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Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: nature, origin, and relations with the hosts

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Abstract

The calc-alkaline granitoids of the central Sierra Nevada batholith are associated with abundant mafic rocks. These include both country-rock xenoliths and mafic magmatic enclaves (MME) that commonly have fine-grained and, less commonly, cumulate textures. Scarce composite enclaves consist of either xenoliths enclosed in MME, or of MME enclosed in other MME with different grain size and texture. Enclaves are often enclosed in mafic aggregates and form meter-size polygenic swarms, mostly in the margins of normally zoned plutons. Enclaves may locally divert schlieren layering. Mafic dikes, which also occur in swarms, are undisturbed, composite, or largely hybridized. In central Sierra Nevada, with the exception of xenoliths that completely differ from the other rocks, host granitoids, mafic aggregates, MME, and some composite dikes exhibit a bulk compositional diversity and, at the same time, important mineralogical and geochemical (including isotopic) similarities. MME and host granitoids display distinct major and trace element compositions. However, strong correlations between MME–host granitoid pairs indicate interactions and parallel evolution of MME and enclosing granitoid in each pluton. Identical mafic mineral compositions and isotopic features are the result of these interactions and parallel evolution. Mafic dikes have broadly the same major and trace element compositions as the MME although variations are large between the different dikes that are at distinctly different stages of hybridization and digestion by the host granitoids. The composition of the granitoids and various mafic rocks reflects three distinct stages of hybridization that occurred, respectively, at depth, during ascent and emplacement, and after emplacement. The occurrence and succession of hybridization processes were tightly controlled by the physical properties of the magmas. The sequential thorough or partial mixing and mingling were commonly followed by differentiation and segregation processes. Unusual MME that contain abundant large crystals of hornblende resulted from disruption of early cumulates at depth, whereas those richer in large crystals of biotite were formed by disruption of late mafic aggregates or schlieren layerings at the level of emplacement. MME and host granitoids are considered cogenetic, because both are hybrid rocks that were produced by the mixing of the same two components in different proportions. The felsic component was produced by partial melting of preexisting crustal

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materials, whereas the dominant mafic component was probably derived from the upper mantle. However, in the lack of a clear mantle signature, the origin of the mafic component remains questionable.

Keywords: Mafic enclaves; Magma mixing; Calc-alkaline granitoids; Sierra Nevada batholith; California

1. Introduction

Mafic magmatic enclaves (MME) are common in calc-alkaline granitoids (Didier and Barbarin, 1991) and are abundant in most of the Cordilleran granitoids (e.g., Pitcher, 1983; Barbarin, 1999). They provide evidence of the role of mafic magmas in the initiation and evolution of calc-alkaline granitoid magmas and thus their origin is of fundamental significance in interpreting the history of batholiths.

Field and petrographic features of MME have been determined in detail by many investigators. The main references are an early paper of Phillips (1880), a descriptive survey of "autoliths" of the Sierra Nevada by Pabst (1928), comprehensive books on the subject by Didier (1973) and Didier and Barbarin (1991), which contain many examples and a review of the various characteristics of MME, and a discussion of microstructures by Vernon (1991). Geochemical and isotopic studies of MME (e.g., Fourcade and Allègre, 1981; Domenick et al., 1983; Tindle and Pearce, 1983; Reid et al., 1983; Noyes et al., 1983a; Barbarin et al., 1985; Kistler et al., 1986; Hill et al., 1988; Dorais et al., 1990; Dodge and Kistler, 1990) emphasize their significance to the genesis of granitoid magmas and their relations to associated mafic rocks.

MME are particularly abundant in the calc-alkaline granitoids of the Sierra Nevada batholith (Fig. 1) (e.g., Pabst, 1928; Bateman, 1992). They have been described in many plutons (Bateman and Nokleberg, 1978; Bateman and Chappell, 1979; Noyes et al., 1983a,b; Bateman, 1992) and represent the main topic of several other investigations (Pabst, 1928; Link, 1969; Reid et al., 1983; Domenick et al., 1983; Furman and Spera, 1985; Frost and Mahood, 1987; Dodge and Kistler, 1990; Dorais et al., 1990; Barbarin, 1991).

This report concerns the characteristics and origin of MME and associated mafic rocks such as mafic aggregates, schlieren layering, undisturbed or composite mafic dikes, mainly from selected plutons in the central Sierra Nevada batholith (Bateman, 1992). The localities described or mentioned in this report are identified in Fig. 1 and Table 1. Petrographic, modal, mineralogical, and chemical data on these rocks (Barbarin et al., 1989) and their host granitoids (Bateman et al., 1984a; Bateman, 1992), impose constraints to a general model for their origin and evolution.

2. The Sierra Nevada granitoids

The Sierra Nevada batholith represents a portion of the nearly-continuous chain of Circum-Pacific granitoids (Pitcher, 1983). Like the Coastal batholith of Peru (Pitcher et al., 1985), the Sierra Nevada batholith is an example of a batholith emplaced in a continental magmatic arc (references in Bateman, 1992). The plutonic rocks of the Sierra Nevada batholith range in composition from gabbro to granite. Tonalite, quartz diorite, granodiorite, and quartz monzonite are the most common types and hornblende is the characteristic mafic silicate. They form normally zoned plutons (e.g., Tuolumne Intrusive Suite: Bateman and Chappell, 1979) that commonly are associated in suites of various ages. In general, the plutons are rounded or elongated ~NE–SW, parallel to the long axis of the batholith (Bateman, 1992).

The axial part of the batholith consists of Cretaceous granitoid suites that progressively young eastward (from ~125 to ~88 Ma) (Stern et al., 1981; Chen and Moore, 1982). Jurassic plutons and suites (from 186 to 155 Ma) are exposed along both margins and, locally, in the interior of the batholith. A single Triassic suite is present in the east side of the batholith. The central part between 37°N and 38°N has been mapped at a scale of 1:62,500 (e.g., Bateman, 1992), and relations between the different plutons and suites are clearly defined (Fig. 1). Many plutons and suites have been studied in detail (Mount

Givens Granodiorite: Bateman and Nokleberg, 1978, Gilder and McNulty, 1999, McNulty et al., 2000; Tolumne Intrusive Suite: Bateman and Chappell, 1979; Red Lake and Eagle Peak plutons: Noyes et al., 1983a,b; Palisade Crest Intrusive Suite: Sawka et al., 1990; Dinkey Creek pluton: Dorais et al., 1990, Cruden et al., 1999; Jackass Lakes pluton: McNulty et al., 1996). Samples from various plutons and suites have been compared mineralogically (Dodge et al., 1968, 1969; Piwinskii, 1968; Barbarin, 1986, 1990), chemically (Kistler and Peterman, 1973; Bateman et al., 1984a,b), and experimentally (Piwinskii, 1973).

3. Petrography and field relations of mafic rocks

The Sierra Nevada batholith granitoids, especially the intermediate rocks that range in composition from tonalite to quartz monzonite, contain abundant MME (e.g., Pabst, 1928; Bateman, 1992) and associated

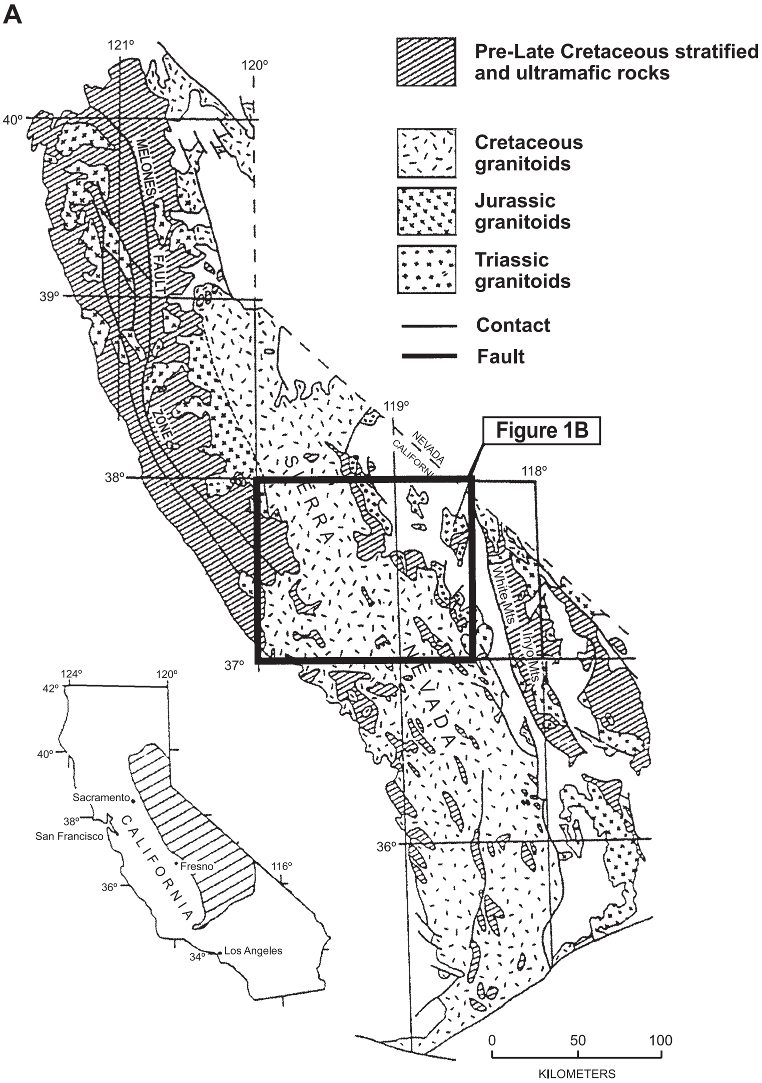

Fig. 1. (A) Simplified geological map of the Sierra Nevada batholith. (B) Simplified geological map of the central part of the Sierra Nevada batholith between latitudes 37°N and 38°N showing sample locations described in the paper (both from Bateman, 1992). See Table 1 for key to sample locations.

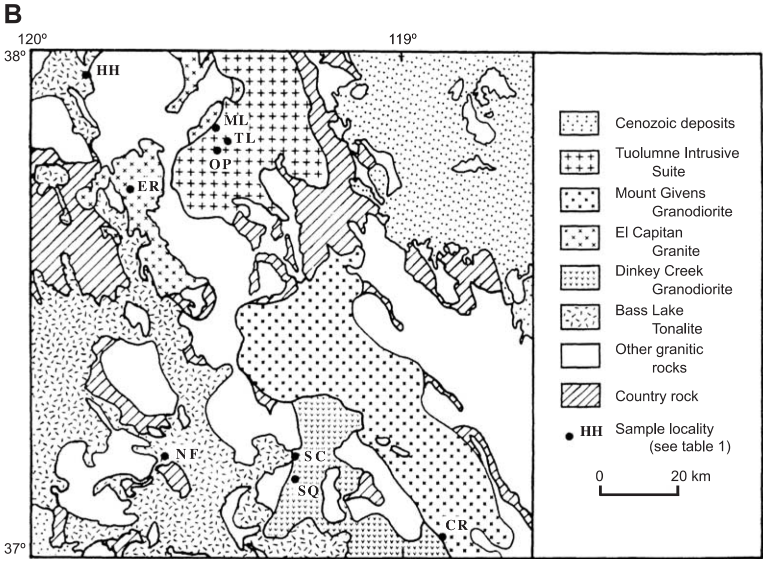

Fig. 1 (*continued*).

mafic rocks. The amount of mafic rocks, including MME, generally increases toward the margins of the plutons, especially those that are normally zoned. MME and other mafic rocks are also found scattered throughout hornblende-bearing plutons and suites but are scarce or absent in biotite granites and in intrusions that contain large K-feldspar megacrysts. The distribution and abundance of MME are mainly related to the composition of the host rock rather than to contacts and magmatic movements as suggested by Pabst (1928). In the normally zoned plutons of the Sierra Nevada batholith, MME and other mafic rocks are concentrated near contacts. A striking connection exists among the abundance of MME, the color index of the host granitoid, and compositional zoning of plutons or suites (e.g., Barbarin, 1989). The absence of biotite-rich and sillimanite-bearing restites is also noticeable in the Sierra Nevada granitoids.

