed where possible in this study.

The Briones overlies the Miocene Monterey Group in the central and western part of the study area. The Monterey Group is composed of interbedded chert, shale and sandstone. In the eastern part of the study area, the Briones overlies diverse rock types of the Mesozoic

Figure 3. Stratigraphy and sample locations at Calaveras Road section.

Figure 4. Stratigraphy and sample locations at Mission Peak section.

Figure 5. Stratigraphy and sample locations at Maguire Peaks section.

Figure 6. Stratigraphy and sample locations at Welch Creek section.

Figure 7. Stratigraphy and sample locations at Apperson Ridge section.

Franciscan Complex and Great Valley Group (Crittenden, 1951; Hall, 1958; Dibblee, 1980; Christie, 1985). Upper Miocene rocks mapped as the Orinda Formation (Crittenden, 1951; Hall, 1958) overlie the Briones. These upper Miocene rocks are predominantly conglomerate and shale, with lesser amounts of sandstone.

In the area between the Hayward and Calaveras faults (Figure 2), Crittenden (1951) mapped a maximum thickness for the Briones of about 1,500 m in the east and 500 m in the west. The maximum thickness interpreted for western exposures of Briones Formation in the current study is about 200 m. The difference in thickness probably is attributable to a difference in interpretation of the base of the Briones. For this study, the base of the Briones (in western exposures) is placed at the base of the lowest coarse-grained, bioclastic sandstone. Fine-grained sandstones and shales directly underlying the bioclastic beds are included in the uppermost Monterey Group; Crittenden (1951) mapped these finer-grained beds as Briones Formation. Coarse-grained, bioclastic sandstone is the most distinctive lithology of the Briones Formation.

Calaveras Road Section. Approximately 200 m of Briones sandstone is exposed along Calaveras Road (Fig. 3; Appendix A). Here, the Briones is composed of shallow-

marine sandstone deposited on Monterey Group sandstone and shale; it is overlain by fluvial conglomerate and sandstone of the Orinda Formation. The contact between the Monterey Group and overlying Briones is complicated by faulting and landslides at Calaveras Road; this contact is an unconformity in exposures to the south in Penitencia Canyon (Crittenden, 1951). The base of the Briones at Calaveras Road is placed at the base of the lowest coarse-grained bioclastic sandstone. The contact with the overlying Orinda Formation, although covered, appears to be conformable because of an increase in the numbers of pebbles and a change in coloration in Briones sandstone near the contact with the Orinda Formation.

Mission Peak Section. The Mission Peak section is composed of about 200 m of upper Briones Formation (Fig. 4; Appendix A). In the Mission Peak area, the Briones overlies the Monterey Group and is conformably overlain by the Orinda Formation. The upper Briones at Mission Peak is composed of sandstone containing fossils indicative of a shallow-marine environment (Hall, 1958). The boundary with the Orinda Formation is gradational, with some interfingering of gray Briones and red Orinda sandstones. The contact with the Orinda is placed at the stratigraphically highest gray sandstone bed.

Maguire Peaks Section. The Briones Formation reaches its maximum thickness of approximately 1,500 m in the Maguire Peaks area (Hall, 1958). Here, the Briones rests unconformably on rocks of the Great Valley Group. The lower and middle members comprise the Maguire Peaks section of this study (Fig. 5; Appendix A).

The lower Briones at Maguire Peaks forms vegetated slopes, with most exposures located in creek beds and road cuts. The well exposed sandstone outcrops on Maguire Peaks belong to the middle member. More samples were collected and analyzed from the well exposed middle member than the relatively poorly exposed lower member.

Volcanic-ash beds are present near the base of the lower member and near the top of the middle member. The stratigraphically highest samples collected at Maguire Peaks are from the top of the middle member of Hall (1958).

Welch Creek Section. Lower and middle members of the Briones exposed in outcrops and road cuts in the Welch Creek drainage comprise the Welch Creek section (Fig. 6; Appendix A). Here, the lower Briones rests unconformably on Franciscan Complex rocks. The lower member contains conglomerate composed of Franciscan Complex clasts (greenstone, shale, and graywacke), interbedded with sandstone and shale.

The middle member is well exposed in lower Welch Creek. Middle Briones cliff-forming sandstone at Welch Creek is nearly identical to that at Maguire Peaks. The Welch Creek section has been truncated by the Calaveras fault, so that the upper part of the middle member and all of the upper member of the Briones Formation are missing.

Apperson Ridge Section. Approximately 60 m of lowermost Briones Formation crops out on the western flank of Apperson Ridge (Fig. 7; Appendix A). Briones conglomerate rests on an erosional surface cut into the underlying Franciscan Complex. The section is composed of sandstone with interbedded conglomerate. The most common conglomerate clasts are chert, greenstone, shale, graywacke and quartz.

A 1-m-thick bed composed of barnacles occurs 38 m above the base of the Briones. The barnacle bed is overlain by a reddish-brown sandstone containing fossilized plant material. Fossils and color changes suggest that the depositional setting of the lower Briones at Apperson Ridge alternated between nearshore marine and nonmarine settings.

The upper half of the Apperson Ridge section, from the middle conglomerate beds to the top of the section, was mapped by Hall (1958) as Cierbo Formation. These sandstones and conglomerates are included in the lower

Briones in this study because of similarity to nearby exposures of lower Briones mapped by Hall (1958). Sandstones above and below the conglomerates at Apperson Ridge are similar in grain size and coloring. The Apperson Ridge section is very similar to the nearby lower Briones at Welch Creek; both have interbedded sandstones and conglomerates, color variations ranging from reddish brown to bluish gray, and similar shallow-marine and plant fossils.

Briones Paleontology. A diverse assemblage of fossils has been reported from the Briones Formation. Mollusks and foraminifera indicate that the Briones Formation is of late Miocene age and that most of it was deposited in a nearshore, marine environment (Trask, 1922; Hall, 1958). Table 1 lists fossils used in determining age and paleoenvironment of the Briones Formation.

Briones Tephra Correlation. Two tephra units were found in the Briones Formation at Maguire Peaks (Fig. 5). Ash unit MGP-14 is located in the lower Briones on the south side of Maguire Peaks. This ash is estimated to be between 30 and 100 m above the base of the Briones at Maguire Peaks. It is approximately 4 m thick and composed of 4 individual beds; 2 of these beds (MGP-14A and MGP-14C) were sampled.

Table 1. SELECTED FOSSILS FROM THE BRIONES FORMATION

Fossil	Reference
Arthropoda	
<u>Balanus</u> sp.	1
Echinodermata	
<u>Astrodapsis brewerianus</u>	1
Pelecypoda	
<u>Mytilus perrini</u>	1
<u>Ostrea bourgeoisi</u>	1
<u>Pecten andersoni goncostus</u>	1
<u>Pecten raymondi brionianus</u>	2
Foraminifera	
<u>Bolivina</u> cf. <u>B. obliqua</u>	2
<u>Buliminella elegantissima</u>	2
<u>Nonion</u> cf. <u>N. costiferum</u>	2
<u>Pullenia</u> cf. <u>P. miocenica</u>	2
<u>Virgulina</u> cf. <u>V. subplana</u>	2
Mammalia	
<u>Desmostylus</u> sp.	2

References: 1 = Trask (1922); 2 = Hall (1958)

Ash bed MGP-16 is from the upper part of the middle Briones Formation at Maguire Peaks. It is approximately 30 cm thick, fine grained, and indurated.

Tephra composition and correlation were determined by Andrei Sarna-Wojcicki of the United States Geological Survey (Appendix B). An electron microprobe was used to determine content of Si, Al, Fe, Mg, Mn, Ca, Ti, Na, and K oxides in extracted volcanic glass shards from samples MGP-14 and MGP-16. Tephra correlation is based on matching oxide composition with tephra of known age.

Ash (MGP-14) from the lower Briones Formation is tentatively correlated with tephra layers of 9 to 7 Ma age in northeastern California or 15.7 to 10.8 Ma age in the Monterey Formation at Santa Barbara. The younger tephra (9 to 7 Ma) from northeastern California is considered a better compositional match (Sarna-Wojcicki, 1991, pers. comm.). Middle Briones tephra MGP-16 correlates well with a tephra layer of about 7 Ma age in the upper part of the Modelo Formation of Balcom Canyon, east of Ventura, southwestern California (Sarna-Wojcicki, 1991, pers. comm.)

A Briones tephra-age range of 9 to 7 Ma is consistent with the late Miocene fossils. In the Contra Costa basin, the Briones is considered to be as old as 12 Ma (Creely and others, 1982) or 13 Ma (Graham and others, 1984) based on the fossils. The Briones Formation in the study area may range in age from 13 Ma to less than 7 Ma. The tephra from the Maguire Peaks section suggests that the age of the Briones between the ash beds is approximately 9 to 7 Ma.

Neroly Formation

The Neroly Formation is a shallow-marine and nonmarine deposit of late Miocene age exposed in the Livermore basin north to Mount Diablo (Wagner, 1978; Graham and others, 1984). The Neroly Formation is, in

part, age equivalent to the Briones, but it also contains some younger beds (Graham and others, 1984). The Neroly was deposited mostly east of the Briones and has not been mapped in the study area.

Neroly sandstones are rich in andesitic detritus that generally is considered to have been derived from the late Miocene volcanic arc of the central Sierra Nevada (Graham and others, 1984). Two samples of Neroly Formation sandstone from the south side of Mount Diablo (Appendix A) were studied in order to compare Briones and Neroly sandstone composition.

Orinda Formation

Fluvial deposits mapped as Orinda Formation overlie the Briones Formation in the study area (Crittenden, 1951; Hall, 1958). The Orinda Formation in the study area probably is late Miocene in age (Crittenden, 1951; Hall, 1958).

The Orinda Formation at Calaveras Road and Mission Peak is composed of approximately 600 m of variegated green and red siltstone, sandstone, and conglomerate (Hall, 1958). Siltstone and fine-grained sandstone of the lower Orinda grade into coarse-grained sandstone and conglomerate up section.

The Orinda Formation in both the Contra Costa and southwest Livermore basins generally is considered to be derived from Coast Range sources (Crittenden, 1951; Graham and others, 1984). Reworked fossiliferous Briones clasts are present in Orinda conglomerates at the Mission Peak and Calaveras Road areas.

LOCATIONS OF STUDY SECTIONS DURING THE LATE MIOCENE

The Calaveras Road and Mission Peak sections probably have been displaced northward by right-lateral movement on the Calaveras fault (Fig. 8). Restored offset of 18 km, based on offset of volcanics and Miocene sedimentary units (Page, 1982), indicates that the study sections originally were distributed north to south along the western side of the Diablo Range. Restored offset shows that, during deposition, the Maguire Peaks area was the most northerly and the Calaveras Road area the most southerly of the sections studied (for present locations see Fig. 2).

Rocks west of the Hayward fault also have been displaced northward. Restored offset of 20 km is based on offset of Franciscan sources of the Orinda Formation in the Contra Costa basin (Graham and others, 1984). Restored offset on the Hayward and Calaveras faults shows that, during the late Miocene, the Franciscan Complex rocks closest to the study sections were located to the east in the central Diablo Range.

- ▲ Section Studied
- ▤ Neogene Sedimentary Rocks
- ▨ Franciscan Complex Rocks

Figure 8. Map showing restored offset of 18 km on the Calaveras fault (Page, 1982) and 20 km on the Hayward fault (Graham and others, 1984).

METHODS

Field and Sampling Techniques

Five sections were chosen for detailed study:

(1) the Calaveras road-cut east of Milpitas, (2) the Mission Peak area northeast of Milpitas, (3) the Maguire Peaks area south of Sunol, (4) Welch Creek (in Maguire Peaks area), and (5) Apperson Ridge (in Maguire Peaks area) (Figs. 1, 2). Field work was conducted during 1988 and 1989.

Outcrops, road cuts, and contacts were examined, and are described in Appendix A. Sandstones of medium- to coarse-grain size were sampled for thin-section analysis. Fine- and very-coarse grained sandstones were sampled where no medium- to coarse-grained sandstones were present. Clasts of pebble size and larger were identified by hand lens, and estimates of relative proportions were made in the field.

Sampling frequency was controlled by vegetation and outcrop weathering. Samples were collected preferentially from well cemented and unweathered outcrops. Because of outcrop weathering, sampling coverage of well cemented Briones sandstones was more complete than for weakly cemented sandstones. Additional samples were collected

where changes in color, grain size, or grain composition were observed.

Thin-section Preparation

Thin sections were cut perpendicular to bedding and mounted on glass slides with Petropoxy. Weakly cemented samples were impregnated with Petropoxy prior to cutting and mounting.

Petrographic Analysis

Thin-section slides were first examined with a petrographic microscope to determine types of framework grains present. Grain-type categories used for thin-section analysis are shown on Table 2. The presence of rare grains not listed in Table 2 also was noted. Grain groupings used for sample description and provenance interpretation are shown on Table 3.

