The nature and polygenetic origin of orbicular granodiorite in the Lower Castle Creek pluton, northern Sierra Nevada batholith, California

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ABSTRACT

Mafic and granodioritic magmas mingled to produce a swarm of microdiorite enclaves in the granodiorite. The enclaves and rare hornfels inclusions were carried upward in an oval-shaped pipe, 30 m long and 15 m wide, probably as a gas-driven mass to a point where an H₂O-rich, superheated felsic melt intruded the pipe and the enclave mass, and upon abrupt undercooling, deposited orbicul ar shells of tangentially oriented microcrystals of sodic plagioclase, quartz, K-feldspar, and biotite on 20% of the enclaves and inclusions now located only against the north margin of the pipe. The mass of orbicular and nonorbicular enclaves was then injected by a quartz monzodiorite magma that now comprises the matrix among the enclaves.

INTRODUCTION

During the course of regional geologic mapping in the Donner Pass region of the Sierra Nevada, several localized swarms of mafic magmatic enclaves were discovered in some of the plutonic rocks that provide good field evidence of the enclaves' origin by magma mingling. Such enclave swarms are relatively common in Sierran granitic plutons (Tobisch et al., 1997; Vernon and Paterson, 2008), and for the purposes of this paper, I accept the field, structural, geochemical, and modeling evidence that mafic enclaves represent globules of mafic magma produced by the mingling of a hot mafic magma with a cooler host granitic magma in the mid- to upper crustal levels of granitic plutons (e.g., Taylor et al., 1980; Vernon, 1983; Reid et al., 1983; Furman and Spera, 1985; Frost and Mahood, 1987; Larsen and Smith, 1990; Foster and Hyndman, 1990; Zorpi et al., 1989; Wiebe, 1991; Barbarin and Didier, 1992; Pitcher, 1993; Wiebe et al., 1997; Barbarin, 2005, and many others).

Much less common, but by no means unique, are concentrations of mafic enclaves with orbicular structure, not only in the Sierra Nevada batholith (Moore and Lockwood, 1973), but also in plutons worldwide, especially in Scandinavia (e.g., Sederholm, 1928; Simonen, 1966; Lahti, 2005). The orbicules themselves may have cores of other kinds of rocks besides mafic rocks, including metamorphic rock fragments and single crystals or clots of minerals such as K-feldspar megacrysts (e.g., Lahti, 2005).

This paper describes an assemblage and origin of some remarkable orbicular rocks in the granodiorite of Lower Castle Creek pluton in the northern Sierra Nevada batholith (Fig. 1). These orbicular rocks bear similarities to some of those elsewhere in the Sierra Nevada (Moore and Lockwood, 1973), although they are larger and better developed than most Sierran examples (Fig. 2). Large mafic enclaves with felsic haloes have also been noted but not described by Tobisch et al. (1997, their fig. 8c, p. 333) in the central Sierra Nevada batholith.

TERMINOLOGY

Mafic magmatic enclaves (MME in the terminology of Barbarin, 2005; also autoliths in the terminology of Pabst, 1928) comprise subrounded globules of mafic microgranular...
igneous rocks in a granitic matrix. Such enclaves are commonly but irregularly distributed throughout Sierran granitic plutons (Pabst, 1928; Mayo, 1935; Bateman et al., 1963; Link, 1969), especially in plutons of tonalitic or granodiorite composition. Mafic magmatic enclaves are distinguished from xenoliths that represent bits of mafic segregations (restite) from the bottoms of plutons (Bateman et al., 1963; Vernon, 1983, 1984; Chappell et al., 1987), or early formed indigenous cumulates of their host magmas (Dodge and Kistler, 1990), or mantle rocks (e.g., Irving, 1980), or of a mafic magmatic neosome (Hopson and Mattinson, 1994). Inclusions are fragments derived from the pluton’s country rocks.

Swarms are concentrations of abundant enclaves typically separated by a minimal amount of host matrix (Pabst, 1928, p. 331). Enclave swarms have subsequently been recognized widely in the Sierra Nevada (e.g., Tobisch et al., 1997; Vernon and Paterson, 2008) and in many granitic bodies worldwide (e.g., Gansser and Gyr, 1964; Didier, 1973; Elburg and Nicholls, 1995; Surour and Kabesh, 1998; Arvin et al., 2004). Most workers have concluded that such swarms formed by disaggregation or pillowing of hybrid mafic dikes during injection into a host felsic magma (e.g., Roddick and Armstrong, 1959; Reid et al., 1983; Frost and Mahood, 1987; Wiebe, 1991; Sylvester, 1998).