3.1. Mafic magmatic enclaves

Because the term “inclusion” has been used to describe fluids or mineral grains enclosed in other minerals, “enclave” is more suitable for describing rock enclosed in another rock (Lacroix, 1893; Holmes, 1928; Read, 1957; Didier, 1973; Vernon, 1983, 1984; Didier and Barbarin, 1991). In this report, the term “mafic magmatic enclave” (Barbarin, 1988) is preferred to “mafic microgranular enclave” (Didier, 1973) or “microgranitoid enclave” (Vernon, 1983, 1984) because descriptions of enclaves from calc-alkaline granitoid plutons throughout the world indicate that they are invariably finer grained than the enclosing granitoids, but not necessarily microgranular or microgranitoid. On the other hand, the use

Table 1
Location and rock unit of the selected localities

Map symbol (cf. Fig. 1)	Locality	Lat. (°N)	Long. (°W)	Rock unit
TL	Tenaya lake	37°49.8′	119°28.0′	Half Dome granodiorite
OP	Olmstead Point	37°48.9′	119°29.2′	Half Dome granodiorite
ML	May Lake	37°50.6′	119°29.9′	Half Dome granodiorite
CR	Courtright Reservoir	37°04.4′	118°58.0′	Mount Givens granodiorite
ER	Elephant Rock	37°43.2′	119°42.8′	El Capitan granite
SQ	Shaver Lake Quarry	37°09.3′	119°17.7′	Dinkey Creek granodiorite
SC	San Joaquin River Canyon	37°11.2′	119°20.9′	Dinkey Creek granodiorite
NF	North Fork	37°11.6′	119°35.8′	Bass Lake tonalite
HH	Hetch Hetchy Reservoir	37°56.8′	119°47.2′	Bass Lake tonalite

of “magmatic” emphasizes the crystallization of these enclaves from magmas, and consequently their typical igneous texture (Fig. 2). In addition, “mafic” indicates that these enclaves are darker-colored than their enclosing granitoid. “Mafic” also distinguishes dark-colored magmatic enclaves from felsic microgranular enclaves, which have a different origin (Didier, 1973).

Detailed descriptions of MME from the northern and southern parts of the Sierra Nevada batholith are given in Pabst’s (1928) benchmark paper and identical observations have been made in the central part. Different types of MME can be distinguished by their grain size, texture, structure, mineral content, nature and abundance of phenocrysts, composition, external morphology, and contacts with host granitoids. Some MME are composite and consist of one MME enclosed in another MME of different grain size or texture (see Fig. 2 in Barbarin, 1991). Composite MME with fine-grained and porphyritic or xenocryst-rich parts are particularly common. However, there is no rule concerning which type of MME is enclosed in another. More than 50% of the MME are fine-grained and dark, contain abundant plagioclase phenocrysts, scarce small hornblende phenocrysts, and are usually surrounded by a fine-grained margin of variable width (Fig. 2). In most comparisons of enclave–host granitoid pairs, these MME are used as a reference. The fine-grained margins are commonly characterized by a trachytic texture where strong flow foliation, parallel to the contact, is shown by plagioclase laths and is locally diverted by plagioclase phenocrysts (Fig. 2B). Close relationships also appear between the grain size of MME and the nature of contacts with hosts, and between aspect ratios of MME and intensity of flow foliation in the hosts. Because contacts correspond to interlocking of crystals of the felsic and mafic components, the larger the grain size of the MME, the more diffuse the contacts.

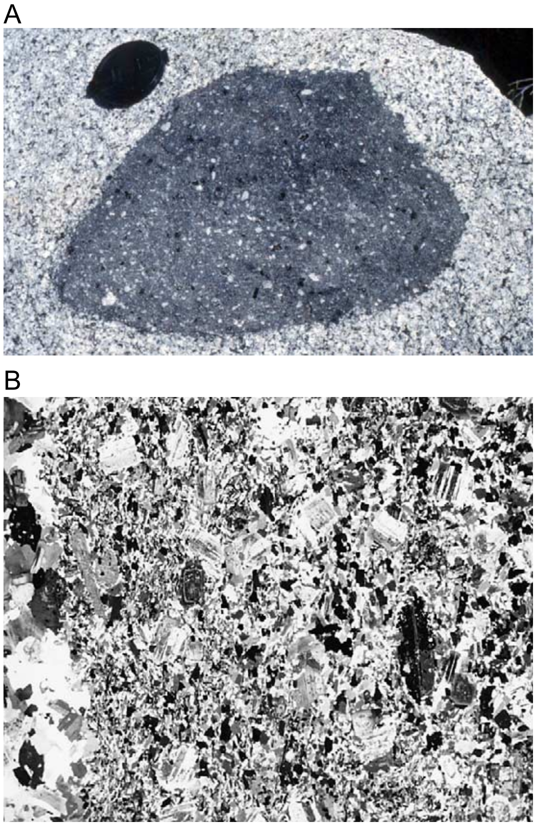

Fig. 2. (A) A typical mafic magmatic enclave in the Cretaceous granodiorite of the central Sierra Nevada batholith (Mount Givens granodiorite at Courtright Reservoir). (B) Photomicrograph of a contact zone of a typical mafic magmatic enclave (right) against the host granodiorite (left). Within the fine-grained margin, flow alignment of elongate plagioclase laths is diverted by the euhedral phenocrysts of hornblende and zoned plagioclase. Crossed polars, base of photomicrograph corresponds to 20 mm.

The same minerals are present in MME as in their granitoid hosts but in different proportions (Barbarin, 1986; Barbarin et al., 1989). MME range from diorite to quartz diorite and are composed of plagioclase (45–55%) and mafic minerals (40–50%). The host granitoids contain less plagioclase (35–45%) and mafic minerals (5–20%), and much more quartz and K-feldspar (35–50%) (Fig. 3). The proportions of hornblende and biotite and color index vary widely from one enclave to another (Fig. 4); in general, the ratio of hornblende to the total amount of mafic minerals increases with color index. The abundance of hornblende in MME also correlates with its abundance in the host: MME enclosed in tonalites generally contain 5–10% more hornblende than MME enclosed in granodiorites. In contrast, the mafic mineral content of the granitoids is relatively constant, and biotite is almost always more abundant than hornblende.

Although quartz and K-feldspar are scarce or absent in most MME, they are present in some MME that are enclosed in felsic granitoids (Fig. 3) and are then interstitial. Quartz and scarce megacrystic K-feldspar xenocrysts are also found in some MME.

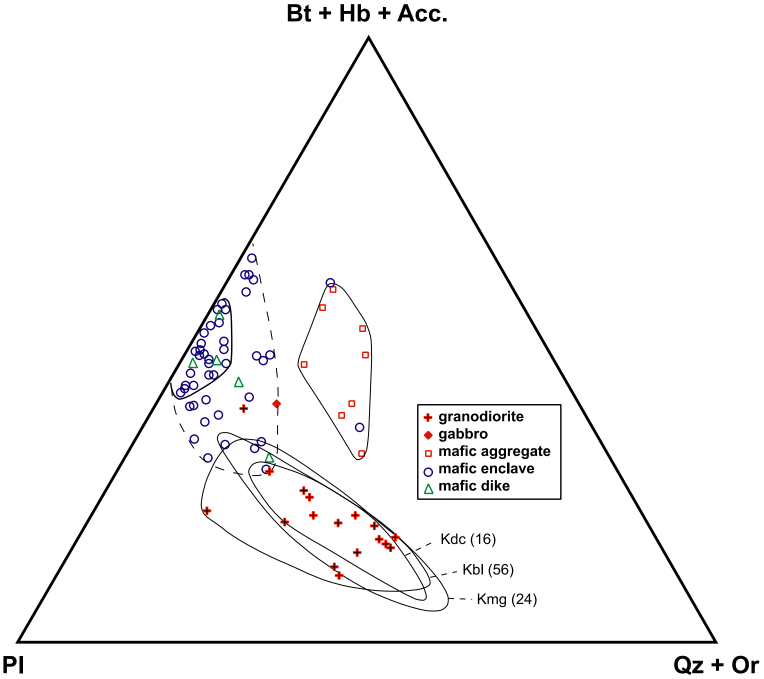

Fig. 3. Modal composition of granitoids and associated mafic rocks plotted in a plagioclase (Pl)-quartz plus K-feldspar (Qz+Or)-mafic plus accessory minerals (Bt+Hb+Acc.) diagram. Granitoids, mafic aggregates, and MME plot in three distinct zones. Mafic dikes plot in the same area as MME. Modes of granitoids (from Bateman et al., 1984a) are for the Dinkey Creek Granodiorite (Kdc: 16 analyses), the Bass Lake Tonalite (Kbl: 56 analyses), and the Mount Givens Granodiorite (Kmg: 24 analyses).

Globular quartz grains about the same size as quartz crystals in the host (a few millimeters in diameter), exhibit a typical ocellar texture with spheric shape, corrosion embayments, and hornblende mantle. However, ocellar texture (e.g., Palivcovà, 1978; Hibbard, 1991) is scarce in the MME of the Sierra Nevada batholith granitoids, except for the El Capitan Granite. K-feldspar megacrysts are rare to absent in MME, even where the host is megacrystic such as the Mount Givens Granodiorite. Titanite, where present in the MME, is also present in the host granitoid and has similar composition, crystal habit, and opaque inclusions (Barbarin and Bateman, 1986). Apatite occurs as large stubby crystals in the granitoids, whereas in MME it occurs as needles enclosed in all other minerals. MME contain rare large zircon grains with pitted surfaces, whereas host granitoids contain abundant small zircon crystals with clear surfaces. Apatite needles, acicular and hollow hornblende prisms, plagioclase laths, and locally thin and elongate biotite crystals are common in MME, mainly in fine-grained margins.

Clots of mafic and accessory minerals are also a distinctive feature of the MME. They consist predominantly of euhedral hornblende crystals intergrown with biotite, titanite, and opaque minerals. They may represent concentrations of dense, early-formed phases as proposed by Reid and Hamilton (1987), but are more probably pseudomorphs of amphibole or pyroxene phenocrysts, as suggested by their commonly geometric shapes.

A rare type of MME occurs only once or twice per hundreds or thousands of regular MME. These MME are 10–30 cm in diameter, contain up to 70% of mafic minerals, and exhibit a cumulate texture (see Fig. 1g in Barbarin, 1991). Detailed microscopic descriptions and analyses of such enclaves are given in Dorais et al. (1990).