During microscopic examination, sample slides were moved a fixed distance with a mechanical stage and the grain under the cross hairs identified and counted. When possible, 300 total QFL (quartz, feldspar and lithic) grains were counted for each sample.

Table 2. GRAIN-TYPE CATEGORIES

Qm:	Monocrystalline quartz
Qp (2-4):	Polycrystalline quartz, 2-4 crystals
Qp (>4):	Polycrystalline quartz, more than 4 crystals
Fp:	Plagioclase feldspar
Fk:	Potassium feldspar
Fu:	Undifferentiated feldspar
Lsu:	Undifferentiated sedimentary lithic fragments
Lsc:	Chert
Lvu:	Undifferentiated volcanic lithic fragments, including silicified volcanic lithic fragments
Lva:	Andesitic lithic fragments
Lvb:	Basaltic lithic fragments
Lmu:	Undifferentiated metamorphic lithic fragments
Lmg:	Greenstone, including metamorphosed volcanics and serpentinite
Lmc:	Metamorphic chert, foliated chert and very fine grained polycrystalline quartz
Lp:	Granitic lithic fragments
	Accessory minerals
	Matrix
	Cement
	Fossils
	Pores

Table 3. GROUPED CATEGORIES

$Q = Q_m + Q_p \text{ (2-4 crystals)} + Q_p \text{ (>4 crystals)}$
$Q_p = Q_p \text{ (2-4 crystals)} + Q_p \text{ (>4 crystals)}$
$F = F_p + F_k + F_u$
$L = L_{vu} + L_{va} + L_{vb} + L_{su} + L_{sc} + L_{mu} + L_{mg} + L_{mc} + L_p$
$L_s = L_{su} + L_{sc}$
$L_v = L_{vu} + L_{va} + L_{vb}$
$L_m = L_{mu} + L_{mg} + L_{mc}$
$L_{sm} = L_s + L_m$
$FL_v = F + L_v$
$Q_p L_{sm} = Q_p + L_{sm}$
$QFL \% Q = 100 * Q / (Q + F + L)$
$L_s L_v L_m \% L_s = 100 * L_s / (L_s + L_v + L_m)$
$Q_p L_s L_m \% Q_p = 100 * Q_p / (Q_p + L_s + L_m)$
$FL_v, Q_p L_{sm} \% FL_v = 100 * FL_v / (FL_v + Q_p L_{sm})$

Size, sorting, roundness, and sphericity of grains were described. Pore filling and alteration of grains also were described. Grain size was determined by hand-specimen and thin-section examination, and presented in Wentworth-scale terminology. Degree of sorting for each sample was estimated by comparing the thin section with standard-deviation comparison images (Folk, 1980). Roundness and sphericity of grains were estimated by thin-section comparison with the roundness scale of Powers (Folk, 1980).

Where possible, samples for point counting were chosen from sandstones in the medium- to coarse-sand size

range (0.25 - 1.00 mm). Because of limited outcrops, samples of fine sand to granule size (0.125 - 4.00 mm) also were collected and point counted.

The counting method for this study differs from the widely used Gazzi-Dickinson (G-D) method (Dickinson, 1972) in the following ways:

- 1) Chert is counted in the chert or metamorphic chert categories rather than the polycrystalline quartz category as in the G-D method.
- 2) Grains with sand-sized crystals and original matrix are counted as lithic grains, not as mineral grains as in the G-D method.

The Gazzi-Dickinson point counting method was not used in this study for the following reasons: (1) some provenance information from rock fragments is lost when using the G-D method, and (2) grain-type categories used in this study were selected so that arc sediment could be distinguished from accretionary prism sediment more easily than with the G-D method.

PETROGRAPHIC RESULTS

Sixty-two thin sections of the Briones Formation were examined. Thirty-nine thin sections with good preservation of grains were point counted (Appendix C). Thin sections of Orinda (3 samples), Neroly (2 samples) and Monterey (1 sample) sandstones also were examined and point counted for comparison.

Grain Size

Generally, grain size in most samples ranges from medium to very coarse. Samples from the lower Briones generally are coarser grained (medium- to very coarse-grained) than samples from the middle and upper Briones (fine- to coarse-grained).

Most samples contain one grain-size population. Sample WCR-15, however, contains two populations of different grain sizes, (1) large polycrystalline quartz and lithic grains and (2) smaller grains of all types.

Sorting

Most Briones samples are moderately sorted, although samples from the lower Briones Formation at Apperson Ridge and Welch Creek and from the Orinda Formation generally are poorly sorted. Sorting probably is related to depositional environment, with shallow-marine environments

in the Briones Formation producing better sorted sandstones than nonmarine environments in the lower Briones and Orinda formations. Poorly sorted samples have a higher percentage of soft and unstable grains.

Roundness

Roundness ranges from rounded to angular, with the majority of grains subrounded to angular. Roundness varies with grain size and grain composition. Larger grains typically are more rounded than smaller grains. Feldspar and monocrystalline grains typically are subangular to angular. Lithic and polycrystalline grains typically are subrounded to subangular. Well-rounded quartz grains, comprising less than 5% of total quartz, are present in two samples (237-22 and MISP-9).

Sphericity

All samples are composed primarily of grains with low to moderate apparent sphericity. Rare well-rounded grains with high sphericity are composed of monocrystalline-quartz or aphanitic-rock fragments.

Cementation and Pore Filling

Calcite is the most common cementing agent, and is best developed in beds containing calcareous fossils. In some fossil-rich samples, unstable lithic grains (typically lithic volcanics) have been replaced by calcite. Samples with extensive replacement of this type were not point counted. Calcite cement in optical continuity over large areas (centimeter scale) is present in sample MGP-27 from the upper Briones Formation at Maguire Peaks. The optically continuous calcite in this sample is thought to be a result of unusual pore filling conditions rather than metamorphism, because no other samples were found to exhibit it.

Sandstone partly cemented by hematite is present in the lower Briones Formation at Apperson Ridge. Weakly cemented samples show a mixture of calcite, matrix, and zeolites partially filling the pores.

Lower Briones Formation sample AR-1 (Figure 7) shows multiple pore-filling materials deposited in the following sequence:

- (1) Development of rhombohedral crystals (dolomite ?) on edges of grains,
- (2) Coating of grains and rhombohedra with blue-colored clay,
- (3) Filling of remaining pores by calcite cement.

Grain Preservation and Alteration

Post-depositional grain preservation and alteration of Briones sandstones is, in part, controlled by degree of cementation and breakage of grains, with degree of cementation being the most significant factor controlling preservation of unstable grains. Samples with little or no cement show pervasive breakdown of feldspar and lithic volcanic grains into silt and clay. Zeolites and associated alteration products of unstable grains also are more prevalent in weakly cemented samples.

Because point counting of samples with significant alteration loss of feldspars and lithic volcanic grains would produce an erroneously high quartz count, well cemented samples were collected wherever possible.

Post-depositional fracturing of grains was observed in some samples. Samples VGTR-10 and MGP-20 show pervasive fracturing of quartz and feldspar grains. Quartz grains show fracturing where they are in contact with other grains. Fractures typically are filled with cement or matrix.

Sandstone Composition

Introduction

Point-count data are tabulated in Appendix D. Categories were selected that best describe the samples

and are the most useful for provenance interpretation. Ternary diagrams showing relative proportions of different categories (those shown on Table 3) were plotted with the following corner designations:

- 1) Quartz-Feldspar-Lithic fragments (QFL)
- 2) Metamorphic-Volcanic-Sedimentary (LmLvLs)
- 3) Polycrystalline Quartz-Sedimentary-Metamorphic (QpLsLm)

On each ternary diagram, only samples with more than 100 total grains of the diagram's constituents were plotted.

Samples from the Briones and Monterey formations are plotted on two QFL diagrams (Figs. 9, 10); those from the Orinda and Neroly formations are plotted on a separate QFL diagram (Fig. 11). Lithic composition is shown on the LmLvLs diagrams (Figs. 12, 13, 14) and samples rich in Qp+Ls+Lm are shown on the QpLsLm diagram (Fig. 15). Sandstone classification following Folk (1980) was determined from the QFL and LmLvLs diagrams.

- Lower Through Upper Briones Formation, Calaveras Road
- Upper Briones Formation, Mission Peak
- △ Monterey Group Sandstone, Calaveras Road

Figure 9. Ternary diagram showing relative proportions of quartz (Q), feldspar (F), and lithic (L) grains in samples from the Briones Formation at Calaveras Road and Mission Peak.

○ Lower - Middle Briones Formation, Maguire Peaks

◻ Lower - Middle Briones Formation, Welch Creek

Δ Lower Briones Formation, Apperson Ridge

Figure 10. Ternary diagram showing relative proportions of quartz (Q), feldspar (F), and lithic (L) grains in samples from the Briones Formation at Maguire Peaks, Welch Creek, and Apperson Ridge.

Figure 11. Ternary diagram showing relative proportions of quartz (Q), feldspar (F), and lithic (L) grains in samples from the Orinda and Neroly formations. Note grouping of samples and difference in lithic content.

Figure 12. Ternary diagram showing relative proportions of metamorphic lithic (Lm), volcanic lithic (Lv) and sedimentary lithic (Ls) grains. Note that Calaveras Road samples (lower and middle Briones) are clustered near the Neroly samples in the Lv corner, whereas the majority of samples from the upper Briones at Mission Peak have a higher proportion of Ls grains.

Figure 13. Ternary diagram showing relative proportions of lithic grains in samples from the Maguire Peaks and Welch Creek sections and from the Orinda and Neroly formations.

Figure 14. Ternary diagram showing relative proportions of lithic grains in lower Briones samples from the Apperson Ridge section and in Orinda and Neroly samples. Note that most Briones samples are characterized by a single lithic grain type, and only one sample shows the same lithic content as Orinda samples.

Figure 15. Ternary diagram showing relative proportions of QpLsLm grains in Briones and Orinda samples that contain more than 30% QpLsLm grains of total grains. Note that Briones samples plot in two groupings: A group composed mostly of Lm grains (lower Briones samples) and a group composed mostly of Qp grains (lower, middle, and upper Briones samples).

Point-count Results by Grain Type

Quartz Grains. The quartz content of samples from the Briones Formation ranges from 2% to 74% (Figs. 9, 10). Monocrystalline quartz generally comprises more than half of total quartz grains in the middle and upper Briones (Appendix A). Polycrystalline quartz generally is more common than monocrystalline quartz in the lower Briones (Appendix D). At Mission Peak, however, polycrystalline quartz is more common in samples from the upper Briones, near the contact with the overlying Orinda Formation (Appendix D).

Samples from the Neroly Formation contain only 1% to 2% quartz grains (Fig. 11). Both monocrystalline and polycrystalline quartz are present. Orinda Formation samples contain 53% to 56% total quartz grains (Fig. 11). Polycrystalline quartz is the most common form (Appendix D).

Feldspar Grains. Briones samples contain 36% (or less) feldspar grains (Appendix E). Lower Briones samples have the lowest feldspar content (Appendix E). Plagioclase and undifferentiated feldspar are the most common of the three feldspar categories recognized (Appendix D). Plagioclase grains typically are zoned, well preserved, and similar in size to the larger feldspars contained in lithic volcanic grains. Because of

similar features, the individual plagioclase grains are interpreted to have been derived primarily from breakup of larger volcanic grains. Many volcanic grains are composed of large plagioclase grains with small areas of volcanic groundmass still attached.

Potassium feldspar is uncommon in Briones sandstones (Appendix D). Some potassium feldspar grains likely were counted in the undifferentiated feldspar category because the samples were not stained. Microcline is the most common potassium feldspar type. Myrmekitic texture was observed in some grains. Because granitic grains are the only lithic grain type with potassium feldspar grains similar to the individual potassium feldspars grains observed, the potassium feldspar grains are interpreted to be derived from the same source as the granitic grains. Neroly samples contain less than 10% feldspar grains (Fig. 11). Orinda samples contain less than 15% feldspar grains (Fig. 11).

Lithic Grains. Lithic content of Briones samples ranges from 10% to 95% of total grains (Figs. 9, 10). The lower Briones generally is richer in lithic fragments than the middle and upper Briones (Appendix E). Three main lithic categories are present in the Briones: (1) volcanic, (2) sedimentary, and (3) metamorphic. All three categories are abundant in the lower Briones, but only the

volcanic group is abundant in the middle and upper Briones (Appendix E).

Lithic grains composed of feldspar with small amounts of attached volcanic groundmass were counted as lithic volcanic. Volcanic grains with minor groundmass silicification are included in the volcanic (Lv) group.

Metamorphic-volcanic grains are distinguished from volcanic grains by their pronounced alteration (typically chloritization) of groundmass and phenocrysts. In this study, serpentinite grains are counted with metamorphic-volcanic grains in the meta-igneous rock (Lmg) category, although it is recognized that serpentinite is not a metamorphic volcanic rock.

Chert is included in the lithic sedimentary group (Lsc). Chert with pressure-solution fabric is included in the lithic metamorphic group (Lmc).

Rare Grains and Grain Features. Table 4 shows grain features and rare-grain types.