Orbs are enclaves or country rock fragments that comprise a core typically consisting of plutonic igneous rocks that may range greatly from gabbro to granite and pegmatite (e.g., Enz et al., 1979; Lahti, 2005), and a concentric layer or orbicule of radially or tangentially oriented plagioclase and/or K-feldspar associated with quartz and biotite and or amphibole. Contacts between the core and the orbicule and between the orbicule and matrix are typically sharp. A plutonic matrix fills the spaces among the orbs; it may be composed of a slightly more mafic phase of the host plutonic rock (Leveson, 1966).

**GEOLOGIC SETTING AND NATURE OF LOWER CASTLE CREEK PLUTON**

The Lower Castle Creek pluton is an oval-shaped body of hornblende-biotite granodiorite ~9 km long and 8 km wide in the center of what Kulow (1996) termed the Castle Valley pluton assemblage (Fig. 1). Lower Castle Creek dikes intruded the adjacent plutons, and, with a U-Pb age of 110 ± 5 Ma (Kulow, 1996), it is the youngest pluton of the assemblage.

The granodiorite is a medium-grained, light-gray rock composed of euhedral to subhedral plagioclase (≥50%), anhedral poikilitic orthoclase (up to 17%), and fine- to medium-grained, subhedral quartz (up to 20%). The remainder of the rock comprises medium- to coarse-grained hornblende and biotite, commonly in mafic aggregates or clots from 5 to 8 mm in width, or in single, anhedral crystals up to 5 mm long. The clotted mafic minerals and its relatively high color index (15–36) distinguish the granodiorite of Lower Castle Creek from the surrounding plutons (Kulow, 1996).

Most of the granodiorite of Lower Castle Creek is homogeneous, but noteworthy outcrops of comb layering, schlieren, and orbicular rocks exist locally especially near its contacts with the Rattlesnake Creek pluton (Kulow, 1996). The mineralogy, fabric, and dimensions of the comb layering are similar to such features elsewhere in the Sierra Nevada batholith (Moore and Lockwood, 1973; Paterson et al., 2008). Discrete mafic enclaves are sparse in the Lower Castle Creek pluton, except in local, rare swarms, and country-rock inclusions have not been found except in the pipe described in this paper.

All of the Castle Creek plutons are cut by aplite dikes up to one meter thick and less commonly by rare diabase dikes from 0.3 m to 5 m thick, which, at their upper extremities within the adjacent Summit Lake and Rattlesnake Creek plutons, have clearly mingled with granodiorite to produce various types of swarms of mafic enclaves, notably at McGlashan Point and Lake Angela near Donner Pass (Fig. 1), and at Rainbow Bend in the southwest part of the Rattlesnake pluton (Pabst, 1928).

**NATURE OF THE ORBICULAR ROCKS**

The orbicular rocks crop out in a singular exposure of a quartz monzodiorite pipe on the north-facing flank of a small hill at the east end of Sand Ridge, 5 km north of Soda Springs, California (Fig. 1). The pipe lies well within the interior of the Lower Castle Creek pluton, about one kilometer west of its eastern contact with the older Summit Lake pluton. Orbicular rocks are generally found nearer the margins of plutons (Moore and Lockwood, 1973; Lahti, 2005), but several instances of them being evenly distributed or accumulated throughout an entire pluton have been cited, and some orbicular rocks may...
coincide with inclusion- or enclave-rich zones in plutonic rocks (Lahti, 2005).

The quartz monzodiorite pipe is ~30 m long and 15 m wide within the hornblende-biotite granodiorite of Lower Castle Creek (Fig. 3). As such, it is almost an order of magnitude larger than most Sierran pipes described by Tobisch et al. (1997) and Paterson (2009). The contact between the pipe and the granodiorite host is fairly sharp or gradational over a zone ~10 cm (Fig. 4), but locally the contact is a schlieren zone from 20 to 50 cm wide (Fig. 5).