3.2. Mafic aggregates and schlieren layering

Mafic aggregates are especially common in the margins of intrusions, adjacent to contacts with other granitoids or with country rocks. They are charac-

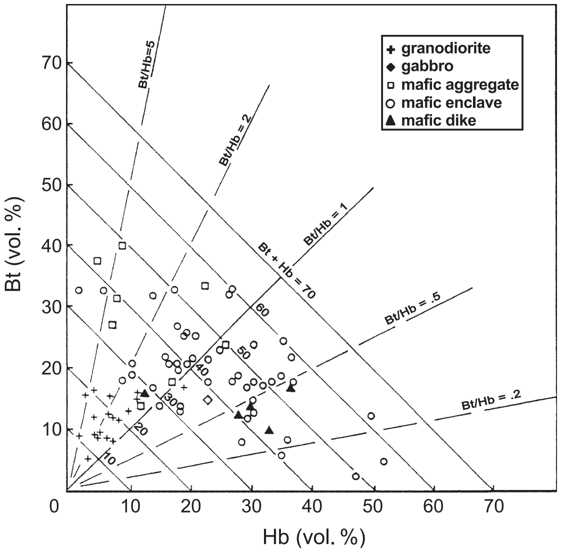

Fig. 4. Biotite versus hornblende contents for the granitoids and associated mafic rocks of the central Sierra Nevada batholith. MME are mostly scattered. Most MME contain broadly the same amount of mica and amphibole, but a few are either unusually hornblende-rich or exceptionally biotite-rich. Hornblende is clearly dominant in mafic dikes, whereas biotite is dominant in mafic aggregates and most granitoids.

terized by abundant large euhedral crystals of biotite and hornblende. Like MME, mafic aggregates contain from 40% to 50% of mafic minerals (Fig. 4). Mafic aggregates, however, contain more quartz and K-feldspar than MME, and the proportions of plagioclase to quartz plus K-feldspar are identical to those in the granitoid (Fig. 3). In some mafic aggregates, the modal abundances of titanite and allanite reach 5%. Mafic aggregates form schlieren layerings, huge masses, or are associated with MME in swarms, many of which are dike-like. Their contacts with the various types of MME and country rock xenoliths are mostly sharp, whereas contacts with the granitoids can be either sharp or diffuse.

Schlieren layering consists of rhythmic successions of layers with graded bedding. In some granitoids, such as the Half Dome Granodiorite at Olmstead Point or Tenaya Lake (cf. Fig. 1B), graded bedding is clearly noticeable within each layer. A 10-cm-thick layer begins with a thin seam of titanite overlain by small crystals of mafic minerals. Upward, hornblende and biotite crystals are progressively replaced by felsic minerals with regularly increasing grain size. These layers were described as “schlieren” by Cloos (1936) and “layered mafic–felsic magma system” by Coleman et al. (1995). The schlieren layerings may locally be several meters thick and extend over more than one hundred meters. At Courtright Reservoir in the Mount Givens Granodiorite, crossbedding is commonly observed (Bateman et al., 1984a,b). These layers were deposited from and partly eroded by flowing magma (Gilbert, 1906). Graded bedding, crossbedding, unconformities, and channel structures are caused by differential magmatic movements along shear planes separating layers that were accompanied by settling of minerals within each layer. The middle and upper parts of the layers actually include large euhedral crystals of hornblende and biotite that are ~10 mm long. These crystals of hornblende and biotite probably represent phenocrysts that were stopped by schlieren layerings while they were settling in the granitoid magma. When the MME were almost solid, they were incorporated into the mafic aggregates. Rare xenoliths of host metamorphic rocks are also enclosed in the mafic aggregates. Contacts between lower parts of the layers and enclosing granitoids are mostly sharp, whereas contacts between their upper parts and granitoids are mostly diffuse. At Courtright Reservoir, some MME are locally found above the upper contact; others deform or divert the layers. Schlieren layerings that include abundant MME of varying nature and size resemble successive lag deposits of solid crystals, MME, and xenoliths, concentrated along pluton margins by flowing magma.

Mechanical concentrations of accessory minerals, euhedral mafic minerals, and MME can also form broadly spherical masses of mafic aggregates from a few centimeters to several meters across and these mafic aggregates may grade to pipes or dikes. Some dikes formed with MME of various type and size enclosed in a mafic aggregate, are described as composite dikes. However, their contacts with the enclosing granitoid are mostly diffuse. At Courtright Reservoir and Shaver Lake Quarry (Fig. 1B), the shapes of the masses of mafic aggregates and their contacts with the host suggest that, after their formation by concentration of solid particles in the granitic magma, they were injected in local early fractures. The mafic aggregates seem to initiate near the margins of the plutons and then move on short distances toward the center by such processes as filter pressing.

MME swarms are abundant in the Sierra Nevada granitoids (e.g., Tobisch et al., 1997). Two types of MME swarms can be distinguished (see Fig. 3 in Barbarin, 1991):

(1) "Polygenic" swarms consist of MME of various types and sizes enclosed in mafic aggregates mainly formed of large crystals of mafic minerals. They may also contain some xenoliths. Their contacts with host granitoids are distinct, but neither sharp nor straight, even where they occur as composite dikes or pipes. They are common especially in the margins of the plutons where MME and other mafic rocks are abundant. The best examples of these MME swarms are exposed at Courtright Reservoir (Bateman et al., 1984b).

(2) "Monogenic" swarms consist of relatively similar MME enclosed in medium to fine-grained granitoids. Country rock xenoliths have not been observed in these swarms. In contrast to the other type of MME swarms, monogenic swarms are common in areas where mafic or composite dikes crosscut the plutons.

3.3. Mafic dikes

The distribution of mafic dikes appears to be independent of the composition of their hosts. Mafic dikes commonly form dense swarms. The thickness of the dikes varies from a few tens of centimeters to 5 m. All the intermediate stages between undisturbed mafic dikes and dike-like monogenic MME swarms are found in the granitoids of the central Sierra Nevada batholith, and can be summarized as follows:

(1) Scarce undisturbed mafic dikes are associated with dense swarms of composite dikes (e.g., San Joaquin River Canyon in the Dinkey Creek pluton; Hetch Hetchy Reservoir and North Fork in the Bass Lake pluton; Fig. 1B). The grain size commonly increases from fine-grained margins towards the center. Locally, undisturbed mafic dikes contain angular xenoliths of the host granodiorite.

(2) A mafic dike exposed in the San Joaquin River Canyon shows the first stage of hybridization: tiny felsic veins a few centimeters thick separate the nearly-continuous mafic dike from the tonalite and divide the mafic rock into angular blocks (Fig. 5A).

(3) North of Stevenson Creek and in the San Joaquin River Canyon, partially hybridized mafic dikes consist of pillows of similar mafic rock separated by veins of felsic rock (Fig. 5B). Contacts between these composite dikes and the enclosing granodiorite remain sharp and straight. The 20- to 50-cm mafic pillows are surrounded by discrete fine-grained margins and show lobate contacts with the medium- to fine-grained matrix of felsic granite. Within each composite dike, mafic pillows have similar or close compositions. However, the nature of the mafic pillows may vary markedly from one locality to another: they display either a basaltic appearance

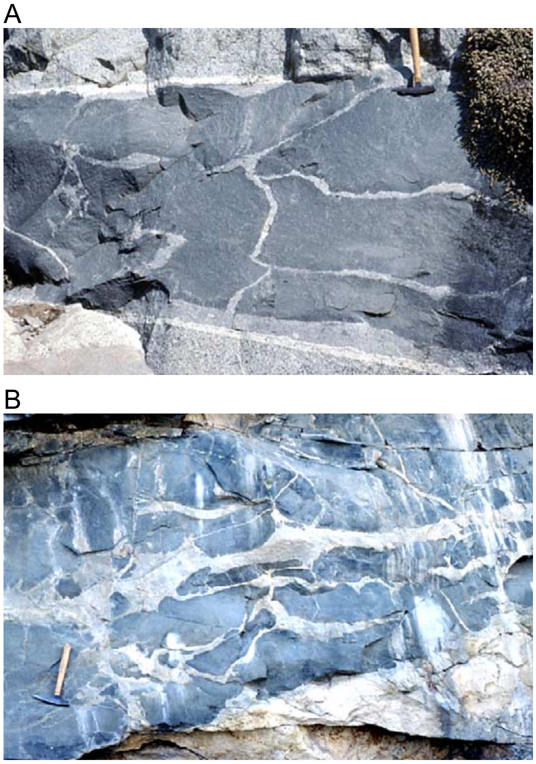

Fig. 5. (A and B) Two types of composite dikes from the Dinkey Creek pluton (San Joaquin River Canyon): the felsic component is much less abundant in A than in B.

with dark color and fine-grained texture (e.g., Highway 140 in the Guadalupe Igneous Complex: Best, 1963), or a more granitic appearance with gray color and fine-grained texture (e.g., Elephant Rock in the El Capitan pluton; Fig. 1B). Intermediate types exist between these two extremes (e.g., Hetch Hetchy Reservoir in the Bass Lake pluton; San Joaquin River Canyon in the Dinkey Creek pluton; Fig. 1B). Whatever their appearance, these mafic pillows have relatively fine-grained, equigranular texture, and phenocrysts or xenocrysts have not been observed. They have fine-grained lobate margins that are well developed where compositional, chemical, and thermal contrasts between the two magmas were strong (dark fine-grained mafic pillows enclosed in a granitic host). Uncommon angular fragments of mafic rocks locally occur in some zones of the composite dikes: they may result from the local disruption of pillows. Mafic pillows are commonly flattened and slightly elongated parallel to the main direction of the dikes. In the bottom of the San Joaquin River Canyon, several composite dikes sharply crosscut each other. A dike of this type, more than 100 m wide, was described and studied in detail in the Eagle Lake quartz monzodiorite pluton, Sequoia National Park, south-central Sierra Nevada batholith (Furman and Spera, 1985).

(4) At Hetch Hetchy Reservoir, in addition to undisturbed or composite dikes, there is a type of more hybridized composite dikes in which mafic enclaves and the felsic host display many textural heterogeneities. The mafic enclaves vary in size, and are commonly elongated. Contacts with the abundant aplitic granitoid host are locally diffuse. The composition varies from one mafic enclave to another both within a dike and within large enclaves. The color, mineralogy, as well as major and trace elements and isotopes of these enclaves are intermediate between those of the undisturbed dikes and the host Bass Lake tonalite (Barbarin et al., 1989). Boundaries between these composite dikes and the host tonalite are relatively diffuse.

(5) The next stage involves relatively rare monogenic MME swarms that may represent fragments of composite dikes. Although these swarms do not exhibit a dike shape with parallel, straight, and sharp contacts with the host, they contain compositionally and texturally identical mafic enclaves enclosed in a medium- to fine-grained granitoid similar to the most hybridized composite dikes.

The suggested evolution from undisturbed mafic dikes through composite dikes to the monogenic MME swarms parallels an increase in the proportion of the felsic component. Although undisturbed mafic dikes, various types of composite dikes, and monogenic MME swarms are commonly found in the same area, neither close structural nor chronological relationships were found between them. At Hetch Hetchy Reservoir, dikes that parallel the foliation of the granodiorite or are close to it, are undisturbed, whereas dikes that cut across the foliation are composite. Unfortunately, contacts between these dikes were not found.

The most mafic enclaves have a dioritic composition and mainly consist of plagioclase and mafic minerals, like the MME (Fig. 3). Relatively more felsic blobs are enriched in quartz and K-feldspar, and their composition tends toward those of the granitoid hosts. The mafic blobs contain more hornblende than biotite (Fig. 4) and the ratio of hornblende to the total amount of mafic minerals is higher than in the MME. Compositions of the mafic dikes (Barbarin et al., 1989) resemble those of the dikes described in detail at Hell Hole Meadow in the upper part of San Joaquin River Canyon (Reid and Hamilton, 1987). The composite dikes that consist of a single type of mafic pillows or fragments enclosed in fine-grained and relatively felsic granitoid differ from the dike-like polygenic MME swarms that consist of various types of MME enclosed in coarse-grained and mafic granitoids.