Table 4. RARE GRAINS AND GRAIN FEATURES

<u>Grain Type</u>	<u>Feature</u>	<u>Samples</u>
Quartz (Qm)	Rutile inclusions	WCR-2, 237-11
Quartz (Qm)	Clay vermicules	WCR-15
Quartz (Qm)	Well rounded	237-22, MISP-9,
Quartz (Qm,Qp)	Abundant vacuoles	WCR-15
Feldspar (Fk)	Myrmekitic	WCR-17
Volcanic (Lv)	Pyrite inclusions	MGP-22, MGP-27
Metamorphic (Lm)	Blue amphibole	WCR-13, WCR-14

Point-count Results By Section

Calaveras Road. Monocrystalline quartz, feldspars, and lithic volcanic grains are the most common grain types counted in the Calaveras Road samples (Appendix D). Samples from the Briones at Calaveras Road contain 31% to 56% lithics and 28% to 56% quartz (Fig. 9; Appendix E). The Calaveras Road samples are classified as litharenites and feldspathic litharenites.

Calaveras Road samples plot in a cluster in the Lv corner (67% to 84% Lv) of the LmLvLs diagram (Fig. 12). Lithic-metamorphic content ranges from 5% to 11%, and lithic-sedimentary content ranges from 8% to 23%. Volcanic grains are the most common rock fragments in Calaveras Road samples (Appendix E).

Calaveras Road samples generally are similar in composition to one another. Samples from the upper Briones at Calaveras Road, however, show 5% to 10% more quartz than other Calaveras Road samples (Appendix E). The sample from the Monterey Group (237-1C) at Calaveras Road is similar to the Briones samples (Fig. 9; Appendix E).

Mission Peak. Monocrystalline quartz, feldspars, and volcanic grains are the most common grain types in the Briones samples from Mission Peak (Appendix E). Mission Peak samples fall into two groups (Fig. 9). Two samples

from the uppermost Briones Formation (MISP-9 and MISP-10) contain 10% to 20% more quartz than other Mission Peak samples (Appendix E). The two samples from the top of the Briones contain more Qp grains and fewer Lv grains (Appendix E). The samples are classified as lithic arkoses or feldspathic litharenites.

Mission Peak samples vary widely in Lv content (19% to 85% of total lithics) and Ls content (12% to 62% of total lithics) as shown on Figure 12. The uppermost Briones samples show an increase in proportion of Ls grains, followed by a higher proportion of Lm grains in the overlying Orinda Formation (Appendix E).

In summary, Briones samples from Mission Peak are similar in composition to the Briones at Calaveras Road. Two samples from the top of the Briones Formation at Mission Peak contain higher proportions of quartz and sedimentary grains than other Mission Peak samples.

Maguire Peaks. Monocrystalline quartz, feldspars, and volcanic grains are the most common grain types in the Maguire Peaks samples (Appendix D). The majority of Maguire Peaks samples fall into a group with a range of 37% to 47% quartz, 19% to 24% feldspars and 32% to 40% lithics (Fig. 10). Maguire Peaks samples are feldspathic litharenites, except MGP-22 which is classified as a litharenite.

Volcanic grains are the most abundant lithic type (71% to 92% of total lithics) in samples from Maguire Peaks (Fig. 13). Metamorphic-lithic content ranges from 1% to 9%, and sedimentary-lithic content ranges from 7% to 25%.

Welch Creek. Welch Creek samples from the lower and middle Briones are variable in composition, as shown on the QFL diagram (Fig. 10). Composition of samples ranges from 10% to 74% quartz, 23% to 89% lithic fragments, and 1% to 36% feldspar (Appendix E). The sandstones are classified as feldspathic litharenites and litharenites.

Welch Creek samples plot in three loose groupings on the LmLvLs diagram (Fig. 13): (1) the Lv group which contains 50% to 80% volcanic grains, (2) the Lm group which contains 75% to 95% metamorphic grains, and (3) the Ls group which contains 60% to 70% sedimentary grains. Samples with lithic populations composed primarily of Lm and Ls grains contain less than 2% Lv grains, whereas samples with numerous Lv grains also contain significant amounts of Ls and Lm grains (10% to 20%). Samples with high Ls and Lm content are from the lower Briones Formation (Appendix E).

In summary, Welch Creek samples vary widely in composition. Lower Briones samples here contain variable percentages of lithic constituents, and show more mixing

of constituents than in the lower Briones at nearby Apperson Ridge.

Apperson Ridge. Polycrystalline quartz and lithic metamorphic, lithic volcanic and lithic sedimentary rock fragments are the most common grain types in the Apperson Ridge samples (Appendix D). Relative proportions of these grain types vary widely at Apperson Ridge (Appendix E). Some Apperson Ridge samples contain more than 75% lithic fragments, while others are widely distributed (10% to 55% L) on the QFL diagram. Quartz content of Apperson Ridge samples AR-1 through AR-11 ranges from 3% to 48% (Appendix E). Of the Apperson Ridge samples, sample AR-12 contains the most quartz (73%). Feldspar content ranges from 0% to 27%. The samples are classified as litharenites, feldspathic litharenites, and one lithic arkose.

Apperson Ridge samples generally show wide variations in lithic type between samples, but little mixing of lithic types within individual samples (Fig. 14). The LmLvLs diagram (Fig. 14) shows that the lithic population of each sample is dominated by one of the three different lithic types. Single samples contain relatively pure populations of each of three main lithic groups: 92% to 97% Lm, 92% to 99% Lv, and 76% to 87% Ls (Appendix E).

A distinctive serpentinite litharenite (sample AR-11) is present near the base of the section (Appendix D).

Sample AR-12, also from the base of the section, is the only sample with a well-mixed population of the three lithic types (42% Lm, 20% Lv, and 38% Ls). Higher in the section, Lv and Ls grains are more common than Lm grains (Appendix E).

In summary, samples from the base of the Briones Formation at Apperson Ridge show great differences in lithic composition. Overall, Lm grains are common in the lower part of the section, whereas Lv and Ls grains are common higher in the section.

Neroly Formation. Neroly samples examined for this study are characterized by a high percentage of lithic grains (88% and 93%), and plot in the lithic corner of the QFL diagram (Fig. 11). Neroly Formation lithic content is 98% volcanic grains, and samples are classified as volcanicarenite (Fig. 12). The Neroly Formation samples generally contain more Lv grains and fewer Lm and Ls grains than Briones samples (Figs. 12, 13, 14).

Orinda Formation. Orinda Formation samples are characterized by high amounts of polycrystalline quartz, sedimentary, and metamorphic grains (Appendix D). Samples from the Orinda Formation consist of 53% to 56% quartz, 31% to 43% lithic, and 4% to 15% feldspar (Fig. 11; Appendix E). Thus, Orinda sandstones are classified as litharenites and feldspathic litharenites.

Orinda Formation samples plot in a group (Fig. 12) characterized by near equal percentages of metamorphic (38% to 55%) and sedimentary (26% to 40%) grains, and a smaller proportion (5% to 25%) of volcanic grains (Appendix E). Orinda samples contain a more mixed lithic population of metamorphic and sedimentary grains than Briones samples (Figs. 12, 13, and 14). Orinda samples plot near upper Briones samples from Mission Peak and lower Briones samples from Apperson Ridge and Welch Creek on the QpLsLm diagram (Fig. 15; Appendix E).

Summary of Point-count Data

Compositions of the Briones and related sandstones are as follows:

- (1) Volcanic grains are the most abundant grain type in a majority of Briones sandstones (Figs 9, 10; Appendix E). Quartz and feldspars also are common, with sedimentary and metamorphic grains abundant locally.
- (2) Neroly Formation samples are characterized by abundant volcanic grains, whereas Orinda Formation samples contain more polycrystalline quartz, sedimentary, and metamorphic grains than volcanic grains (Appendix D).
- (3) Unaltered volcanic grains in the Briones are similar to unaltered volcanic grains in the Neroly Formation. Polycrystalline quartz, sedimentary, and metamorphic

grains in the Briones Formation are similar to those in Orinda Formation samples.

- (4) Lower Briones sandstones at Apperson Ridge and Welch Creek contain beds composed almost solely of abundant volcanic grains intercalated between beds composed almost solely of sedimentary and metamorphic grains (Fig. 14; Appendix E).
- (5) Briones sandstones at Calaveras Road, Mission Peak, and the middle Briones at Welch Creek and Maguire Peaks show more mixing of grain types than those in the lower Briones of Apperson Ridge (Appendix E).
- (6) Briones sandstones show an increase in quartz near the contact with the overlying Orinda Formation (Appendix E).

Briones Conglomerates

Conglomerate beds are present in the lower Briones in the Welch Creek and Apperson Ridge sections, and isolated pebbles and pebble stringers are present in the middle Briones in the Welch Creek, Maguire Peaks, and Calaveras Road sections. Estimates of conglomerate composition were made in the field during collection of sandstone samples (Table 5).

Table 5. COMPOSITION OF BRIONES FORMATION CONGLOMERATES

Location	Composition (Percentage)
<u>Middle Briones</u>	
Calaveras Road	
237-4 (IP)	Red chert (70%), quartz (30%).
Maguire Peaks	
MGP-16 (IP)	Red chert (80%), und. (20%).
MGP-22 (PS)	Black chert (40%), red chert (20%), quartz (20%), und. (15%), volcanic (5%).
Welch Creek	
WCR-2 (PS)	Und. (50%), chert (20%), greenstone (20%), shale (10%).
<u>Lower Briones</u>	
Welch Creek	
WCR-13 (Cgl)	Greenstone (80%), und. (20%).
WCR-15 (Cgl)	Greenstone (40%), chert (20%), und. (20%), graywacke (10%), shale (10%).
Apperson Ridge	
AR-1 (Cgl)	Black chert (30%), greenstone (20%), quartz (20%), und. (20%), red chert (10%).
AR-5 (Cgl)	Red chert (20%), greenstone (20%), shale (20%), quartz (20%), und. (20%).
AR-12 (Cgl)	Shale (60%), graywacke (20%), greenstone (20%).

Note: IP = isolated pebbles; PS = pebble stringers;
 Cgl = conglomerate bed; und = undetermined.
 Composition of grains determined by field examination
 with hand lens.

Pebbles in the Briones Formation were derived primarily from metamorphic and sedimentary rocks. Distinctive rock types include red chert, greenstone, and sandstone (graywacke). The black chert and undetermined categories may contain multiple rock types (such as volcanics and sedimentary chert) from more than one provenance.

PROVENANCE

Introduction

Potential sediment-source areas for the Briones Formation are primarily the Sierran volcanic arc and the Coast Ranges (Fig. 16). Although the Sierran arc and Coast Ranges have some rock types in common, each area is characterized by certain rock types that yield distinctive sand grains that can be used for interpretation of provenance. The Sierran arc is characterized by granitic, metamorphic, and andesitic volcanic rocks. The Coast Ranges are characterized by mafic igneous rocks (greenstone and serpentinite) and sedimentary rocks (gray-wacke and chert).

To evaluate the provenance of the Briones Formation for this study, individual grain-type categories (Table 2) were grouped together into either a Sierran or a Coast Range group, based on their inferred sources. These groups then were refined by comparing the results with sandstones generally attributed to either a Sierran

SAF = San Andreas Fault

MTJ = Mendocino Triple Junction

Figure 16. Schematic diagram showing sediment sources during deposition of the Briones Formation. Approximate location of Mendocino triple junction after Graham and others (1984). "San Pablo embayment" from Buising and Walker (1995).

(Neroly Formation) or a Coast Range (Orinda Formation)

source.

Source Areas

Sierran Arc

During the late Miocene, the central Sierra was an active volcanic arc built on Mesozoic granitic plutons (Dickinson, 1970). The Sierran arc shed massive amounts of andesitic detritus westward during the late Miocene, producing the Mehrten and Etchegoin formations, and much of the Neroly Formation (Graham and others, 1984; Perkins, 1987). Subsurface correlations indicate that the Neroly grades eastward into the Mehrten, providing a link to the inferred Sierran source for the Neroly Formation (Graham and others, 1984). The two Neroly sandstones examined for this study contain 91% and 86% lithic-volcanic grains (Fig. 17), which is consistent with abundant lithic-volcanic content in undissected-arc-derived sandstones (Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992). The abundant andesitic detritus in these formations suggest that most of the upper Miocene

Figure 17. Average percentage of grain types in Orinda and Neroly formation samples.

sediment shed westward from the central Sierran arc was from the volcanic cover rather than the underlying granitic batholith or metamorphic belts.

The lithic volcanic grains (Lv) in Briones sandstones in the study area are very similar to the volcanic detritus in the Neroly and Mehrten formations. Feldspars in the Briones often are of the same type and show zoning similar to that of feldspars contained in volcanic grains, suggesting they were derived from breakup of volcanic grains. Therefore, the feldspar and volcanic grains are inferred to be primarily of Sierran origin. The proportion of Sierran arc detritus in Briones sandstones was estimated by combining point-count data of feldspar (F) and lithic-volcanic (Lv) grains into a FLv group.