In the Sierra Nevada batholith, undisturbed mafic dikes or composite dikes with various stages of hybridization have not been traced to trains of enclaves, as for example in Donegal (Pitcher, 1991), the Coastal Batholith of Peru (Cobbing and Pitcher, 1972), or the Klamath Mountains of California (Barnes, 1983). In the Sierra Nevada batholith, the genesis of MME and mafic dikes may correspond to two distinct events; this is implied by mafic dikes that sharply crosscut MME (e.g., North Fork in the Bass

Lake pluton; Highway 168 in the Big Sandy Bluffs granite) and may define the foliation in the host granitoids (e.g., Hetch Hetchy Reservoir in the Bass Lake pluton). This suggests that MME were as crystalline as their granitoid host at the time mafic or composite dike intrusion. However, as will be shown in a model developed later, these observations do not exclude the possibility that MME were formed by the disruption of earlier mafic dikes. The modes and evolution of mafic dikes and MME are quite similar, and they might share the same origin, although they were formed at two distinct periods of the history of the pluton (e.g., Barbarin and Didier, 1992).

3.4. Xenoliths

The margins of plutons that are bounded by metamorphic screens or roof pendants commonly contain country-rock xenoliths ranging from some millimeters to some meters in diameter. These xenoliths are commonly mixed with the other enclave types in polygenic enclave swarms (e.g., Courtright Reservoir: Bateman et al., 1984b). However, they are readily distinguished from other enclaves by their angular shapes and rusty halos. Pabst (1928) listed several characteristics, which distinguish country-rock xenoliths from MME even when they are chemically and mineralogically very similar. At Courtright Reservoir, scattered strongly foliated xenoliths enclosed in MME form composite enclaves. Contacts between xenoliths and MME are always sharp. Although xenoliths are relatively common in the margins of the plutons, neither residues of melting nor thoroughly digested xenoliths, commonly referred to as restites (e.g., Didier and Barbarin, 1991), were observed in the surveyed granitoid plutons of the central Sierra Nevada batholith.

4. Whole-rock and mineral chemistry

Whole-rock major, trace, and rare-earth element and isotope data on the MME and various mafic rocks associated with granitoids in four plutons of central Sierra Nevada were compiled by Barbarin et al. (1989). Major and minor element variation diagrams for MME and host granitoids are given in Dodge and Kistler (1990). The diversity in modal composition of MME and mafic rocks associated with the granitoids (Fig. 3) also shows in chemical composition (Fig. 6). In the granitoids, MgO ranges from <1% to 3.5% and CaO from <1% to 7%, whereas in MME MgO ranges from 2% to 7% and CaO from 4% to 8.5%. The

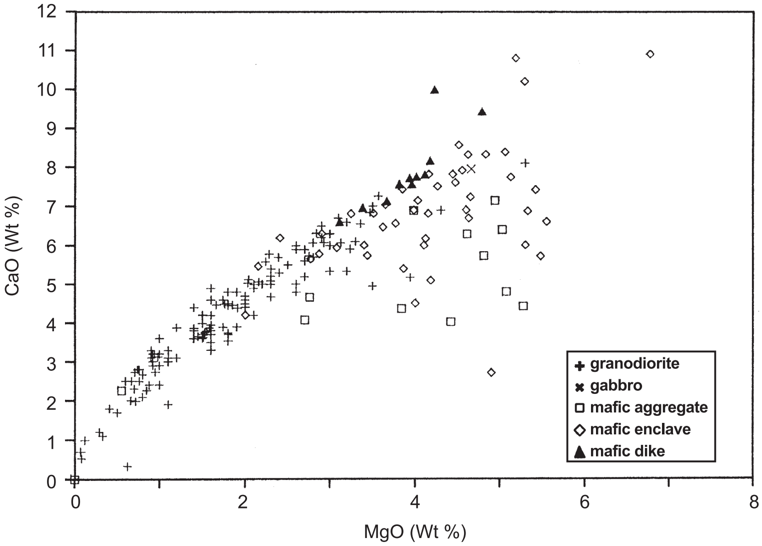

Fig. 6. MgO versus CaO diagram for the granitoids and associated mafic rocks of the central Sierra Nevada batholith. Analyses are given in Bateman et al. (1984a) for most of the granitoids, and in Barbarin et al. (1989) for the other rocks.

composition of the MME spreads over a large area and about half the MME follow the trend of the host granitoids. The rest are enriched in MgO (or depleted in CaO) and plot below the trend for granitoids. These compositional differences are also apparent in the El Capitan granite and the Tuolumne Intrusive Suite, although MME are not so widely scattered here (Reid et al., 1983). MME are distinctly enriched in CaO, MgO, FeOt, and less strongly enriched in TiO_2, MnO, and P_2O_5 compared to their hosts, reflecting their greater abundance of plagioclase, mafic minerals, and apatite. Mafic aggregates and schlieren layerings commonly contain less CaO (about 4%) than MgO (2.5–5%). Where MgO content is about 5%, CaO content may vary from about 4% to 7%. Differences between MME and mafic aggregates are related to the relative abundance of andesine in MME and of mafic minerals and especially of biotite in mafic aggregates. The MME that plot below the main granitoid trend are enriched in mafic minerals, especially biotite. Mafic dikes form a trend parallel to that of the granitoid hosts, with the exception of one mafic dike and one MME. Xenoliths (not shown in Fig. 6) are poor in MgO (1.5–2.5%). One xenolith plots close to the trend and two others that contain 15% and 17% CaO plot far above all the other rocks.

An even more striking relation shown by the major elements is that MgO and FeOt in MME and their host granitoids vary sympathetically within the same pluton and from one pluton to another (Barbarin, 1991). Where MME are relatively poor in MgO and FeOt, the host granitoid is also poor in them. Furthermore, the FeOt/MgO ratios are almost constant in the various rocks. These relations reflect similar chemical compositions of the mafic minerals in each enclave–granitoid pair.

The relative abundance of REE, especially of heavy REE, and their slight fractionation in MME results in flatter REE patterns, whereas the relatively greater fractionation of REE in host granitoids results in steeper REE patterns (Fig. 7). There is a close relationship between the slope of REE patterns in MME and granitoids (Barbarin et al., 1985). It is noticeable that granitoids with less fractionated REE (tonalites) contain MME with less fractionated REE, whereas granitoids with relatively more fractionated REE (granodiorites) contain MME with relatively more fractionated REE. Like the MgO and FeOt contents, the differences in REE contents and their fractionation between enclave–host granitoid pairs are broadly constant. In contrast, the relative Eu anomaly characteristic of the MME is commonly absent in the host granitoids. Enrichment of REE in MME and especially of HREE can be explained either by concentration of hornblende and possibly apatite in the MME, or more probably, by preferential partitioning of REE between mafic and felsic liquids (Watson, 1976; Ryerson and Hess, 1978).

The trace element contents of MME and host granitoids are distinct (Barbarin et al., 1989; Dodge and Kistler, 1990). Generally, MME contain larger amounts of the transition elements (Sc, Cr, Co, Zn, Sb, Nb) and smaller amounts of Ba and Th than the granitoids (Fig. 8). The contents of Sr, Zr, Hf, and Ta are broadly the same in MME and their hosts. Cs and Th vary differently in the various pairs. However, enrichment patterns are similar for all MME–granitoid pairs, and a strong correlation exists between the trace element content of MME and the nature of their granitoid hosts (Fig. 8). The variations are mainly related to the degree of differentiation of the granitoids and the abundance of minerals such as K-feldspar. Fig. 8 shows that the Mount Givens granodiotite is particularly enriched in K, Rb, Cs, and Ba compared to its MME, because it is enriched in K-feldspar (3- to 5-cm-long megacrysts). The trace element contents of the mafic dikes are similar to those of the MME and distinct from those of the granitoids. Large compositional variations exist between the different types of dikes (undisturbed, composite, or largely hybridized).

Sr and Nd isotope compositions have been determined for MME, mafic aggregates, mafic dikes, and host granitoids (Barbarin et al., 1989). For each pluton, MME and some of the mafic aggregates plot on Rb–Sr isochrons previously defined using granitoid samples only (Dodge and Kistler, 1990). In addition, there are no significant differences in the ε_{Nd} and ε_{Sr} values between MME and the host granitoids. Similar results have been obtained from many other MME–granitoid pairs worldwide (e.g., Holden et al., 1987; Pin et al., 1990). In contrast, mafic dikes may plot above or below the isochrons when they are undisturbed or slightly hybridized (e.g., San Joaquin River Canyon in the Dinkey Creek pluton), and close

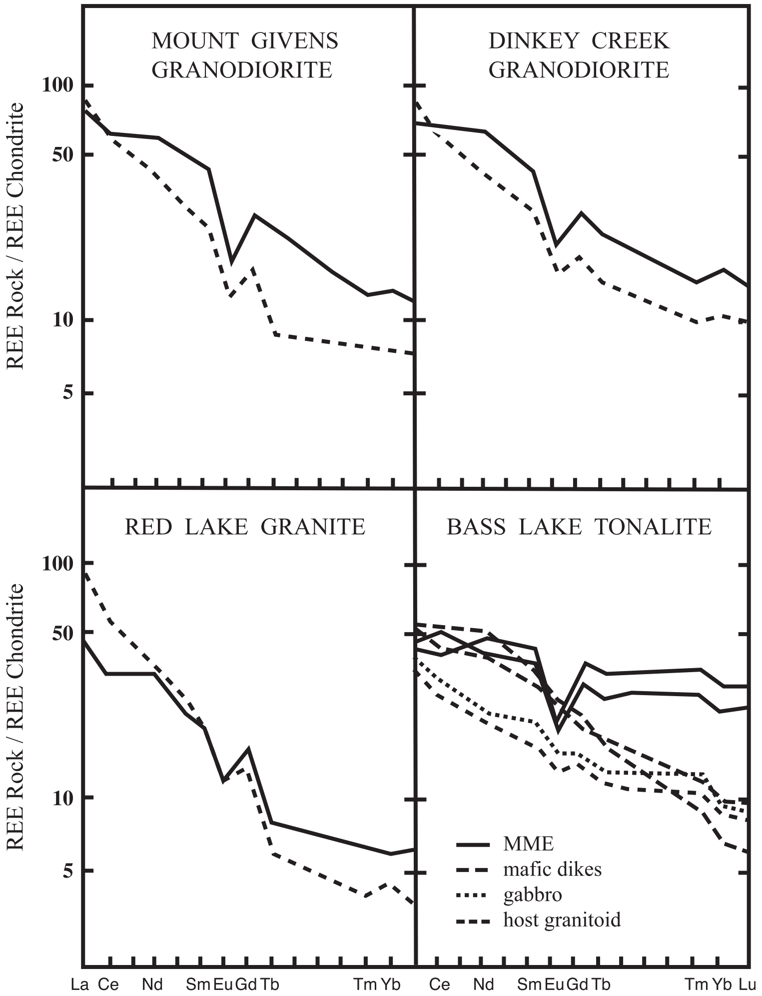

Fig. 7. Selected and typical chondrite-normalized REE patterns of host granitoids, mafic magmatic enclaves and mafic dikes from some plutons of the central Sierra Nevada batholith (data from Barbarin et al., 1989).

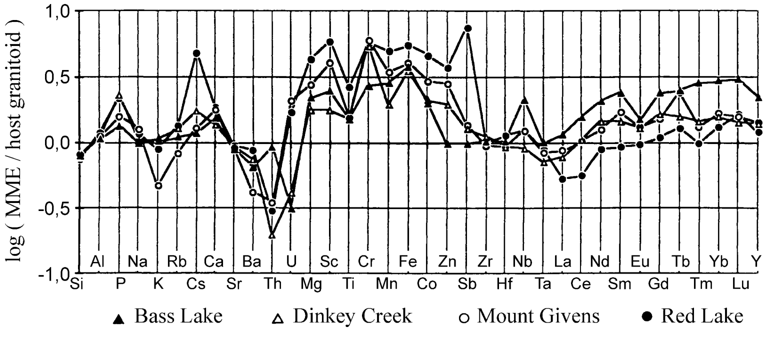

Fig. 8. Host granitoid-normalized major and trace element patterns for selected mafic magmatic enclaves from some plutons of the central Sierra Nevada batholith (data from Barbarin et al., 1989).

to or on the isochrons when they are composite and partially digested (e.g., Hetch Hetchy Reservoir in the Bass Lake pluton).

Electron microprobe analyses of biotite, hornblende, and plagioclase from MME, host granitoids, and mafic aggregates are given in Barbarin et al. (1989). The mafic minerals from the cores and the fine-grained, darker margins of a few enclaves were analyzed separately. Despite differences in whole-rock composition, biotite and hornblende in MME have the same chemical compositions as in contiguous mafic aggregates or host granitoid, regardless of differences in grain size, morphology, crystal habit, or location within the MME, mafic aggregates, or granitoids (Fig. 9). Atomic Fe/(Fe+Mg) ratios clearly show this relation. When compositions of mafic minerals change within a pluton, parallel changes are observed in the MME and mafic aggregates (Fig. 9). These compositional variations are also found in biotite and hornblende from closely spaced enclave–granitoid or enclave–mafic aggregate pairs from the same locality. Identical chemical compositions of the mafic minerals in each enclave–granitoid pair may explain the sympathetic variations of MgO and FeOt in MME and their host granitoids (Barbarin, 1991) and the almost constant FeOt/MgO ratios. Plagioclase phenocrysts in enclaves and large crystals of plagioclase in host granitoids are also compositionally similar and show similar zoning (Barbarin, 1990). However, small crystals from the matrix of enclaves are more albitic and generally unzoned.

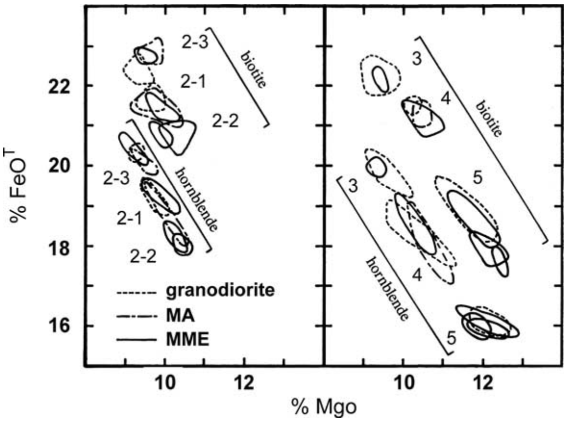

Fig. 9. MgO and FeOt contents in biotite and hornblende in various host granitoid or mafic aggregate–MME pairs from either the same locality (2-1, 2-2, and 2-3: quarry near the Shaver Lake Dam) or from different localities of the Dinkey Creek pluton (data from Barbarin et al., 1989). Each zone is defined by analyses from about five different grains.

5. The role of hybridization processes in granitoid magmas

Morphology, magmatic textures, mineralogy, and chemical features of MME indicate that they crystallized from a relatively mafic magma of intermediate composition. Varying textures and chemical compositions (Barbarin et al., 1989), and exceptional composite enclaves that consist of xenolith(s) enclosed in a MME (see Fig. 2a in Barbarin, 1991), clearly show that MME cannot have formed by partial or total transformation and recrystallization of wall rocks xenoliths such as plagioclase–diopside hornfelses (e.g., Link, 1969). The presence of phenocrysts of hornblende and oscillatory zoned andesine in the fine-grained margins and the magmatic foliation (Fig. 2B) favor magmatic origin. MME are not restites and cannot have formed by transformation of the residues of partial melting of crustal rocks (as proposed by Bateman and Chappell, 1979): they do not contain peraluminous minerals (like most restites do in which at least sillimanite is present), and their metaluminous composition also excludes indirect derivation by melting of peraluminous restites.

It is commonly accepted that mafic magma was associated with granitic magma in most plutons and that MME represent modified blobs of this mafic magma. Furthermore, observations of xenocrysts in MME (Hibbard, 1981, 1991; Reid and Hamilton, 1987; Barbarin, 1990; Didier and Barbarin, 1991) and the development of felsic haloes in the granitoid hosts near the contact with the enclaves (see Fig. 1d in Barbarin, 1991) infer interaction between mafic and granitic magmas. Although some investigators have questioned the importance of magma mixing or mingling (e.g., Furman and Spera, 1985; Frost and Mahood, 1987), no one denies their significance in the calc-alkaline granitoid plutons of the Sierra Nevada batholith.

The different granitoids and associated mafic rocks in the Sierra Nevada batholith may result from hybridization processes that acted at three distinct but continuous periods and at different levels in the crust: (1) thorough mixing at depth produced homogeneous magmas that crystallized to granitoids, possibly with some MME; (2) mingling and local mixing during ascent and emplacement produced the many types of MME; (3) mingling and limited mixing at the emplacement level produced the MME of the composite and strongly hybridized dikes. Differentiation or local segregation commonly followed mixing and mingling (Barbarin and Bateman, 1986).

Granitoids represent homogeneous hybrid rocks in which the two original mafic and felsic components are obscure. Sr, Nd, and O isotopic data indicate that most of the Sierran calc-alkaline granitoid magmas were initially hybrids produced by mixing of mafic mantle-derived melts and felsic crustal materials (Kistler and Peterman, 1973; DePaolo, 1981; Domenick et al., 1983; Kistler et al., 1986; Hill et al., 1988).

The many different types of MME were produced by mingling and local mixing of mafic magma with granitoid magma during ascent and emplacement. Local mixing occurred between each blob of mafic magma and the enclosing granitoid magma, and differed from the thorough mixing at depth. Mafic magma could melt surrounding crustal rocks in the lower crust only if it was trapped long enough to permit thermal exchange (Marsh, 1982; Huppert and Sparks, 1988; Annen and Sparks, 2002). Thus, mafic magma that was injected into an open system in which granitoid magma was already moving upward did not have enough time to thoroughly mix with the felsic host and was disrupted into small scattered blobs in the moving granitoid magma. During ascent and emplacement, mingling continued and interaction between granitoid and MME involved thermal, mineral, and chemical transfers. The many types of MME (Figs. 3 and 6) crystallized from distinct magmas related to distinct mixing events that involved different proportions of the end members. These local mixings explain the similar mineralogical and chemical traits of each MME–granitoid pair and the differences between the various pairs in the same pluton. The various types of MME may then have aggregated into swarms. Other relatively solid particles (crystals, xenoliths) that were present in the granitoid magma were also concentrated in the swarms. These polygenic swarms typically consist of many different types of MME and scattered xenoliths, both enclosed in a matrix rich in biotite and hornblende phenocrysts. They are concentrated near the margins of the plutons, because, in a flowing magma, they formed lag deposits between domains of contrasting temperatures and rheologies. Polygenic swarms that include many different types of MME should be distinguished from monogenic swarms in which MME are similar and formed at the same time.

At the emplacement level, incompletely crystallized granitoid magmas were affected by early fractures (cf. Hibbard and Watters, 1985) that channelled the residual liquid and fluids. Mafic magmas that were injected into the fractures fragmented into many blobs and interacted with the residual granitoid magma (e.g., Furman and Spera, 1985). Each fracture represented a particular mixing system with characteristic proportions of the end members and physical conditions, and then produced a certain type of MME. Enclaves followed their host, moved within the fracture, became slightly flattened or elongated, but did not leave the fracture. The great variety of dikes indicates that they formed and evolved differently. Major controlling factors were the relative physical properties of the two components and, consequently, depended on the amount of felsic magma available and the time when mafic magma was injected into the early fractures (e.g., Barbarin and Didier, 1992). Hybridization of MME scattered in a tonalite or granodiorite matrix resulted in incorporation of crystals and chemical components from the host and partial or complete isotopic equilibration. Development of fine-grained and lobate margins in the mafic blobs reflects the contrasts in temperature, viscosity, and rheology (e.g., Bacon, 1986). The fine-grained chilled margins of the MME limited further chemical exchange and prohibited complete isotopic equilibration (cf. Didier, 1973; Huppert and Sparks, 1989).

The other extreme type of mafic dikes is the result of later injections of mafic magma into fractures of a quasi-solid granitoid. In this case, pillowing was quite limited and the felsic component could only form tiny veins in the mafic host. The granitoid matrix commonly displays an aplitic texture, regardless of its composition. The composite dikes that sharply crosscut each other in the bottom of San Joaquin River Canyon show that intervals between injections of mafic magma were relatively short. Immediately following the emplacement of a composite dike, a new fracture formed and allowed injection of another batch of mafic magma and crystallization of a new composite dike.

The distribution of MME and different types of mafic dikes in the granitoid plutons of the Sierra Nevada batholith vary a great deal. The abundance of MME decreases from the most mafic to the most felsic facies of the intrusive suites. Both the abundance of MME and the relatively mafic composition of the host granitoids are explained by the higher proportion of mafic component involved in the hybridization processes (Kistler et al., 1986; Barbarin, 1989). If the addition of the mafic component to the mixing system was continuous, the entire pluton has a relatively mafic composition and contain many MME (e.g., the western Cretaceous tonalite pluton of the Sierra Nevada batholith such as the Bass Lake Tonalite; Bateman, 1992). If a large batch of mafic magma was introduced into the mixing system at depth only once, the first pulse of granitoid would consist of mafic granitoids that contain many MME, whereas the next pulses would consist of more felsic granitoids and fewer MME (e.g., the Tuolumne Intrusive Suite; Bateman and Chappell, 1979). As the amount of the mafic component decreased and that of the anatectic magma increased by enchanged melting of crustal rocks (cf. Huppert and Sparks, 1988), involvement of the mafic component decreased progressively and possibly was nil during the latest granitoid pulses (Barbarin, 1989). Consequently, MME are scarce or absent in the latest suites such as Tuolumne. In contrast, the distribution of mafic dikes is independent of the nature of the host and is not controlled by the relative proportion of the end members in a mixing system at depth, but mainly depends on the presence of fracture systems in the partially crystallized plutons and availability of mafic magma.