The FLv group is considered to represent the contribution from the Sierran arc because abundant volcanic detritus was shed westward from the Sierran arc during the late Miocene, and Briones FLv grains are similar to grains almost certainly derived from Sierran sources in other formations such as the Mehrten Formation and much of the Neroly Formation. Samples of Neroly

sandstone derived from the Sierran arc are composed mostly of the FLv group.

Other potential sources of volcanic grains seem unlikely. Volcanic detritus could have been derived from the Quien Sabe and Berkeley Hills volcanic centers, located approximately 100 km south and 50 km north, respectively, of the study area (Fig. 18). However, the volcanic-rock types in these areas include rhyolite and basalt in addition to andesite (Johnson and O'Neil, 1983), rather than the predominant andesite in the Sierran arc. Also, because of the distance of the Quien Sabe and Berkeley Hills volcanic centers from the study area, volcanic detritus transported by streams from these areas probably would have mixed with other Coast Range grain types which are lacking in the relatively pure beds of volcanic detritus in the lower Briones at Apperson Ridge. Conversely, lower Briones sandstone rich in Coast Range lithic types such as sedimentary and metamorphic grains, contain little or no unaltered volcanic grains.

■ Franciscan Complex Rocks

Figure 18. Present locations of Berkeley Hills and Quien Sabe volcanic centers relative to study area. Locations after Johnson and O'Neil (1983).

Coast Range

Miocene Coast Range-sediment sources (uplands) in central California include the Bay block west of the Contra Costa basin (Graham and others, 1984) and the central Diablo range south of the Livermore basin (Wagner, 1978; Perkins, 1987). These uplands are characterized by mafic igneous rocks (greenstone and serpentinite), sedimentary rocks (graywacke and chert), and blueschist-grade metamorphic rocks. Sandstones from accretionary-complex sources commonly contain abundant sedimentary and metamorphic grains (Dickinson and Suczek, 1979).

Sandstones derived from Coast Range sources (Orinda Formation) are characterized by high percentages of polycrystalline quartz and sedimentary- and metamorphic-rock fragments (Graham and others, 1984). Three samples of the Orinda Formation in the study area contain high percentages of polycrystalline quartz, sedimentary, and metamorphic grain types (QpLsm) as shown in Figure 17, and thus, probably were derived mostly from the Coast Ranges. The Orinda Formation also contains distinctive Coast Range lithotypes, such as glaucophane schist and red chert.

A small amount of Sierran detritus (FLv) is present in Orinda sandstones. This Sierran detritus probably is reworked Sierran sediment from older units (including the Briones) within the Coast Range provenance. Monterey and Briones formation clasts have been reported in the Orinda Formation, suggesting that Miocene sediments were uplifted and reworked into Orinda Formation fluvial systems during the late Miocene (Crittenden, 1951; Hall, 1958).

The proportion of Coast Range detritus in Briones sandstones was estimated by combining point-count data of polycrystalline quartz (Qp) and sedimentary (Ls) and metamorphic (Lm) grains into a Coast Range-derived group (QpLsm). The QpLsm group is considered to represent Coast Range detritus in the Briones because sandstones from subduction-complex sources generally are rich in these grain types and sandstones derived mostly from the Coast Ranges (Orinda Formation) are rich in grains in the QpLsm group.

Provenance of the Briones Formation

Two provenance-sensitive groups were developed:

(1) a lithic-volcanic and feldspar group (FLv grains) attributable to a Sierran source, and (2) a poly-crystalline quartz and lithic-sedimentary and lithic-metamorphic group (QpLsm grains) attributable to a Coast Range source. The provenance of Briones sandstones then was determined by calculating the relative percentage of grains in the provenance-sensitive groups.

Calaveras Road Section

Relative proportions of Sierran (FLv) versus Coast Range (QpLsm) detritus for the Calaveras Road section are shown on Figure 19. The plot shows that the Briones Formation at Calaveras Road contains more Sierran detritus than Coast Range detritus. Proportions of Sierran and Coast Range detritus remain relatively constant throughout this section. The apparent increase in Coast Range detritus in samples 237-6 and 237-20 probably is a product of greater alteration loss of Sierran-derived Lv grains in these weakly cemented samples. Weakly cemented samples

Figure 19. Relative percentages of QpLsm and FLv grains in samples from Calaveras Road section. Relative percentages are as proportions of total Qp+F+Ls+Lm+Lv only; Qm is not included. QpLsm grains represent Coast Range sources, and FLv grains represent Sierran sources.

show a greater loss of unstable framework grains than do well cemented samples.

Mission Peak Section

Relative proportions of Sierran (FLv) versus Coast Range (QpLsm) detritus for the Mission Peak section are shown on Figure 20. The plot shows that the lower part of the upper Briones Formation at Mission Peak is composed mostly of Sierran detritus with some admixed Coast Range detritus. Coast Range detritus becomes dominant near the contact with the overlying Orinda Formation.

Maguire Peaks Section

Relative proportions of Sierran (FLv) versus Coast Range (QpLsm) detritus for the Maguire Peaks section are shown on Figure 21. The plot shows that the lower and middle Briones Formation at Maguire Peaks contain much more Sierran detritus than Coast Range detritus. Proportions of Sierran and Coast Range sediment remain fairly constant in the Maguire Peaks samples.

Figure 20. Relative percentages of QpLsm and FLv grains in samples from Mission Peak section. Relative percentages are as proportions of total Qp+F+Ls+Lm+Lv only; Qm is not included. QpLsm grains represent Coast Range sources, and FLv grains represent Sierran sources.

Figure 21. Relative percentages of QpLsm and FLv grains in samples from Maguire Peaks section. Relative percentages are as proportions of total Qp+F+Ls+Lm+Lv only; Qm is not included. QpLsm grains represent Coast Range sources, and FLv grains represent Sierran sources.

Welch Creek Section

Relative proportions of Sierran (FLv) and Coast Range (QpLsm) detritus in the Welch Creek section are shown on Figure 22. The plot shows that the lowermost Briones Formation contains beds composed almost entirely of Coast Range detritus, and others composed almost entirely of Sierran detritus. Middle Briones samples are composed of mixed Sierran and Coast Range detritus in varying proportions. Sandstone of Coast Range origin in the lower Briones Formation at Welch Creek contains abundant greenstone and graywacke with lesser amounts of chert.

Apperson Ridge Section

Relative proportions of Sierran (FLv) and Coast Range (QpLsm) detritus for the lower Briones at Apperson Ridge are shown on Figure 23. The plot shows a distinctive interfingering of beds composed primarily of Sierran detritus with beds composed almost entirely of Coast Range detritus. There is little or no mixing of sediment from the two provenances within a given bed.

Figure 22. Relative percentages of QpLsm and FLv grains in samples from Welch Creek section. Relative percentages are as proportions of total Qp+F+Ls+Lm+Lv only; Qm is not included. QpLsm grains represent Coast Range sources, and FLv grains represent Sierran sources.

Figure 23. Relative percentages of QpLsm and FLv grains in samples from Apperson Ridge section. Relative percentages are as proportions of total Qp+F+Ls+Lm+Lv only; Qm is not included. QpLsm grains represent Coast Range sources, and FLv grains represent Sierran sources.

Interfingering of beds derived almost entirely from either Sierran or Coast Range sources may have been a product of depositional setting. Red beds and fossil mollusks and barnacles suggest that the lower Briones east of the Calaveras fault, where the Apperson Ridge section is located, was deposited in shallow-marine, rocky-marine and nonmarine environments. Intervals dominated by sand-sized grains and containing marine fossils contain mostly Sierran detritus, whereas coarser-grained intervals with nonmarine features (reddish color and fossil wood) contain mostly Coast Range detritus. Thus, the Sierra appears to have contributed most of the sand in the inner-shelf marine environment, and the Coast Range appears to have supplied most of the sediment in the nonmarine environment. The lack of Sierran detritus in the coarse-grained, nonmarine intervals suggests that Sierran sediment was transported into the area by long-shore transport in the marine environment, rather than by streams within the Coast Ranges.

Sandstone derived from the Coast Ranges changes in composition upsection at Apperson Ridge. Samples from

lower in the section contain mostly metamorphic grains, including serpentinite, whereas samples from higher in the section contain mostly sedimentary grains, including graywacke and shale.

Metamorphic and sedimentary clasts in the Apperson Ridge section probably were derived from Franciscan Complex rocks exposed nearby in the central core of the Diablo Range, here referred to as the "Mt. Hamilton block". The Mt. Hamilton block contains most rock types typical of the Franciscan Complex, such as serpentinite, greenstone, chert, graywacke, shale, and blueschist. Fragments of all of these rock types are present as sand grains and pebbles in the lower Briones at Apperson Ridge and Welch Creek.

The lower Briones at Apperson Ridge and Welch Creek also contains beds dominated by greenstone and graywacke, with little admixing of other rock types, suggesting a nearby source. The Mt. Hamilton block is the closest source of these rock types, and it is inferred to be the main source of Coast Range detritus in the Briones Formation in the study area.

Provenance Summary

The provenance of the Briones Formation in the study area is interpreted as follows:

- (1) Briones Formation sandstone contains grains from both the Sierran arc and Coast Ranges.
- (2) Lower Briones sandstone in the eastern part of the study area at Welch Creek and Apperson Ridge shows distinctive interfingering of beds composed of either Sierran or Coast Range detritus, with little mixing of Sierran and Coast Range detritus. Lower Briones sandstone in the western part of the study area is composed mainly of Sierran detritus.
- (3) Middle and upper Briones sandstones are composed primarily of Sierran-derived sediment mixed with a smaller amount of Coast Range-derived sediment.
- (4) Uppermost Briones sandstone at Mission Peak shows an increase in the amount of sediment from the Coast Range provenance.
- (5) The mixed provenance of the Briones Formation indicates that, during the late Miocene, Coast Range

uplands were contributing sediment to shallow-marine basins of central California, but were not a barrier to transport of sediment from the Sierran arc (Fig. 24).

- (6) The higher proportion of Sierran-derived sediment indicates that most of the Briones in the study area is closer compositionally to the Neroly Formation than to the Orinda Formation.
- (7) Coast Range detritus in the lower Briones east of the Calaveras fault probably was derived from the Mt. Hamilton block, east and south of the study area.

Figure 24. Diagram showing paleogeographic location of Briones adjacent to upland Coast Range blocks, and west of Sierran-derived Neroly Formation.

DISCUSSION

Late Miocene depositional setting and provenance of the Briones Formation in the southwestern Livermore basin and the west side of the central Diablo Range is summarized below:

- (1) About 10 to 9 Ma, shallow-marine sandstones of the Briones Formation were deposited on uplifted Monterey Formation and on an erosional surface cut into Franciscan Complex and Great Valley Group rocks.
- (2) Subsidence allowed accumulation of up to 1,500 m of shallow-marine Briones sediment (Crittenden, 1951; Hall, 1958).
- (3) The Sierran arc, and to a lesser degree the Franciscan Complex core of the Mt. Hamilton block, were the major sources of Briones sediment.
- (4) During the late Miocene, shallow-marine sedimentation, as represented by the Briones Formation, was replaced by fluvial sedimentation, as represented by the overlying Orinda Formation.

Fluvial sediments of the Orinda Formation were derived from Coast Range sources (Graham and others, 1984).

- (5) During deposition of the Briones Formation, part of the Mt. Hamilton block probably remained an upland, supplying sediment to late-Miocene basins, but it was not a barrier to westward transport of Sierran arc sediment.

The late Miocene geologic history of the southwestern Livermore basin and west-central Diablo Range is likely the result of change from a convergent to transform tectonic setting (Graham and others, 1984). Upper Miocene stratigraphy and provenance show that during the change from convergent to transform tectonics, the southwestern Livermore basin and western flank of the central Diablo Range were modified by widespread uplift, followed by development of a subsiding basin with nearby Coast Range uplands. Subsidence of late Miocene basins is consistent with extension east of the Mendocino Triple Junction (MTJ), as predicted by Dickinson and Snyder (1979).

Marine sedimentation of mainly Sierran detritus, as represented by the Briones Formation, was followed by fluvial sedimentation of mainly Coast Range detritus.

The late Miocene sedimentary history of the study area generally is similar to the late Miocene history of the Contra Costa basin as described by Graham and others (1984). In both areas, upper Miocene sediment was deposited on deformed Mesozoic through middle Miocene rocks. The shallow-marine Briones Formation, composed of mixed Sierran and Coast Range sediment, is present in both areas. Nonmarine, Coast Range-derived sediment replaces mixed-provenance sediment up section in both areas.

The provenance of the Briones Formation in the two areas differs in some important ways. The Briones in the study area generally is closer genetically to the Sierran arc-derived Neroly Formation, rather than to the Coast Range-derived Orinda Formation in the Contra Costa basin, as asserted by Graham and others (1984). Additionally, Franciscan sediment was supplied to the two areas from different sources. The Mt. Hamilton block supplied Franciscan sediment to the Briones of the study area,

whereas the Bay block was the source of Franciscan sediment in the Briones of the Contra Costa basin.

The sources of Briones sediment in the study area suggest that the Bay block upland did not extend southward to the study area. Graham and others (1984) asserted that the Bay block was a large, regional upland (present between 12 and 8 Ma) located to the west of the Hayward fault trend in the present location of San Francisco Bay, and that it shed Franciscan sediment eastward to the Orinda and Briones deposystems. Briones sandstones located near the Hayward fault in the study area, however, do not contain the large quantities of sediment derived from the Franciscan Complex observed by Graham and others (1984) in some Briones sandstones of the Contra Costa basin. The abundance of Sierran detritus, with lesser amounts of admixed Franciscan sediment, in Briones sections close to the Hayward fault and inferred Bay block suggests that the Bay block upland did not extend southward to the study area.

Much research remains to be done on the late Miocene through early Pliocene deposits of the west-central Diablo Range. If the Orinda and Briones formations in the Contra Costa basin are the result of localized uplift, then the Briones and Orinda formations to the south may contain a clearer record of uplift along the Hayward fault trend than those formations in the better studied Contra Costa basin to the north.

CONCLUSIONS

This study shows that the Briones and related formations in the southwestern Livermore basin and west-central Diablo Range contain important information about tectonism and sedimentation in the central Coast Ranges during the late Miocene. Major findings of this study of the Briones Formation in the west-central Diablo Range are as follows:

- (1) The Briones in the study area is composed mostly of sediment derived from the Sierran arc, with lesser amounts of sediment from the Coast Ranges.
- (2) The Briones in the study area generally is closer in composition to the Neroly Formation than to the Orinda Formation.
- (3) Part of the Mt. Hamilton block probably remained an upland during the late Miocene and supplied Franciscan sediment to the southwest Livermore basin and western Diablo Range area.

- (4) Coast Range uplands did not form a barrier to transport of Sierran sediment to the western side of the present Diablo Range.
- (5) Age dating of volcanic ash from marine units in the lower Briones indicates that the southwestern San Pablo embayment began subsiding by about 9 Ma.
- (7) Uplift of the Bay block (a source of Franciscan sediment) between 12 and 8 Ma appears to have been localized in the north, based on the relative paucity of Franciscan-type grains in the Briones Formation.

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APPENDIX A. DESCRIPTIONS OF SECTIONS AND SAMPLE LOCATIONS

Calaveras Road Section

Section-location Description

Briones Formation is exposed in road cuts and outcrops on the north side of Calaveras Road west of intersection with Downing Road and 1.5 km east of Milpitas in Santa Clara County (Fig. 25).

Briones Formation sandstone is in contact with Hambre Formation shale and sandstone at this location. The contact between the two formations appears to be a fault. Beds at the contact are fractured and have very different dip angles. In this study, the base of the Briones Formation is placed at the lowermost bioclastic-sandstone bed.

Orinda Formation conglomerate overlies Briones Formation sandstone at the top of the Calaveras Road section. The contact is not exposed and the nature of the contact is uncertain.

Sample-location Descriptions

Sample locations are described in the following format: Sample Number: Date collected. Formation. Location.

▲ Sample Locations

Figure 25. Map of sample locations at Calaveras Road.

237-1C: 5-8-89. Hambre Formation (Monterey Group) sandstone. Collected from Calaveras Road cut 0.5 km west of intersection with Downing Road. Sample from bed 2 m stratigraphically above distinctive sole-marked sandstone.

237-2: 5-8-89. Briones Formation sandstone. Collected from lowermost fossiliferous (bivalves) bed approximately 125 m east of 237-1C at Calaveras Road cut.

237-4: 5-8-89. Briones Formation sandstone. Collected from fossiliferous bed 6 m stratigraphically above 237-2. Bed contains barnacles and isolated chert pebbles.

237-6: 5-8-89. Briones Formation sandstone. Collected from bed approximately 10 m stratigraphically above 237-4. Discontinuous cross bedding (10 cm thick) occurs in sandstone 7 m east of 237-6.

237-10: 5-8-89. Briones Formation sandstone. Collected from fossiliferous bed approximately 27 m stratigraphically above 237-6.

237-11: 5-8-89. Briones Formation sandstone. Collected from fossiliferous bed approximately 3 m stratigraphically above 237-10. Isolated aphanitic pebbles.

237-12: 5-8-89. Briones Formation sandstone. Collected from fossiliferous bed approximately 9 m stratigraphically above 237-11.

237-13: 5-8-89. Briones Formation sandstone.
Collected from fossiliferous bed approximately 15 m
stratigraphically above 237-12.

237-20: 5-8-89. Briones Formation sandstone.
Collected from Calaveras Road cut 30 m southwest of
intersection with Downing Road.

237-22: 5-8-89. Briones Formation sandstone.
Collected from fossiliferous bed at intersection of
Calaveras Road and Downing Road.

MP-2: 7-14-89. Orinda Formation sandstone.
Collected from sandstone outcrops on lower slopes of
Monument Peak, located 2 km north of Calaveras Road
section.

Mission Peak Area Samples

Section-location Description

Upper Briones Formation sandstone, and Orinda
Formation sandstone and conglomerate are exposed in
outcrops on the slopes of Mission Peak northeast of
Milpitas in Alameda County (Fig. 26). Samples MISP-6
through MISP-8 are from upper Briones Formation sandstones
that crop out on the northwest trending ridge of Mission
Peak. The contact between the Briones Formation and the
Orinda Formation is exposed in outcrop immediately west of

U.S.G.S. topographic map, Milpitas, 7.5 min.

▲ Sample Locations

Figure 26. Map of sample locations at Mission Peak.

Mission Peak summit. The area is accessed by the Warm Springs trailhead at Stanford Avenue in Fremont.

Sample-location Descriptions

Sample locations are described in the following format: Sample Number: Date collected. Formation. Location.

MISP-6: 11-1-89. Briones Formation sandstone. Collected from approximately 1 km N65W from the summit of Mission Peak and 30 m up slope from a spring.

MISP-7: 11-1-89. Briones Formation sandstone. Collected 10 m stratigraphically above MISP-6.

MISP-8: 11-1-89. Briones Formation sandstone. Collected 20 m stratigraphically above MISP-7.

MISP-10: 11-1-89. Briones Formation sandstone. Samples MISP-10 and MISP-9 are collected from vertical dipping Briones sandstone beds located 0.25 km west of Mission Peak. MISP-10 collected from sandstone bed 2 m stratigraphically below contact with overlying Orinda Formation.

MISP-9: 11-1-89. Briones Formation sandstone. Collected from topmost gray-colored Briones sandstone bed (2 m above MISP-10) at contact with overlying red and green colored Orinda shale and sandstone. Contact is at change in slope where cliff-forming Briones sandstone

gives way to gentler slopes underlain by Orinda shale and siltstone.

MISP-15: 11-1-89. Orinda Formation sandstone. Collected from sandstone outcrops on lower slopes of Mission Peak (Fig. 26).

MISP-16: 11-1-89. Orinda Formation sandstone. Collected from sandstone outcrops on lower slopes of Mission Peak (Fig. 26).

Maguire Peaks Section

Section-location Description

Outcrops of lower through middle Briones Formation occur in the Maguire Peaks area approximately 7 km southeast of Sunol (Fig. 27). Bioclastic-sandstone beds of the middle Briones form well-exposed outcrops near the summits of Maguire Peaks. The lower Briones occurs south and east of Maguire Peaks, and the middle and possibly upper Briones occur on the ridge extending northwest from Maguire Peaks.

Sample-location Descriptions

Sample locations are described in the following format: Sample Number: Date collected. Formation. Location.

MGP-14 (A,C): 9-1-89. Lower Briones Formation tephra. Multiple tephra beds occur in road cut

U.S.G.S. topographic map, La Costa Valley, 7.5 min.

▲ Sample Locations

Figure 27. Map of sample locations at Maguire Peaks, Welch Creek, and Apperson Ridge.

approximately 0.75 km south of east Maguire Peaks. Tephra beds are 0.2 m to 1 m thick, with total thickness of tephra-bearing interval approximately 4 m. Tephra unit is lighter color than surrounding sandstone.

MGP-20: 9-1-89. Lower Briones sandstone. Collected from road bed, and estimated to be 15 m stratigraphically above MGP-14.

MGP-22: 11-14-89. Middle Briones sandstone. Collected from blue-colored sandstone underneath cliff-forming sandstone on southeast ridge of Maguire Peaks.

MGP-23: 11-14-89. Middle Briones sandstone. Collected from fossiliferous (bivalve) sandstone bed at summit of west Maguire Peaks.

MGP-26: 11-14-89. Middle Briones sandstone. Collected from blue-colored sandstone on northwest ridge of Maguire Peaks.

MGP-16: 9-1-89. Middle Briones Formation tephra. Tephra bed collected from road cut approximately 0.5 km northwest of Maguire Peaks. Tephra is approximately 5 m stratigraphically below resistant fossiliferous bed at hairpin turn in road. Tephra bed approximately 0.5 m thick. Tephra unit is lighter color than surrounding sandstones.

MGP-27: 11-14-89. Middle Briones sandstone. Collected from fossiliferous (bivalve) sandstone bed at hairpin turn of road on northwest ridge of Maguire Peaks.

Welch Creek Section

Section-location Description

Samples collected from lower through middle Briones Formation outcrops in the Welch Creek drainage of Sunol Regional Park (Fig. 27). Access to the area is by Welch Creek Road, which intersects Calaveras Road approximately 8 km south of Sunol.

Sample-location Descriptions

Sample locations are described in the following format: Sample Number: Date collected. Formation. Location.

WCR-15: 8-19-89. Lower Briones sandstone. Collected from outcrop in bed of Welch Creek 2.6 km east of Calaveras Road intersection. Contact (erosional) between Briones Formation and underlying Franciscan sandstone is exposed at this location. A conglomerate bed approximately 0.3 m thick, composed of Franciscan sandstone and greenstone clasts is the lowermost bed of the Briones Formation. Sample was collected from a discontinuous, fossiliferous (bivalves) sandstone 0.5 m above the base.

WCR-8: 8-19-89. Lower Briones sandstone. Collected from Welch Creek Road cut, approximately 4 km east of intersection with Calaveras Road.

VGTR-11: 8-17-89. Lower Briones sandstone.
Collected from road cut at top of Vista Grande Ridge
between Welch Creek and Indian Joe Creek.

VGTR-10: 8-17-89. Lower Briones sandstone.
Collected from road cut at top of Vista Grande Ridge
between Welch Creek and Indian Joe Creek.

VGTR-4: 8-17-89. Lower Briones sandstone.
Collected from road cut at top of Vista Grande Ridge
between Welch Creek and Indian Joe Creek. Contact
(erosional) between Briones Formation and Franciscan
Complex occurs along this ridge. Sample from
approximately 10 m above basal conglomerate. Basal
conglomerate has wide variety of rock types.

WCR-14: 8-19-89. Lower Briones sandstone.
Collected from outcrops adjacent to Maguire Peaks trail,
approximately 0.1 km north of Welch Creek.

WCR-13: 8-19-89. Lower Briones sandstone.
Collected from outcrop in bed of Welch Creek, 60 m
upstream from junction of Welch Creek Road and Valley
Ranch Road.

WCR-2: 8-3-89. Middle Briones sandstone. Collected
from lowermost sandstone of Middle Briones 0.75 km east of
Welch Creek Road intersection with Calaveras Road.
Sandstone contains bivalve fossils.

WCR-17: 8-19-89. Middle Briones sandstone.

Collected from creek bed approximately 0.6 km east of Calaveras Road intersection. Collected from base of lowermost cliff-forming-sandstone unit of Middle Briones Formation.

Apperson Ridge Section

Section-location Description

Lower Briones sandstones and contact with underlying Franciscan Complex are well exposed on the western flank of Apperson Ridge, located immediately east of Maguire Peaks (Fig. 27). Section sampled is located 0.5 km, N50E of east Maguire Peaks.

Sample-location Descriptions

Sample locations are described in the following format: Sample Number: Date collected. Formation. Location.

AR-12: 11-20-89. Lower Briones sandstone.

Collected from fossiliferous (bivalves) sandstone approximately 3 m above the base of the Briones. The base of the Briones is exposed in a road cut about midway up the ridge. The lowermost Briones bed is a conglomerate composed of shale, greenstone, and sandstone clasts, deposited on an erosional surface of Franciscan Complex shale.

AR-11: 11-20-89. Lower Briones sandstone. Collected from sandstone approximately 2 m stratigraphically above AR-12 and about 5 m above the base of the Briones.

AR-10: 11-20-89. Lower Briones sandstone. Collected from sandstone approximately 2 m stratigraphically above AR-11. Sandstone overlies a conglomerate with abundant greenstone clasts.

AR-9: 11-20-89. Lower Briones sandstone. Collected from blue-colored sandstone approximately 20 m stratigraphically above AR-10.

AR-7: 11-20-89. Lower Briones sandstone. Collected from sandstone approximately 4 m stratigraphically above AR-9.