In granitoid plutons, different types of interactions between felsic and mafic components are constrained

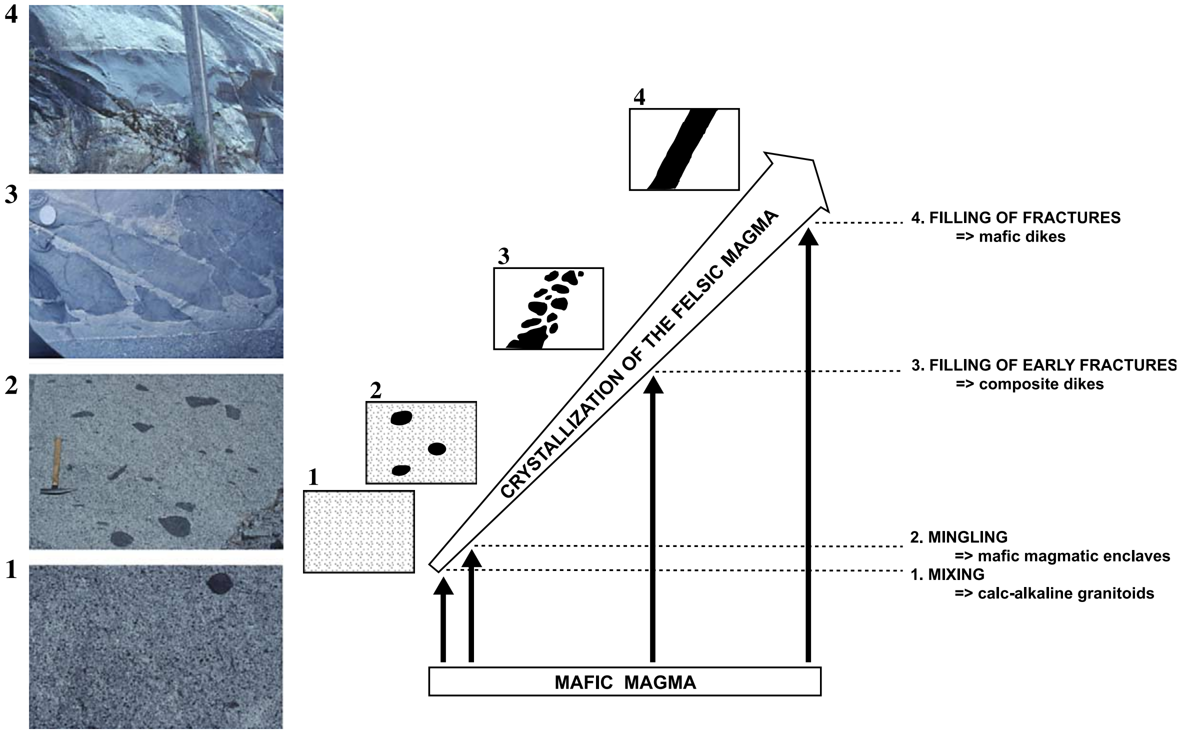

Fig. 10. Sketch showing the various types of hybridization processes resulting from injection of mafic magma into a felsic magma at different stages of crystallization of the felsic magma (from Barbarin and Didier, 1992), illustrated with cases from the Dinkey Creek pluton: granodiorite (photograph 1) and MME (photograph 2) from Shaver Lake Quarry; composite dike (photograph 3) and undisrupted dike (photograph 4) from San Joaquin River Canyon. See text for detailed explanation.

not only by the relative proportions of the two components but also by the physical properties of the contrasted magmas (e.g., Furman and Spera, 1985; Sparks and Marshall, 1986; Frost and Mahood, 1987). The physical features of these magmas and especially the relative rheology of the felsic and mafic magmas are closely related to their compositions, temperatures, and rates of crystallization. As these factors do not change simultaneously during the evolution of the system, several types of interactions may appear sequentially, and yield various types of hybrid rocks from the same parent magmas (e.g., Barbarin, 1988). Barbarin and Didier (1992) proposed that the various types of mafic rocks and enclaves are produced by injection of mafic magma into granitoid magma at different stages of crystallization of the latter. Accordingly, a fourfold model can be applied to the Sierra Nevada granitoids and associated mafic rocks (Fig. 10). (1) If mafic magma is introduced before the beginning of the crystallization of the felsic magma, thorough mixing results in homogeneous hybrid magmas and calc-alkaline granitoids. This type of mixing occurs at depth and is usually favored by convection. If crystals are already present in one or both of the components, they may become xenocrysts in apparently-homogeneous hybrid rocks. (2) If the mafic magma is introduced slightly later, the viscosities of the two magmas can be sufficiently different to permit only mingling. The mafic magma may break up into blobs and be scattered in the felsic magma to form MME. Mingling results in an increase of contact surfaces between the two components and promotes chemical transfer between MME and the granitoid host. In the granitoid plutons of the Sierra Nevada batholith, the large proportions of mafic magma probably delayed crystallization of the felsic magmas and kept mixing and mingling efficient for a long time. (3) If the mafic magma is introduced when the felsic magma is largely crystallized, the mafic magma is channelled into the early fractures of the nearly-solid granitoid rock and interacts with the last magmatic liquids only locally to form composite or fragmented dikes. (4) Late injections of mafic magma into an essentially solid granitoid rock result in undisturbed mafic dikes. Rheologies of the two components are so different that most exchanges are inhibited.

6. Origin of the mafic magma

In the Sierra Nevada batholith, as in many other plutons worldwide, the problem of the origin of the mafic magma remains. Most MME probably represent modified blobs of mafic magma and their study might give information on the nature and origin of this magma. The mafic magma is broadly coeval with the felsic magma and interactions of these magmas are evident particularly at the emplacement level. In the many models proposed (e.g., Kistler and Peterman, 1973; Brown, 1977; DePaolo, 1981; Hill et al., 1988; Kistler et al., 1986; Dodge and Kistler, 1990), the mafic magma either originates in the upper mantle or represents non-differentiated, cumulative parts of the granitoid magma. In the central part of the Sierra Nevada batholith, one of the goals of the petrographic, mineralogical, geochemical, and isotopic survey of the MME and host granitoids from several selected plutons (Barbarin et al., 1989) was to determine the origin of the MME and consequently of the mafic magma. Unfortunately, the data do not clearly favor either of the hypotheses. The isotopic correlation between MME and granitoids requires either a common source or complete equilibration of dissimilar materials.

The cogenetic nature of MME and host granitoids is based upon the following arguments (Dodge and Kistler, 1990): (1) mafic minerals have identical compositions in MME and host, although they vary in modal abundance; (2) although contents of major and trace elements are different in MME and hosts, differences in some major elements (e.g., FeOt, MgO) are relatively constant, and strong correlations exists between variation of major and trace elements; (3) in each pluton, MME plot along Rb–Sr isochrons determined using granitoid samples only and do not display significant differences in either ε_{Nd} and ε_{Sr} values with host granitoids. MME can be thus called autoliths (Dodge and Kistler, 1990). In this model, differentiation (or unmixing) of a magma produced mafic, intermediate, and felsic magmas within a zoned magma chamber.

The model above explains the identical isotopic features of MME and host granitoids, but it does not explain why the isotopic values are intermediate between those of crustal and upper mantle materials

(Kistler and Peterman, 1973; DePaolo, 1981; Domenick et al., 1983; Kistler et al., 1986; Hill et al., 1988; DePaolo et al., 1992). As it is quite impossible to produce magmas with such isotopic features by melting crustal rocks only, addition of upper mantle magma is necessary. Furthermore, the upper mantle provides not only material but also the heat necessary to melt the crustal rocks (e.g., Didier and Lameyre, 1969; Brown and Fyfe, 1970; Reid et al., 1983; Huppert and Sparks, 1988; Annen and Sparks, 2002). Even if the MME of the Sierra Nevada batholith do not display a distinctive mantle signature, they are mixtures of crustal melt and mantle-derived magma like their calc-alkaline granitoid hosts (Kistler and Peterman, 1973; DePaolo, 1981; Domenick et al., 1983; Kistler et al., 1986; Hill et al., 1988; DePaolo et al., 1992). Some investigators have gone further to propose that calc-alkaline granitoids and MME were produced by the differentiation of upper mantle magmas without addition of crustal melt (e.g., Brown, 1977). Such models may be supported by the absence of aluminous mineral-bearing restites that imply involvement crustal rocks. Isotopic data, however, generally indicate incorporation of a crustal component even if the mantle-derived component is dominant (e.g., DePaolo, 1981; Kistler et al., 1986).

Considering that mafic dikes in the Sierra Nevada batholith may represent the mafic magma from which the MME were derived, isotopic systematics indicate that, through hybridization processes, isotopic equilibration for Rb–Sr may occur between the most hybridized blobs of mafic rocks and the host granitoid in the composite dikes; these then plot on the same isochron, whereas some darker and non-hybridized blobs plot off of it (Barbarin et al., 1989; Dodge and Kistler, 1990). After mingling, during ascent and emplacement, and until the pluton cooled off, diffusion processes were active between blobs of mafic magma and the enclosed granitoid magma and induced partial chemical and complete isotopic equilibration. Experimental studies indicate that diffusion processes induce chemical and isotope equilibration between silicates of contrasted compositions, and that isotopic equilibration is generally more easily achieved than chemical equilibration, because isotopic exchanges proceed more quickly than chemical exchanges (Lesher, 1990). Isotopic equilibration between MME and host granitoids is a feature of mingling and mixing in the plutonic environment. In the volcanic environment, as eruption and cooling occur immediately after mixing and mingling, there is no time for isotopic equilibration: enclaves and host lavas may display distinct signatures.

Parallel variations in the chemistry of MME and granitoids are related to different contents of minerals having similar compositions (Barbarin, 1986). In each MME–granitoid pair, constant differences for FeOt and MgO contents result from the occurrence of hornblende and biotite with identical chemical compositions but in different proportions. Furthermore, mechanical mineral transfer helps to explain some chemical relationships between MME and hosts. Correlations between the abundance and fractionation of REE in MME and host granitoids probably result from mechanical transfer of accessory minerals. Exchanges of apatite crystals between MME and granitoids have been demonstrated in several plutons worldwide (e.g., Didier and Barbarin, 1991). In the Sierra Nevada batholith, granitoids rich in titanite enclose MME rich in titanite (e.g., Mount Givens granodiorite), whereas granitoids poor in titanite enclose MME in which titanite is rare. This correlation between titanite content in MME and host granitoids may either result from mechanical transfer of crystals or chemical transfer of the elements necessary for crystallization of titanite.

Identical compositions of minerals such as biotite and hornblende in MME and contiguous granitoid (Fig. 9) might be explained by crystallization under the same physical conditions (Barbarin, 1986). Even if mafic minerals are commonly more elongated and sometimes acicular in the MME, the differences in size or shape do not imply variations in composition. Most phenocrysts of mafic minerals and plagioclase were probably transferred either from the mafic to the felsic magmas or reversely (Barbarin, 1990). Unlike isotopic equilibration that occurred throughout the pluton, chemical compositions that are identical for the same minerals of MME and contiguous granitoids may change from one locality to another in the same pluton. Local variations in mineral compositions reflect local evolution of the host granitoids. Uniform mineral compositions and similar chemical affinities in the MME and hosts may also indicate that, concomitantly with mixing and mingling, diffusive processes affected the MME and host granitoids (e.g., Lesher, 1990; Baker, 1990).

Autoliths certainly exist but are relatively rare in the plutons of the Sierra Nevada batholith. Rare MME with large crystals and cumulate textures are autoliths and come from early disruption of cumulate layers in the plutons. Autoliths do not show signs of recrystallization even where they are associated with common MME in some swarms (Dorais et al., 1990; Barbarin, 1991). The rarity of these enclaves and their preserved cumulate texture exclude the model where MME with fine-grained texture are supposed to result from the recrystallization of coarse-grained cumulate rocks. Some unusual MME also have large grains and are identical with the rock that forms the schlieren layerings and mafic aggregates so common in the margins of the plutons (e.g., Courtright Reservoir: Bateman et al., 1984b). These MME come from the disruption of schlieren layerings or mafic aggregates, and differ from the usual fine-grained MME. When mechanical processes concentrate large crystals of biotite, hornblende, titanite, and other accessory minerals to schlieren layerings and mafic aggregates, MME were already present in the magma: they are invariably in sharp contact with the coarse-grained mafic mineral-rich matrix (Barbarin and Bateman, 1986). Some MME are commonly included in the schlieren layerings or mafic aggregates, as are large crystals and xenoliths that floated in the granitoid magma. Many polygenic swarms consist of MME enclosed in mafic aggregates (e.g., Courtright Reservoir: Bateman et al., 1984b). Disruption of these swarms by magma movement has locally produced isolated MME surrounded by granitoid rich in large crystals of mafic minerals (e.g., May Lake in the Tuolumne Intrusive Suite). Furthermore, in some polygenic swarms, contacts between MME may look more like contacts between pebbles than contacts between blobs of magma. These features suggest that when mechanical processes produced mafic aggregates and schlieren layerings, most MME were already formed and thus there is no genetic relationships between the common mafic aggregates or schlieren layerings and MME.

Rare MME display a cumulate texture and are autoliths (Dorais et al., 1990; Barbarin, 1991). One problem is whether the more common and fine-grained MME enclosed in the plutons of the Sierra Nevada batholith are also autoliths. No petrographic, mineralogical, or chemical data clearly indicate whether the mafic magma that crystallized MME came from the upper mantle or from the same magma as the granitoid host. The above review of the different arguments suggests that the two origins are both possible. Actually, MME and host granitoids can be considered cogenetic, because they are both hybrid rocks resulting from the mixing of two magmatic components. Isotopic systematics indicate that the Sierra Nevada batholith granitoids consist of up to 30 vol.% of preexisting crustal material (DePaolo, 1981). MME probably contain from 10 vol.% to a few volume percent of crustal materials. The relatively limited difference in composition between the end members and the chemical equilibration that occurred during and after emplacement explain why so many similarities exist between the MME and host granitoids in the Sierra Nevada batholith. The mafic magma is presumed to have come from the upper mantle (e.g., Didier et al., 1982; Cantagrel et al., 1984) and to have been andesite (Reid et al., 1983) or high-alumina, calc-alkaline, or tholeiitic basalt in composition (Dorais et al., 1990).

7. General model for the formation of granitoids and associated mafic rocks

Considering the petrographic, mineralogical, geochemical, and isotopic data, a general model can be proposed for the origin and evolution of the Sierra Nevada granitoids and the associated mafic rocks including MME and dikes (Fig. 11). This model uses a triangular diagram in which granitoids, mafic aggregates, MME, and mafic dikes are plotted according to their content of mafic minerals (plus accessories), plagioclase, and quartz and K-feldspar (Fig. 3): (1) a mantle-derived mafic component M (basalt composition) thoroughly mixes with a felsic component F (graywacke composition) to create hybrid magmas H, which then fractionate to produce the different granitoids; (2) when contrasting physical conditions inhibit thorough mixing between the mafic and felsic components (Fig. 10), mingling occurs and

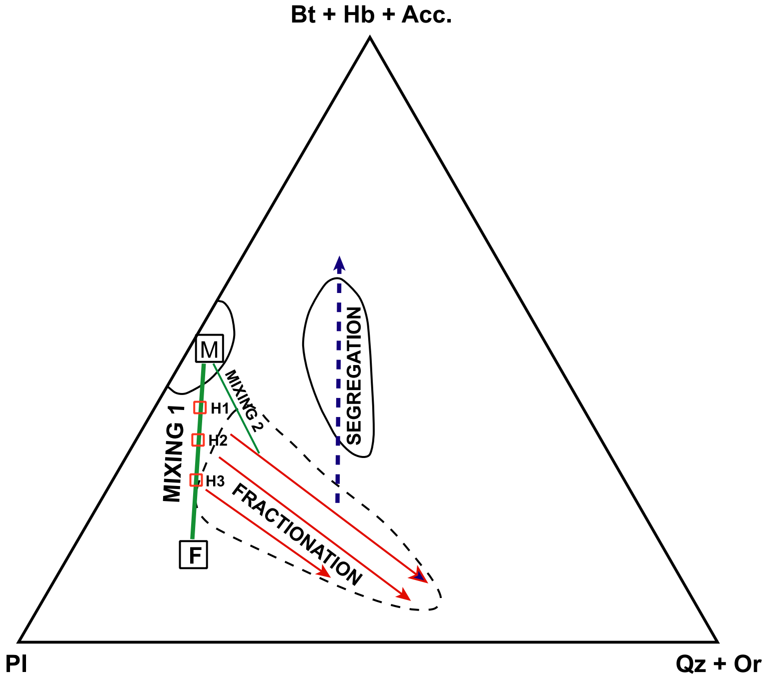

Fig. 11. Complex model proposed for the formation of the granitoids and various associated mafic rocks of the central Sierra Nevada batholith. This model is based on the modes of the different rocks (cf. Fig. 3) and is constrained by field, geologic, mineralogical, chemical, and isotopic data. (F) and (M) represent the supposed parent felsic and mafic end members and (H) the various homogeneous hybrid magmas that differentiated to produce the various granitoids. See text for detailed explanation.

leads to the formation of MME (local mixing between each MME and host results in enrichment of the MME in K-feldspar and quartz); (3) late surges of mafic magma mix with evolved granitoid magmas to produce the hybrid magmas of the composite dikes or monogenic swarms; (4) coarse-grained mafic aggregates represent mechanical concentrations of mafic minerals and accessory phases from evolved granitoid magmas. MME and xenoliths commonly are included in these segregations.

This model differs from the models proposed for plutons elsewhere (review in Didier and Barbarin, 1991), because it involves complex and multiple mixing and mingling processes instead of a single one-stage process. The sequential occurrence of the hybridization processes depends on the relative proportions of the two components and on their physical properties (Furman and Spera, 1985; Sparks and Marshall, 1986; Frost and Mahood, 1987; Barbarin, 1988; Barbarin and Didier, 1992). The complex model is consistent with the large diversity of MME in the same pluton, the existence of composite enclaves that consist of a MME enclosed in another MME, and explains why the MME do not invariably plot on the granitoid trends in binary evolution diagrams (Fig. 6). In the Sierra Nevada batholith, hybridization processes cannot be either demonstrated or modeled using simple mixing tests, because they were of various types, commonly affected local areas and limited volumes of magmas, and occurred at different stages of the evolutionary history of the plutons.

8. Conclusions

A complex combination of hybridization, differentiation, and segregation processes governed the genesis and evolution of the granitoids and mafic rocks, including MME, in the plutons of the central Sierra Nevada batholith. Commonly, mixing and mingling of two contrasting end member components were followed by differentiation and segregation processes that affected the hybrid magmas produced during mixing. The occurrence and succession of the various hybridization processes were constrained by the physical properties of the coeval magmas and, consequently, by their nature and mass fractions:

1. Host granitoids were produced by thorough mixing at depth of two or more components.
2. The many types of fine-grained MME were formed by mingling and local mixing during ascent and emplacement. Similar chemical affinities and isotopic equilibration between MME and hosts were mainly produced at the emplacement level through diffusion and percolation processes.
3. Scarce coarse-grained and hornblende-rich MME that display cumulate textures are autoliths and resulted from disruption at depth of early cumulates. Rare MME that are enriched in large mafic minerals, especially biotite, were produced by the disruption of mafic aggregates or schlieren layering at the emplacement level.
4. In the evolved granitoid magmas, mafic aggregates and schlieren layering resulted from mechanical segregation and concentration of mafic minerals and other solid particles such as xenoliths or MME.
5. Mafic dikes represent injection of mafic magma into early fractures in the cooling and crystallizing plutons. If some granitoid magma was still present, the mafic magma fragmented into blobs and formed composite dikes. The nature and extent of the fragmentation and exchanges depended on the rheology contrasts and relative abundance of the two components in the mixing systems.

Detailed field observations and petrographic, mineralogical, chemical, and isotope studies of the granitoids, MME, and other mafic rocks in some plutons of the central Sierra Nevada batholith provide information of their genesis and evolution. The model involving multiple hybridization processes can probably be applied to most calc-alkaline plutons worldwide (Barbarin, 1988; Didier and Barbarin, 1991), in particular Cordilleran batholiths that contain abundant associated mafic rocks and MME.

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References

Annen, C., Sparks, R.S.J., 2002. Effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust. Earth and Planetary Science Letters 203, 937–955.

Bacon, C.R., 1986. Magmatic inclusions in silicic and intermediate volcanic rocks. Journal of Geophysical Research 91, 6091–6112.

Baker, D.R., 1990. Chemical interdiffusion of dacite and rhyolite: anhydrous measurements at 1 atm and 10 Kbar, application of transition state theory, and diffusion in zoned magma chambers. Contributions to Mineralogy and Petrology 104, 407–423.

Barbarin, B., 1986. Comparison of mineralogy of mafic magmatic enclaves and host granitoids, central Sierra Nevada, California. Abstracts with Programs-Geological Society of America 18, 83.

Barbarin, B., 1988. Field evidence for successive mixing and mingling between the Piolard Diorite and the Saint Julien-la-Vêtre Monzogranite (Nord Forez, Massif Central, France). Canadian Journal of Earth Sciences 25, 49–59.

Barbarin, B., 1989. Mélange de magmas et origine de la zonation normale des plutons granitiques crétacés du batholite de la Sierra Nevada, Californie. Comptes rendus de l'Académie des Sciences Paris 309, 1563–1569.

Barbarin, B., 1990. Plagioclase xenocrysts and mafic magmatic enclaves in some granitoids of the Sierra Nevada Batholith, California. Journal of Geophysical Research 95, 17747–17756.

Barbarin, B., 1991. Enclaves of the Mesozoic calc-alkaline granitoids of the Sierra Nevada batholith, California. In: Didier, J., Barbarin, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology, vol. 13. Elsevier, Amsterdam, pp. 135–153.

Barbarin, B., 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. Lithos 46, 605–626.

Barbarin, B., Bateman, P.C., 1986. Origin and evolution of mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada. 14th International Mineralogical Association Meeting, Stanford, California, 1986, Abstracts with Programs, p. 50.

Barbarin, B., Didier, J., 1992. Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas. Transactions of the Royal Society of Edinburgh: Earth Sciences 83, 145–153.

Barbarin, B., Dodge, F.C.W., Kistler, R.W., 1985. REE contents and Rb–Sr systematics of mafic enclaves and other associated mafic rocks, central Sierra Nevada, California. EOS Transactions of the American Geophysical Union 66, 1150.

Barbarin, B., Dodge, F.C.W., Kistler, R.W., Bateman, P.C., 1989. Mafic inclusions and associated aggregates and dikes in granitoid rocks, central Sierra Nevada Batholith. Analytic Data, U.S. Geological Survey Bulletin, 1899.

Barnes, C.G., 1983. Petrology and upward zonation of the Wooley Creek Batholith, Klamath Mountains, California. Journal of Petrology 24, 495–537.

Bateman, P.C., 1992. Plutonism in the Central Part of the Sierra Nevada Batholith, California. U.S. Geological Survey Professional Paper, 1483.

Bateman, P.C., Chappell, B.W., 1979. Crystallization, fractionation, and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California. Geological Society of America Bulletin 90, 465–482.

Bateman, P.C., Nokleberg, W.J., 1978. Solidification of the Mount Givens granodiorite, Sierra Nevada, California. Journal of Geology 86, 563–579.

Bateman, P.C., Dodge, F.C.W., Bruggman, P.E., 1984a. Major oxide analyses, CIPW norms, modes, and bulk specific gravities of plutonic rocks from the Mariposa $1^\circ \times 2^\circ$ sheet, central Sierra Nevada, California. U.S. Geological Survey Open-File, 84–162.

Bateman, P.C., Kistler, R.W., DeGraff, J.V., 1984b. Courtright intrusive zone: Sierra National Forest, Fresno County, California. California Geology 37, 91–98.

Best, M., 1963. Petrology of the Guadalupe igneous complex, southwestern Sierra Nevada foothills, California. Journal of Petrology 4, 223–259.

Brown, G.C., 1977. Mantle origin of Cordilleran granites. Nature 265, 21–24.

Brown, G.C., Fyfe, W.S., 1970. The production of granitic melts during ultrametamorphism. Contributions to Mineralogy and Petrology 28, 310–318.

Cantagrel, J.M., Didier, J., Gourgaud, A., 1984. Magma mixing: origin of intermediate rocks and “enclaves” from volcanism to plutonism. Physics of the Earth and Planetary Interiors 35, 63–76.