AR-5: 11-20-89. Lower Briones sandstone. Collected from sandstone approximately 8 m stratigraphically above AR-7. Nearby conglomerate composed of red chert, quartz, sandstone, and greenstone clasts. Fossils include abundant barnacles.

AR-4: 11-20-89. Lower Briones sandstone. Collected from sandstone approximately 3 m stratigraphically above AR-5.

AR-3: 11-20-89. Lower Briones sandstone. Collected from blue-colored sandstone approximately 3 m stratigraphically above AR-4.

AR-2: 11-20-89. Lower Briones sandstone. Collected from blue-colored sandstone located upslope and approximately 2 m stratigraphically above AR-3.

AR-1: 11-20-89. Lower Briones sandstone. Sample AR-1 is from the top of the stratigraphic section at Apperson Ridge. Collected from outcrop at base of ridge, from sandstone bed overlying conglomerate about 10 m stratigraphically above AR-2. Conglomerate shows inverse grading. Conglomerate composed of the following clasts: black chert (30%), greenstone (20%), quartz (20%), red chert (10%), undetermined (20%).

Neroly Samples

Neroly Formation samples are from the northeast Livermore basin.

TN-WB1: Neroly Formation sandstone. Collected by David Andersen from highest-exposed sandstone south of Shell Ridge in Walnut Creek, 500 m northwest of the white cliff section of Isaacson (1990).

60-B: Neroly Formation sandstone. Collected by Kathleen Isaacson from south flank of Mount Diablo, approximately 1.5 km north of the intersection of Green Valley Road and Blackhawk Road (Isaacson, 1990).

APPENDIX B. BRIONES FORMATION TEPHRA COMPOSITION

Microprobe analysis and tephra matching by Andrei M. Sarna-Wojcicki, USGS, Menlo Park, California.

Component	<u>Briones Samples</u>		<u>USGS Samples</u>			
	<u>MGP-14A</u>	<u>MGP-14C</u>	<u>ALT-2A</u>	<u>ALT-3</u>	<u>ALT-4</u>	<u>DPB-11</u>
	%	%	%	%	%	%
SiO ₂	77.56	77.48	77.89	77.77	77.64	77.90
Al ₂ O ₃	12.70	12.72	12.55	12.68	12.84	12.90
Fe ₂ O ₃	0.68	0.67	0.65	0.63	0.64	0.65
MgO	0.09	0.10	0.08	0.09	0.08	0.09
MnO	0.04	0.05	0.05	0.05	0.05	0.06
CaO	0.54	0.52	0.50	0.51	0.50	0.54
TiO ₂	0.11	0.11	0.10	0.10	0.10	0.09
Na ₂ O	2.98	3.06	3.91	3.87	3.86	3.23
K ₂ O	5.30	5.28	4.27	4.28	4.28	4.53
Total	100.00	99.99	100.00	99.98	99.99	99.99
R Sim. Cff.	0.9891	1.0000	0.9644	0.9647	0.9629	0.9646
Correlation			Best	Best	Best	Poss.
Age, in Ma	ND	ND	9-7	9-7	9-7	11.5-10.8 15.7-11.2

ND = not determined

Microprobe analysis and tephra matching by Andrei M.
Sarna-Wojcicki, USGS, Menlo Park, California.

COMPONENT	Briones Samples	USGS Samples				
	MGP-16	MOD-6	PU-17	1753	BE-28	PU-17
	%	%	%	%	%	%
SiO ₂	76.07	76.26	76.89	76.54	74.73	77.09
Al ₂ O ₃	12.95	12.71	13.31	12.82	13.80	13.55
Fe ₂ O ₃	1.33	1.33	1.27	1.40	1.23	1.31
MgO	0.21	0.20	0.21	0.21	0.21	0.19
MnO	0.03	0.03	0.03	0.04	0.06	0.04
CaO	0.84	0.86	0.85	0.82	0.82	0.84
TiO ₂	0.27	0.27	0.25	0.30	0.28	0.25
Na ₂ O	3.54	3.66	4.1	4.28	1.87	3.2
K ₂ O	4.77	4.67	3.08	3.57	7.02	3.53
Total	100.01	99.99	99.99	99.98	100.02	100.00
R Sim. Cff.	1.0000	0.9847	0.9719	0.9683	0.9643	0.9597
Correlation		BEST	FAIR	FAIR	FAIR	FAIR
Age, in Ma	ND	7	NA	NA	NA	NA

ND = not determined

APPENDIX C.
THIN-SECTION PETROGRAPHIC DESCRIPTIONS AND OBSERVATIONS

Format of Descriptions and Observations

Sample Number: Wentworth grain-size class, sorting (Folk, 1980), roundness scale of Powers (Folk, 1980), sphericity of Powers (Folk, 1980). Observations.

Calaveras Road-cut and Vicinity Samples

237-1C: Medium sand, moderately sorted, angular, moderate sphericity. Sample well cemented.

237-2: Coarse sand, moderately sorted, subangular, moderate sphericity. Some alteration loss of Lv grains. Some Lv grains have quartz or altered feldspar phenocrysts. Some rare greenstone (?) clasts.

237-4: Coarse to very coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. Common fossil. Some Lv grains are almost completely replaced by calcite. Replaced but recognizable Lv grains are counted in Lv category.

237-6: Medium sand, moderately sorted, angular, moderate sphericity. Some monocrystalline quartz (Qm) contains opaque inclusions. Altered sample. Many unstable grains are altered to matrix. Most feldspars are altered beyond recognition. Much of the polycrystalline

quartz (Qp) is cloudy with inclusions and appears to be a product of vein filling and replacement of feldspars.

237-10: Medium to coarse sand, poorly sorted, subangular to angular, low to moderate sphericity. Very abundant fossils. Rare greenstone (?) grains. Some alteration of unstable framework grains (feldspars and Lv) to clay matrix and calcite cement.

237-11: Medium to coarse, moderately sorted, subrounded to angular, low to moderate sphericity. Some Qm grains have rutile needles and others are cloudy with inclusions. Qm may contain some unidentified feldspars. Much of the plagioclase is likely derived from alteration of Lv groundmass surrounding plagioclase phenocrysts. Contains fossils.

237-12: Medium to coarse sand, moderately sorted, angular to very angular, low to moderate sphericity. Contains fossils.

237-13: Coarse to very coarse sand, moderately sorted, angular, low to moderate sphericity. Contains fossils and wood fragments.

237-20: Medium sand, moderately sorted, subrounded to angular, low to moderate sphericity. Some Qm grains with bubbles and opaque inclusions.

237-22: Coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. Contains fossils

and phosphatic grains. Some rare Qm grains are very well rounded, and possibly reworked.

MP-2: Coarse sand, poorly sorted, sub-rounded to angular, moderate sphericity.

Mission Peak Area Samples

MISP-6: Coarse sand, poorly to moderately sorted, subrounded to angular, low to moderate sphericity.

MISP-7: Medium sand, moderately sorted, subrounded to angular, low to moderate sphericity.

MISP-8: Medium sand, moderately sorted, subrounded to angular, low to moderate sphericity. Many hypabyssal grains (little or no fine groundmass) in Lv category.

MISP-10: Medium sand, moderately sorted, subrounded to angular, low to moderate sphericity. Some "chert" grains may be of volcanic origin. The undetermined feldspar category contains many altered and pitted feldspars. The large number of Qm grains counted may contain some feldspars.

MISP-9: Medium sand, moderately sorted, subrounded to angular, low to moderate sphericity. Some rare Qm are very well rounded and spherical, suggesting reworking.

MISP-15: Coarse to very coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. Volcanic (Lv) grains are altered. Lv grains typically

have very little groundmass and may be hypabyssal. Much of Lv may be from Franciscan Complex or reworked.

MISP-16: Medium to coarse sand, moderately sorted, subrounded to angular, low sphericity.

Maguire Peaks Samples

MGP-20: Medium to coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. Some Qm is shattered by post depositional stress, and can be mistaken for Qp. Zeolites. Many of the Lv grains contain iron-bearing accessory minerals.

MGP-22: Medium to coarse sand, moderately sorted, subangular to angular, low to moderate sphericity. Sample contains numerous volcanic glass fragments (counted as Lv).

MGP-23: Medium sand, well sorted, subangular to angular, low to moderate sphericity. Sample has numerous fossils and much calcite cement, which may indicate alteration loss of some unstable framework grains.

MGP-26: Medium sand, moderately sorted, subangular to angular, low to moderate sphericity.

MGP-27: Medium to coarse sand; moderately sorted, subrounded to angular, low to moderate sphericity. Calcite cement has crystallized in optical continuity. Lv grains commonly have pyrite cubes as accessory mineral.

Welch Creek Area Samples

WCR-15: Medium to very coarse sand, poorly sorted, rounded to subangular, low to moderate sphericity. Bimodal grain size; very coarse sand (Qm, Qp, lithics), and medium sand (all types). Much of Qm contains vacuoles, also rarely with clay vermiculites. Rare granitic (?) grains.

WCR-8: Very coarse sand, poorly to moderately sorted, lithic grains are rounded to subrounded, quartz and feldspar angular, moderate sphericity.

VGTR-11: Coarse to very coarse sand, moderately sorted, subrounded to angular, moderate sphericity. Fossils.

VGTR-10: Coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. Quartz and feldspar grains are shattered with the fractures partly filled by calcite. Lv is distinguished from greenstone (Lmg) by the higher degree of alteration shown in the Lmg feldspars. A large granitic fragment is present in this sample.

VGTR-4: Coarse to very coarse sand, moderately sorted, subrounded to angular, moderate sphericity. Alteration of this sample appears to have followed this sequence: (1) coating of grains with yellow-colored (plain light) clay; (2) coating of grains with blue-gray-

colored (plain light) clay; (3) formation of blocky zeolite, also more rarely an acicular zeolite. The zeolites appear to have filled the last of the pore spaces and in some places replaced Lv grains.

WCR-14: Very coarse sand to granule, poorly sorted, subrounded to angular, moderate sphericity. This sample appears to be derived from Franciscan Complex, but is different from the upper Welch Creek samples. Sample contains a grain of foliated Qp with blue amphibole.

WCR-13: Coarse to very coarse sand, poorly sorted, subrounded to subangular, moderate sphericity.

WCR-2: Coarse sand, moderately sorted, rounded to angular, low to medium sphericity. Lithic grains show greatest rounding and quartz and feldspar the least. Qm is a mixture of quartz with rutile and quartz with opaque inclusions. Some of the Lv in this sample is altered to clay. Altered Lv are still distinguishable from the pervasively altered and chloritized greenstone. Greenstone grains typically have crescent shaped alteration structures. Fossils.

WCR-17: Medium sand, well sorted, subrounded to angular, moderate sphericity. Qm may contain some unidentified feldspars. Common myrmekitic feldspar in this sample.

Apperson Ridge Samples

AR-12: Fine to medium sand, moderately sorted, subrounded to angular (most grains are angular), moderate sphericity. Fossils.

AR-11: Coarse sand, poorly sorted, rounded to angular, low to moderate sphericity. Greenstone grains are counted in Lm if foliation is strong. Fossils.

AR-10: Coarse sand to granule, poorly sorted, subrounded to angular, low to moderate sphericity. Pore-filling zeolites. Greenstone fragments (Lmg) are most common grain type.

AR-9: Fine to medium sand, poorly to moderately sorted, subrounded to angular, low to moderate sphericity. Pore-filling zeolites and hematite.

AR-7: Coarse sand, poorly sorted, sub-rounded to subangular, low to moderate sphericity. Pore-filling/ cementation sequence: (1) zeolites (?) form on surface of grains; (2) calcite; (3) hematite.

AR-5: Coarse sand, poorly to moderately sorted, sub-rounded to angular (most grains subangular), low to moderate sphericity. Sedimentary-rock fragments (very fine-grained sandstone and siltstone) are most common clast type. Hematite and zeolites.

AR-4: Medium sand, moderately sorted, subrounded to angular, low to moderate sphericity.

AR-3: Medium to coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. Hematite cement.

AR-2: Medium to coarse sand, moderately sorted, subrounded to angular, low to moderate sphericity. The Lv grains are more basaltic than higher in the section.

AR-1: Very coarse sand to granule, poorly sorted, subrounded to angular, low to moderate sphericity. This sample shows that much of the Qp (>4) comes from metamorphic Ls and other Franciscan-Complex lithotypes. The cementation sequence shown in AR-1 is as follows:

- (1) dolomite (?) rhombs form on surface of grains;
- (2) multiple layers of clay (montmorillonite ?) coats grains and dolomite, partly filling pore spaces;
- (3) sparry calcite fills remaining pore spaces.

APPENDIX D. THIN-SECTION POINT COUNTS

Calaveras Road samples, Monterey Group and Briones Formation

Grains	Monterey	Sample Location - Briones				
	237-1C	237-2	237-4	237-6	237-10	237-11
		(number of grains counted)				
Qm Monocrystalline Quartz	87	85	73	56	66	64
Qp Poly. Quartz (2-4 crystals)	25	15	15	44	10	11
Qp Poly. Quartz (>4 crystals)	21	20	22	46	29	9
Fp Plagioclase	21	18	14	8	25	20
Fk K-Feldspar	1	2	4	2	3	1
Fu Feldspar, type undetermined	27	20	18	25	28	28
Lsu Sedimentary	5	10	4	4	6	6
Lsc Chert	5	6	17	10	5	7
Lvu Volcanic and Silicified Vol.	97	105	118	91	115	128
Lva Andesitic	-	6	3	1	2	6
Lvb Basaltic	1	6	2	-	-	5
Lmu Metamorphic	8	1	5	10	5	12
Lmg Greenstone	2	6	4	3	6	4
Lmc Metachert	-	-	1	-	-	-
Lg Granitic	-	1	-	-	-	2
TOTAL QFL	300	301	300	300	300	303
Hornblende	1	8	3	5	8	10
Mica	1	2	-	-	-	-
Olivine	-	4	-	-	1	2
Unknown	-	-	3	5	5	5
Matrix and Cement						
Matrix (Clay and Silt)	NC	4	23	104	20	6
Calcite	NC	NC	173	-	232	153
Zeolite	NC	-	-	3	-	-
Fossils	NC	A	A	-	A	A
Phosphatic clasts	NC	-	2	-	1	-
Pores	NC	-	-	-	-	-

NC = not counted; A = abundant

Calaveras Road samples, Briones Formation and Orinda Formation

Grains	Sample Location - Briones				Orinda
	237-12	237-13	237-20	237-22	MP-2
	(number of grains counted)				
Qm Monocrystalline Quartz	82	71	72	118	41
Qp Poly. Quartz (2-4 crystals)	8	12	40	22	24
Qp Poly. Quartz (>4 crystals)	11	15	44	29	96
Fp Plagioclase	16	32	20	20	5
Fk K-Feldspar	1	-	2	3	1
Fu Feldspar, type undetermined	29	39	27	13	5
Lsu Sedimentary	9	4	5	6	23
Lsc Chert	14	9	8	16	28
Lvu Volcanic and silicified Vol.	118	109	75	64	6
Lva Andesitic	3	-	-	-	-
Lvb Basaltic	1	1	-	-	-
Lmu Metamorphic	7	3	7	4	51
Lmg Greenstone	1	5	-	5	13
Lmc Metachert	-	1	-	1	7
Lg Granitic	2	2	1	-	1
TOTAL QFL	302	303	301	301	301
Hornblende	6	4	-	2	-
Mica	-	-	-	-	-
Glaucophane	-	-	-	-	-
Olivine	1	-	-	-	-
Unknown	1	3	3	6	1
Matrix and Cement					
Matrix (Clay and Silt)	NC	5	135	26	3
Calcite	NC	232	-	188	-
Zeolite	NC	-	13	-	-
Glaucinite	NC	-	-	-	-
Fossils	A	A	A	-	-
Phosphatic clasts	NC	-	2	-	-
Pores	-	-	-	-	-

NC = not counted; A = abundant

Mission Peak samples, Briones Formation

Grains		Sample Location				
		MISP-6	MISP-7	MISP-8	MISP-10	MISP-9
		(number of grains counted)				
Qm	Monocrystalline Quartz	86	100	90	105	109
Qp	Poly. Quartz (2-4 crystals)	10	10	18	38	27
Qp	Poly. Quartz (>4 crystals)	28	16	24	36	39
Fp	Plagioclase	23	33	24	44	30
Fk	K-Feldspar	2	-	2	3	2
Fu	Feldspar, type undetermined	49	50	40	29	36
Lsu	Sedimentary	5	4	3	2	1
Lsc	Chert	31	7	19	22	34
Lvu	Volcanic and silicified Vol.	57	73	66	18	11
Lva	Andesitic	-	4	-	-	-
Lvb	Basaltic	-	-	-	-	-
Lmu	Metamorphic	4	-	2	3	5
Lmg	Greenstone	5	3	12	-	6
Lmc	Metachert	-	-	-	-	-
Lg	Granitic	3	-	1	3	1
TOTAL QFL		303	300	301	303	301
Hornblende		5	3	5	-	-
Mica		-	-	-	-	-
Glaucophane		-	-	-	-	-
Olivine		-	2	1	-	-
Unknown		4	1	2	-	-
Matrix and Cement						
Matrix (Clay and Silt)		16	15	12	85	105
Calcite		170	165	168	-	25
Zeolite		-	-	-	-	-
Glaucinite		-	-	-	-	-
Fossils		A	-	-	-	-
Phosphatic clasts		-	-	2	-	-
Pores		-	-	-	-	-

A = abundant

Maguire Peaks samples, Briones Formation

Grains		Sample Location				
		MGP-20	MGP-22	MGP-23	MGP-26	MGP-27
		(number of grains counted)				
Qm	Monocrystalline Quartz	94	37	93	75	120
Qp	Poly. Quartz (2-4 crystals)	3	3	19	9	6
Qp	Poly. Quartz (>4 crystals)	18	13	19	14	16
Fp	Plagioclase	36	18	36	24	13
Fk	K-Feldspar	2	3	3	-	4
Fu	Feldspar, type undetermined	32	37	33	51	39
Lsu	Sedimentary	2	5	9	4	5
Lsc	Chert	13	9	10	7	21
Lvu	Volcanic and silicified Vol.	81	152	71	107	69
Lva	Andesitic	-	20	2	2	3
Lvb	Basaltic	-	1	-	1	-
Lmu	Metamorphic	8	-	2	6	4
Lmg	Greenstone	-	2	3	2	-
Lmc	Metachert	1	-	-	-	-
Lg	Granitic	-	1	-	-	-
TOTAL QFL		290	301	300	302	300
	Hornblende	3	5	3	7	7
	Mica	-	4	-	1	1
	Glaucophane	-	-	-	-	-
	Olivine	-	1	3	1	1
	Augite	-	-	-	-	-
	Unknown	-	-	9	2	3
Matrix and Cement						
	Matrix (Clay and Silt)	103	38	9	24	5
	Calcite	-	-	230	173	142
	Hematite	3	-	-	-	-
	Zeolite	8	1	-	-	-
	Glauconite	-	-	-	-	-
	Fossils	-	-	A	-	A
	Phosphatic clasts	-	-	-	-	-
Pores		22	27	4	-	3

A = abundant

Welch Creek samples, Briones Formation

Grains	Sample Location				
	WCR-15	WCR-8	VGTR-11	VGTR-10	VGTR-4
	(number of grains counted)				
Qm Monocrystalline Quartz	65	11	15	17	24
Qp Poly. Quartz (2-4 crystals)	20	3	9	3	4
Qp Poly. Quartz (>4 crystals)	27	16	51	22	12
Fp Plagioclase	14	3	6	75	10
Fk K-Feldspar	2	-	1	4	1
Fu Feldspar, type undetermined	22	3	8	30	6
Lsu Sedimentary	10	6	115	5	7
Lsc Chert	18	7	20	19	17
Lvu Volcanic and silicified Vol.	3	-	5	56	177
Lva Andesitic	-	-	-	33	9
Lvb Basaltic	-	-	-	1	2
Lmu Metamorphic	28	27	2	15	12
Lmg Greenstone	90	217	42	17	18
Lmc Metachert	1	10	2	3	1
Lg Granitic	-	-	-	-	1
TOTAL QFL	300	303	276	300	301
Hornblende	1	-	3	8	4
Mica	-	-	-	-	-
Glaucophane	-	-	-	-	-
Olivine	-	-	-	-	-
Augite	-	-	-	-	1
Unknown	4	-	1	-	-
Matrix and Cement					
Matrix (Clay and Silt)	63	40	36	137	63
Calcite	167	85	96	9	-
Hematite	-	-	-	-	-
Zeolite	-	-	1	-	23
Glaucinite	-	-	-	-	-
Fossils	A	-	R	-	A
Phosphatic clasts	-	-	-	-	-
Pores	8	6	2	2	9

A = abundant; R = rare

Welch Creek samples, Briones Formation

Grains		Sample Location			
		WCR-14	WCR-13	WCR-2	WCR-17
Qm	Monocrystalline Quartz	32	46	55	102
Qp	Poly. Quartz (2-4 crystals)	21	23	3	38
Qp	Poly. Quartz (>4 crystals)	159	153	15	34
Fp	Plagioclase	4	6	8	17
Fk	K-Feldspar	-	-	5	2
Fu	Feldspar, type undetermined	4	2	16	15
Lsu	Sedimentary	41	27	9	17
Lsc	Chert	7	22	17	23
Lvu	Volcanic and silicified Vol.	-	-	151	70
Lva	Andesitic	-	-	1	-
Lvb	Basaltic	-	-	1	-
Lmu	Metamorphic	28	10	7	10
Lmg	Greenstone	3	10	14	15
Lmc	Metachert	1	1	-	-
Lg	Granitic	-	-	2	-
TOTAL QFL		300	300	304	343
Hornblende		-	-	3	2
Mica		-	-	-	2
Glaucophane		-	-	-	-
Olivine		-	-	-	-
Augite		-	-	-	-
Unknown		1	1	3	1
Matrix and Cement					
Matrix (Clay and Silt)		67	48	6	14
Calcite		71	70	144	116
Hematite		-	-	-	-
Zeolite		9	-	-	-
Glaucinite		-	-	-	-
Fossils		-	-	-	A
Phosphatic clasts		-	-	-	-
Pores		6	39	1	16

A = abundant

Apperson Ridge samples, Briones Formation

Grains	Sample Location				
	AR-12	AR-11	AR-10	AR-9	AR-7
	(number of grains counted)				
Qm Monocrystalline Quartz	119	4	-	37	4
Qp Poly. Quartz (2-4 crystals)	41	13	4	21	4
Qp Poly. Quartz (>4 crystals)	59	48	32	16	54
Fp Plagioclase	21	-	2	40	4
Fk K-Feldspar	-	-	-	1	-
Fu Feldspar, type undetermined	20	-	-	24	5
Lsu Sedimentary	6	6	3	3	15
Lsc Chert	9	2	5	3	3
Lvu Volcanic and silicified Vol.	8	-	8	150	-
Lva Andesitic	-	-	-	1	-
Lvb Basaltic	-	-	-	-	-
Lmu Metamorphic	11	63	16	1	16
Lmg Greenstone	6	164	230	3	196
Lmc Metachert	-	-	-	-	-
Lg Granitic	-	-	-	-	-
TOTAL QFL	300	300	300	300	301
Hornblende	1	-	2	3	-
Mica	-	-	-	3	-
Glaucophane	-	-	-	-	-
Olivine	-	-	-	-	-
Augite	-	-	-	-	-
Unknown	-	-	-	5	-
Matrix and Cement					
Matrix (Clay and Silt)	14	22	12	31	23
Calcite	110	115	-	-	13
Hematite	-	-	-	8	5
Zeolite	12	4	62	6	59
Glaucinite	-	-	-	-	-
Fossils	A	A	-	-	-
Phosphatic clasts	-	-	-	-	-
Pores	1	1	1	27	6

A = abundant

Apperson Ridge samples, Briones Formation

Grains		Sample Location				
		AR-5	AR-4	AR-3	AR-2	AR-1
		(number of grains counted)				
Qm	Monocrystalline Quartz	7	43	3	3	5
Qp	Poly. Quartz (2-4 crystals)	9	7	1	2	7
Qp	Poly. Quartz (>4 crystals)	127	11	2	4	129
Fp	Plagioclase	-	37	15	18	2
Fk	K-Feldspar	-	1	1	-	-
Fu	Feldspar, type undetermined	2	42	12	8	-
Lsu	Sedimentary	117	-	1	2	133
Lsc	Chert	1	6	2	4	4
Lvu	Volcanic and silicified Vol.	3	125	201	186	-
Lva	Andesitic	-	2	5	5	-
Lvb	Basaltic	-	20	57	60	-
Lmu	Metamorphic	19	2	-	-	5
Lmg	Greenstone	15	4	-	8	16
Lmc	Metachert	-	-	-	-	-
Lg	Granitic	-	-	-	-	-
TOTAL QFL		300	300	300	300	301
Hornblende		-	2	6	2	1
Mica		-	-	-	3	-
Glaucophane		-	-	-	-	-
Olivine		-	4	20	1	-
Augite		-	2	10	4	-
Unknown		-	-	7	1	-
Matrix and Cement						
Matrix (Clay and Silt)		35	8	50	9	55
Calcite		-	202	-	173	68
Hematite		6	1	47	-	-
Zeolite		12	-	-	-	-
Glaucinite		-	-	-	-	-
Fossils		-	-	-	-	-
Phosphatic clasts		-	-	-	-	-
Pores		2	-	36	-	-