Chen, J.H., Moore, J.G., 1982. Uranium–lead isotopic ages from the Sierra Nevada batholith, California. Journal of Geophysical Research 87, 4761–4784.

Cloos, E., 1936. Der Sierra Nevada pluton in Californien, Neues Jahrbuch fur Mineralogie. Geologie und Palaontologie 76, 355–450.

Cobbing, E.J., Pitcher, W.S., 1972. The Coastal Batholith of central Peru. Journal of the Geological Society [London] 128, 421–460.

Coleman, D.S., Glazner, A.F., Miller, J.S., Bradford, K.J., Frost, T.P., Joyce, J.L., Bachl, C.A., 1995. Exposure of a Late Cretaceous layered mafic–felsic magma system in the central Sierra Nevada batholith, California. Contributions to Mineralogy and Petrology 120, 129–136.

Cruden, A.R., Tobisch, O.T., Launeau, P., 1999. Dinkey Creek pluton, central Sierra Nevada, California: magnetic evidence for conduit-fed emplacement of a tabular granite. Journal of Geophysical Research 104, 10511–10530.

DePaolo, D.J., 1981. A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. Journal of Geophysical Research 86, 10470–10488.

DePaolo, D.J., Perry, F.V., Baldridge, W.S., 1992. Crustal versus mantle sources of granitic magmas: a two-parameter model based on Nd isotopic studies. Transactions of the Royal Society of Edinburgh. Earth Sciences 83, 439–446.

Didier, J., 1973. Granites and their enclaves. The Bearing of Enclaves on the Origin of Granites, Development in Petrology, vol. 3. Elsevier, Amsterdam.

Didier, J., Barbarin, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology, vol. 13. Elsevier, Amsterdam.

Didier, J., Lameyre, J., 1969. Les granites du Massif Central Français. Etude comparée des leucogranites et granodiorites. Contributions to Mineralogy and Petrology 24, 219–238.

Didier, J., Duthou, J.L., Lameyre, J., 1982. Mantle and crustal granites, genetic classification of orogenic granites and the nature of their enclaves. Journal of Volcanology and Geothermal Research 14, 125–132.

Dodge, F.C.W., Kistler, R.W., 1990. Some additional observations on inclusions in the granitic rocks of the Sierra Nevada. Journal of Geophysical Research 95, 17841–17848.

Dodge, F.C.W., Papike, J.J., Mays, R.E., 1968. Hornblendes from granitic rocks of the central Sierra Nevada Batholith, California. Journal of Petrology 9, 378–410.

Dodge, F.C.W., Smith, C., Mays, R.E., 1969. Biotites from granitic rocks of the central Sierra Nevada Batholith, California. Journal of Petrology 10, 250–271.

Domenick, M.A., Kistler, R.W., Dodge, F.C.W., Tatsumoto, M., 1983. Nd and Sr study of crustal and mafic inclusions from the Sierra Nevada and implications for batholith petrogenesis. Geological Society of America Bulletin 94, 713–719.

Dorais, M.J., Whitney, J.A., Roden, M.F., 1990. The origin of mafic enclaves from the Dinkey Creek pluton, central Sierra Nevada Batholith. Journal of Petrology 31, 853–881.

Fourcade, S., Allègre, C.J., 1981. Trace elements behavior in granite genesis: a case study. The calc-alkaline plutonic association from the Quérigut complex (Pyrénées, France). Contributions to Mineralogy and Petrology 76, 177–195.

Frost, T.P., Mahood, G.A., 1987. Field, chemical, and physical constraints on mafic–felsic magma interaction in the Lamarck Granodiorite, Sierra Nevada, California. Geological Society of America Bulletin 99, 272–291.

Furman, T., Spera, T., 1985. Co-mingling of acid and basic magma with implications for the origin of mafic I-type xenoliths, field and petrochemical relations of an usual dike complex at Eagle Peak Lake, Sequoia National Park, California, U.S.A. Journal of Volcanology and Geothermal Research 24, 151–178.

Gilbert, G.K., 1906. Gravitational assemblages in granite. Geological Society of America Bulletin 17, 321–328.

Gilder, S.A., McNulty, B.A., 1999. Tectonic exhumation and tilting of the Mount Givens pluton, central Sierra Nevada, California. Geology 27, 919–922.

Hibbard, M.J., 1981. The magma mixing origin of mantled feldspars. Contributions to Mineralogy and Petrology 76, 158–170.

Hibbard, M.J., 1991. Textural anatomy of twelve magma-mixed granitoid systems. In: Didier, J., Barbarin, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology, vol. 13. Elsevier, Amsterdam, pp. 431–444.

Hibbard, M.J., Watters, R.J., 1985. Fracturing and diking in uncompletely crystallized granitic plutons. Lithos 18, 1–12.

Hill, M., O'Neil, J.R., Noyes, H., Frey, F.A., Wones, D.R., 1988. Sr, Nd, and O isotopic variations in compositionally zoned and unzoned plutons in the central Sierra Nevada batholith. American Journal of Science 288, 213–241.

Holden, P., Halliday, A.N., Stephens, W.E., 1987. Neodymium and strontium isotope content of microdiorite enclaves points to mantle input into granitoid production. Nature 330, 53–56.

Holmes, A., 1928. The Nomenclature of Petrology. Murby, London.

Huppert, H.E., Sparks, R.S.J., 1988. The generation of granitic magmas by intrusion of basalt into the crust. Journal of Petrology 29, 599–624.

Huppert, H.E., Sparks, R.S.J., 1989. Chilled margins in igneous rocks. Earth and Planetary Science Letters 92, 397–405.

Kistler, R.W., Peterman, Z.E., 1973. Variations in Sr, Rb, K, Na, and initial 87Sr/86Sr in Mesozoic granitic rocks and intruded wall rocks in central California. Geological Society of America Bulletin 84, 3489–3512.

Kistler, R.W., Chappell, B.W., Peck, D.L., Bateman, P.C., 1986. Isotopic variation in the Tuolumne Intrusive Suite, central Sierra Nevada, California. Contributions to Mineralogy and Petrology 94, 205–220.

Lacroix, A., 1893. Les enclaves des roches volcaniques. Protat, Mâcon.

Lesher, C.E., 1990. Decoupling of chemical and isotopic exchange during magma mixing. Nature 344, 235–237.

Link, A.J., 1969. Inclusions in the Half Dome quartz monzonite, Yosemite National Park, California. PhD Thesis, Northwestern University, Illinois, U.S.A.

Marsh, B.D., 1982. On the mechanics of igneous diapirism, stoping, and zone melting. American Journal of Science 282, 808–855.

McNulty, B.A., Tong, W., Tobisch, O.T., 1996. Assembly of a dike-fed magma chamber: the Jackass lakes pluton, central Sierra Nevada, California. Geological Society of America Bulletin 108, 926–940.

McNulty, B.A., Tobisch, O.T., Cruden, A.R., 2000. Multistage emplacement of the Mount Givens pluton, central Sierra Nevada batholith, California. Geological Society of America Bulletin 112, 119–135.

Noyes, H.J., Wones, D.R., Frey, F.A., 1983a. A tale of two plutons: geochemical evidence bearing on the origin and differentiation of the Red Lake and Eagle Peak plutons, central Sierra Nevada, California. Journal of Geology 91, 487–509.

Noyes, H.J., Wones, D.R., Frey, F.A., 1983b. A tale of two plutons: petrographic and mineralogic constraints on the petrogenesis of the Red Lake and Eagle Peak plutons, central Sierra Nevada, California. Journal of Geology 91, 353–379.

Pabst, A., 1928. Observations on inclusions in the granitic rocks of the Sierra Nevada. University of California Publications 17, 325–386.

Palivcovà, M., 1978. Ocellar quartz leucogabbro (Central bohemian pluton) and genetic problems of ocellar rocks. Geologisky Zbornick Geologica Carpathica 29, 19–41.

Phillips, J.A., 1880. On concretionary patches and fragments of other rocks contained in granites. Quaternarly Journal of the Geological Society of London 36, 1–21.

Pin, C., Binon, M., Belin, J.M., Barbarin, B., Clemens, J.D., 1990. Origin of microgranular enclaves in granitoids: equivocal Sr–Nd evidence from Hercynian rocks in the Massif Central (France). Journal of Geophysical Research 95, 17821–17828.

Pitcher, W.S., 1983. Granite Type and Tectonic Environment. In: Hsu, K. (Ed.), Mountain Building Processes. Academic Press, London, pp. 19–40.

Pitcher, W.S., 1991. Synplutonic dykes and mafic enclaves. In: Didier, J., Barbarin, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology, vol. 13. Elsevier, Amsterdam, pp. 383–391.

Pitcher, W.S., Atherton, M.P., Cobbing, E.J., Beckinsale, R.D. (Eds.), Magmatism at a plate edge: the Peruvian Andes. Blackie and Son, Glasgow.

Piwinskii, A.J., 1968. Studies of batholithic feldspars: Sierra Nevada, California. Contributions to Mineralogy and Petrology 17, 204–223.

Piwinskii, A.J., 1973. Experimental studies of igneous rock series, central Sierra Nevada Batholith, California Part II. Neues Jahrbuch fur Mineralogie Monatshefte 5, 193–215.

Read, H.H., 1957. The Granite Controversy. Murby, London.

Reid, J.B., Hamilton, M.A., 1987. Origin of Sierra Nevadan granite: evidence from small scale composite dikes. Contributions to Mineralogy and Petrology 96, 441–454.

Reid, J.B., Evans, O.C., Fates, D.G., 1983. Magma mixing in granitic rocks of the central Sierra Nevada, California. Earth and Planetary Science Letters 66, 243–261.

Ryerson, F.J., Hess, P.C., 1978. Implications of liquid–liquid distribution coefficients to mineral–liquid partitioning. Geochimica et Cosmochimica Acta 42, 921–932.

Sawka, W.N., Chappell, B.W., Kistler, R.W., 1990. Granitoid compositional zoning by side-wall boundary layer differentiation: evidence from the Palisade Crest intrusive suite, central Sierra Nevada, California. Journal of Petrology 31, 519–553.

Sparks, R.S.J., Marshall, L.A., 1986. Thermal and mechanical constraints on mixing between mafic and silicic magmas. Journal of Volcanology and Geothermal Research 29, 99–124.

Stern, T.W., Bateman, P.C., Morgan, B.A., Newall, M.F., Peck, D.L., 1981. Isotopic U–Pb ages of zircon from granitoids of the central Sierra Nevada, California. U.S. Geological Survey Professional Paper, 1185.

Tindle, A.G., Pearce, J.A., 1983. Assimilation and partial melting of continental crust: evidence from the mineralogy and geochemistry of autoliths and xenoliths. Lithos 16, 185–202.

Tobisch, O.T., McNulty, B.A., Vernon, R.H., 1997. Microgranitoid enclave swarms in granitic plutons, central Sierra Nevada, California. Lithos 40, 321–339.

Vernon, R.H., 1983. Restite, xenoliths and microgranitoid enclaves in granites. Journal and Proceedings of the Royal Society of New South Wales 116, 77–103.

Vernon, R.H., 1984. Microgranitoid enclaves in granites–globules of hybrid magma quenched in a plutonic environment. Nature 309, 438–439.

Vernon, R.H., 1991. Interpretation of microstructures of microgranitoid enclaves. In: Didier, J., Barbarin, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology, vol. 13. Elsevier, Amsterdam, pp. 277–291.

Watson, E.B., 1976. Two-liquid partition coefficients: experimental data and geochemical implications. Contributions to Mineralogy and Petrology 56, 119–134.