Neroly Formation

Grains	Sample Location	
	Tn-WB1	60-B
	(number of grains counted)	
Qm Monocrystalline Quartz	1	1
Qp Poly. Quartz (2-4 crystals)	-	2
Qp Poly. Quartz (>4 crystals)	2	4
Fp Plagioclase	7	13
Fk K-Feldspar	4	-
Fu Feldspar	-	18
Lsu Sedimentary	1	1
Lsc Chert	2	-
Lvu Volcanic and silicified Vol.	154	220
Lva Andesitic	20	15
Lvb Basaltic	5	25
Lmu Metamorphic	-	1
Lmg Greenstone	-	-
Lmc Metachert	-	-
Lg Granitic	-	1
TOTAL QFL	196	301
Hornblende	4	12
Mica	-	-
Glaucophane	-	-
Olivine	1	11
Augite	-	9
Unknown	-	7
Matrix and Cement		
Matrix (Clay and Silt)	23	28
Calcite	4	-
Hematite	-	-
Zeolite	-	-
Glauconite	-	-
Fossils	-	R
Phosphatic	-	-
Pores	8	52

R = rare

Mission Peak samples, Orinda Formation

Grains	Sample Location	
	MISP-15	MISP-16
	(number of grains counted)	
Qm Monocrystalline Quartz	28	51
Qp Poly. Quartz (2-4 crystals)	17	54
Qp Poly. Quartz (>4 crystals)	122	59
Fp Plagioclase	7	18
Fk K-Feldspar	-	-
Fu Feldspar, type undetermined	8	27
Lsu Sedimentary	18	15
Lsc Chert	13	21
Lvu Volcanic and silicified Vol.	29	20
Lva Andesitic	-	-
Lvb Basaltic	-	-
Lmu Metamorphic	45	23
Lmg Greenstone	13	12
Lmc Metachert	-	-
Lg Granitic	-	1
TOTAL QFL	300	301
Hornblende	-	5
Mica	-	-
Glaucophane	-	-
Olivine	-	1
Unknown	-	2
Matrix and Cement		
Matrix (Clay and Silt)	62	88
Calcite	-	1
Zeolite	-	-
Glaucinite	-	-
Fossils	-	-
Phosphatic clasts	-	-
Pores	-	-

APPENDIX E. GROUPED-CATEGORY PERCENTAGES

Calaveras Road samples, Monterey Group and Briones Formation

Grain Categories	Monterey	Sample Location - Briones				
	237-1C	237-2	237-4	237-6	237-10	237-11
QFL						
Number of grains	300	301	300	300	300	303
Percent Q	44%	40%	37%	49%	35%	28%
Percent F	16%	13%	12%	12%	19%	16%
Percent L	40%	47%	51%	39%	46%	56%
Total percent QFL	100%	100%	100%	100%	100%	100%
LmLvLs						
Number of grains	118	140	154	119	139	168
Percent Lm	9%	5%	6%	11%	8%	9%
Percent Lv	83%	84%	80%	77%	84%	83%
Percent Ls	8%	11%	14%	12%	8%	8%
Total percent LmLvLs	100%	100%	100%	100%	100%	100%
QpLsLm						
Number of grains	66	58	68	117	61	49
Percent Qp	70%	60%	54%	77%	64%	41%
Percent Ls	15%	28%	31%	12%	18%	26%
Percent Lm	15%	12%	15%	11%	18%	33%
Total percent QpLsLm	100%	100%	100%	100%	100%	100%
QpLsm+FLv						
Number of grains	213	215	227	244	234	237
Percent QpLsm	31%	27%	30%	48%	26%	21%
Percent FLv	69%	73%	70%	52%	74%	79%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%	100%

Calaveras Road samples, Briones Formation and Orinda Formation

Grain Categories	Sample Location - Brion				Orinda
	237-12	237-13	237-20	237-22	MP-2
QFL					
Number of grains	302	303	301	301	301
Percent Q	34%	33%	52%	56%	53%
Percent F	15%	24%	17%	12%	4%
Percent L	51%	43%	31%	32%	43%
Total percent QFL	100%	100%	100%	100%	100%
LmLvLs					
Number of grains	153	132	95	96	128
Percent Lm	5%	7%	7%	10%	55%
Percent Lv	80%	83%	79%	67%	5%
Percent Ls	15%	10%	14%	23%	40%
Total percent LmLvLs	100%	100%	100%	100%	100%
QpLsLm					
Number of grains	50	49	104	83	242
Percent Qp	38%	56%	81%	61%	50%
Percent Ls	46%	26%	12%	27%	21%
Percent Lm	16%	18%	7%	12%	29%
Total percent QpLsLm	100%	100%	100%	100%	100%
QpLsm+FLv					
Number of grains	218	230	228	183	259
Percent QpLsm	23%	21%	46%	44%	93%
Percent FLv	77%	79%	54%	56%	7%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%

Mission Peak samples, Briones Formation

Grain Categories	Sample Location				
	MISP-6	MISP-7	MISP-8	MISP-10	MISP-9
QFL					
Number of grains	304	300	301	303	301
Percent Q	41%	42%	44%	59%	58%
Percent F	34%	28%	22%	25%	23%
Percent L	25%	30%	34%	16%	19%
Total percent QFL	100%	100%	100%	100%	100%
LmLvLs					
Number of grains	102	91	102	45	57
Percent Lm	9%	3%	14%	7%	19%
Percent Lv	56%	85%	65%	40%	19%
Percent Ls	35%	12%	21%	53%	62%
Total percent LmLvLs	100%	100%	100%	100%	100%
QpLsLm					
Number of grains	83	40	78	101	112
Percent Qp	46%	65%	54%	73%	59%
Percent Ls	43%	28%	28%	24%	31%
Percent Lm	11%	7%	18%	3%	10%
Total percent QpLsLm	100%	100%	100%	100%	100%
QpLsm+FLv					
Number of grains	214	200	210	195	191
Percent QpLsm	39%	20%	37%	52%	59%
Percent FLv	61%	80%	63%	48%	41%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%

Maguire Peaks samples, Briones Formation

Sample Location

Grain Categories	MGP-20	MGP-22	MGP-23	MGP-26	MGP-27
QFL					
Number of grains	300	301	300	302	300
Percent Q	42%	18%	44%	37%	47%
Percent F	23%	19%	24%	23%	19%
Percent L	35%	63%	32%	40%	34%
Total percent QFL	100%	100%	100%	100%	100%
LmLvLs					
Number of grains	105	189	97	129	102
Percent Lm	9%	1%	5%	6%	4%
Percent Lv	77%	92%	75%	85%	71%
Percent Ls	14%	7%	20%	9%	25%
Total percent LmLvLs	100%	100%	100%	100%	100%
QpLsLm					
Number of grains	45	32	62	42	52
Percent Qp	47%	50%	61%	58%	42%
Percent Ls	33%	44%	31%	28%	50%
Percent Lm	20%	6%	8%	14%	8%
Total percent QpLsLm	100%	100%	100%	100%	100%
QpLsm+FLv					
Number of grains	196	263	207	227	180
Percent QpLsm	23%	12%	30%	19%	29%
Percent FLv	77%	88%	70%	81%	71%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%

Welch Creek samples, Briones Formation

Grain Categories	Sample Location				
	WCR-15	WCR-8	VGTR-11	VGTR-10	VGTR-4
QFL					
Number of grains	300	300	276	300	300
Percent Q	37%	10%	27%	14%	13%
Percent F	13%	1%	6%	36%	6%
Percent L	50%	89%	67%	50%	81%
Total percent QFL	100%	100%	100%	100%	100%
LmLvLs					
Number of grains	140	267	186	149	241
Percent Lm	78%	95%	25%	24%	13%
Percent Lv	2%	0%	3%	60%	77%
Percent Ls	20%	5%	72%	16%	10%
Total percent LmLvLs	100%	100%	100%	100%	100%
QpLsLm					
Number of grains	184	286	243	84	71
Percent Qp	25%	7%	27%	30%	22%
Percent Ls	15%	4%	52%	28%	34%
Percent Lm	60%	89%	21%	42%	44%
Total percent QpLsLm	100%	100%	100%	100%	100%
QpLsm+FLv					
Number of grains	235	292	261	283	276
Percent QpLsm	83%	98%	92%	30%	26%
Percent FLv	17%	2%	8%	70%	74%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%

Welch Creek samples, Briones Formation

Grain Categories	Sample Location			
	WCR-14	WCR-13	WCR-2	WCR-17
QFL				
Number of grains	300	300	302	343
Percent Q	71%	74%	24%	51%
Percent F	3%	3%	10%	10%
Percent L	26%	23%	66%	39%
Total percent QFL	100%	100%	100%	100%
LmLvLs				
Number of grains	80	246	200	135
Percent Lm	40%	30%	11%	18%
Percent Lv	0%	0%	76%	52%
Percent Ls	60%	70%	13%	30%
Total percent LmLvLs	100%	100%	100%	100%
QpLsLm				
Number of grains	260	246	65	137
Percent Qp	70%	72%	28%	52%
Percent Ls	12%	20%	40%	30%
Percent Lm	18%	8%	32%	18%
Total percent QpLsLm	100%	100%	100%	100%
QpLsm+FLv				
Number of grains	268	254	247	241
Percent QpLsm	97%	97%	26%	57%
Percent FLv	3%	3%	74%	43%
Total percent QpLsm+FLv	100%	100%	100%	100%

Apperson Ridge samples, Briones Formation

Grain Categories	Sample Location				
	AR-12	AR-11	AR-10	AR-9	AR-7
QFL					
Number of grains	300	300	300	300	301
Percent Q	73%	22%	12%	25%	21%
Percent F	14%	0%	1%	21%	3%
Percent L	13%	78%	87%	54%	76%
Total percent QFL	100%	100%	100%	100%	100%
LmLvLs					
Number of grains	40	235	262	161	230
Percent Lm	42%	97%	94%	2%	92%
Percent Lv	20%	0%	3%	94%	0%
Percent Ls	38%	3%	3%	4%	8%
Total percent LmLvLs	100%	100%	100%	100%	100%
QpLsLm					
Number of grains	132	296	290	47	288
Percent Qp	76%	21%	12%	79%	20%
Percent Ls	11%	2%	3%	13%	6%
Percent Lm	13%	77%	85%	0%	74%
Total percent QpLsLm	100%	100%	100%	92%	100%
QpLsm+FLv					
Number of grains	181	296	300	263	297
Percent QpLsm	73%	100%	97%	18%	97%
Percent FLv	27%	0%	3%	82%	3%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%

Apperson Ridge samples, Briones Formation

Grain Categories	Sample Location				
	AR-5	AR-4	AR-3	AR-2	AR-1
QFL					
Number of grains	300	300	300	300	301
Percent Q	48%	20%	2%	3%	47%
Percent F	1%	27%	9%	9%	1%
Percent L	51%	53%	89%	88%	52%
Total percent QFL	100%	100%	100%	100%	100%
LmLvLs					
Number of grains	155	159	266	265	158
Percent Lm	22%	4%	0%	3%	13%
Percent Lv	2%	92%	99%	95%	0%
Percent Ls	76%	4%	1%	2%	87%
Total percent LmLvLs	100%	100%	100%	100%	100%
QpLsLm					
Number of grains	288	30	6	20	294
Percent Qp	47%	60%	50%	30%	46%
Percent Ls	41%	20%	50%	30%	47%
Percent Lm	12%	20%	0%	40%	7%
Total percent QpLsLm	100%	100%	100%	100%	100%
QpLsm+FLv					
Number of grains	293	257	293	293	296
Percent QpLsm	98%	12%	2%	7%	99%
Percent FLv	2%	88%	98%	93%	1%
Total percent QpLsm+FLv	100%	100%	100%	100%	100%

Neroly Formation		
Grain Categories	Sample Location	
	Tn-WB1	60-B
QFL		
Number of grains	196	301
Percent Q	1%	2%
Percent F	6%	10%
Percent L	93%	88%
Total percent QFL	100%	100%
LmLvLs		
Number of grains	184	262
Percent Lm	0%	1%
Percent Lv	98%	99%
Percent Ls	2%	0%
Total percent LmLvLs	100%	100%
QpLsLm		
Number of grains	5	8
Percent Qp	40%	80%
Percent Ls	60%	10%
Percent Lm	0%	10%
Total percent QpLsLm	100%	100%
QpLsm+FLv		
Number of grains	195	300
Percent QpLsm	2%	3%
Percent FLv	98%	97%
Total percent QpLsm+FLv	100%	100%

Mission Peak samples, Orinda Formation

Grain Categories	Sample Location	
	MISP-15	MISP-16
QFL		
Number of grains	300	301
Percent Q	56%	54%
Percent F	5%	15%
Percent L	39%	31%
Total percent QFL	100%	100%
LmLvLs		
Number of grains	118	91
Percent Lm	49%	38%
Percent Lv	25%	22%
Percent Ls	26%	40%
Total percent LmLvLs	100%	100%
QpLsLm		
Number of grains	228	184
Percent Qp	61%	61%
Percent Ls	14%	20%
Percent Lm	25%	19%
Total percent QpLsLm	100%	100%
QpLsm+FLv		
Number of grains	272	249
Percent QpLsm	84%	74%
Percent FLv	16%	26%
Total percent QpLsm+FLv	100%	100%