Eighty percent of the enclaves in the pipe are quite ordinary rounded or subrounded mafic magmatic enclaves, generally 5–15 cm in longest dimension grading upward to outsized individuals of 20 cm (Fig. 6). Enclave packing is moderate to tight, their axial ratios are ~2:1, and they lack preferred orientation. All consist of fine-grained microdiorite and are now more feldspathic than their inferred initial diabasic composition because of extensive chemical exchange with the quartz monzodioritic matrix and perhaps also with granodiorite of the host pluton, a common phenomenon among mafic enclaves in other Sierran granitic plutons (Pabst, 1928; Barbarin, 1990; Sisson et al., 1996) and elsewhere (e.g., Zorpi et al., 1991).

The remaining 20% of the enclaves in the quartz monzodiorite pipe are orbicular mafic magmatic enclaves and rare, angular fragments of hornfels characterized by felsic orbicules (Fig. 7). The hornfels stems from locally and widely exposed country rocks of the Jurassic Sailor Canyon Formation. The orbicular rocks are concentrated exclusively at the north margin of the pipe (Fig. 3) right up to its sharp contact with the host pluton, whereas the contact between the orbicular and the nonorbicular enclaves in the pipe is gradational over a few centimeters. The orbicular enclaves are moderately packed; their axial ratios are from 1:1 to 3:1, and they are generally twice as large as the nonorbicular enclaves.

The felsic orbicules are typically symmetrical and well developed, ranging in thickness from 7 to 40 mm; most are ~20 mm thick. Each orbicule maintains its thickness around its enclave, at least in the two-dimensional exposures afforded by the outcrop. In most instances, the orbicules are in direct contact with their cores and, thus, are concentric to the edge of the semirounded enclaves (Fig. 2). Orbicules of some enclaves touch or overlap in a shared arrangement (Fig. 8) as if stuck together, flattened, or molded and thinned against one another, suggesting they were plastic and agglutinated in the mafic state. Some of the microdiorite cores have a slice of granodiorite between them and their orbicule (Fig. 9), demonstrating that mingling of granodiorite and the mafic protolith occurred before formation of the orbicules, and that separation of the enclaves from granodiorite was not always complete before being mantled with a felsic orbicule.

Regardless of the composition of the core, the orbicules are identical in mineralogy, fabric, and layer stratigraphy. Thus, the orbicules consist of ~75% microcrystalline sodic plagioclase, 20% quartz, and 5% K-feldspar. Discontinuous, wispy biotite-rich platelets and layers define a foliation that is tangential to the margin of each core (Fig. 10). Whereas the crystals in orbicules described by other writers are usually characterized by a radial fabric (e.g., Fig. 11), tangential fabrics are relatively common in orbicules composed mainly of felsic minerals and biotite (Lahti, 2005), and are probably due to epitaxis controlled by the minimum interfacial energy achieved by crystal-lattice arrangements.

Closer examination of the layers in the orbicules reveals that several orbs in a small area, a couple meters square, contain a distinctive white layer of anhedral K-feldspar and quartz.
located about one-third of the thickness from the inner margin of the orbicule (Figs. 10 and 12). Like a distinctive tree ring, this layer indicates that some of the orbicules experienced a common depositional event when the orbicules had achieved about one-third of their growth. In none of the orbicules are inner layers partly missing or transected by unconformities; all in all, the felsic layers are concentric with the core.

DISCUSSION

The diverse rock types, ranging from microdiorite enclaves to granodiorite plutonic host to felsic orbicules to quartz monzodiorite matrix in the pipe, imply that a multiplicity of syn-plutonic magma injection events occurred to form the remarkable assemblage of orbicular and nonorbicular rocks. The following events may be inferred from the field relationships: (1) mingling of the microdiorite protolith and granodiorite to form a swarm of discrete microdiorite enclaves; (2) variable hybridization of the mafic enclaves with the host granodiorite; (3) injection of a felsic melt or aqueous fluid that deposited orbicules on 20% of the enclaves and on rare hornfels inclusions that at some point were spatially separated from the other 80%; and (4) infusion of quartz monzodiorite melt to form the matrix among both the orbicular and nonorbicular rocks.

It is reasonable to infer that the swarm of mafic magmatic enclaves originated by mingling of parent hornblende-biotite granodiorite magma with a mafic magmatic intrusion for two reasons: (1) thin sections of the microdiorite reveal the presence of quartz ocelli, acicularapatite, and fritted plagioclase, three mineral habits that are distinctive of mingled mafic rock (Angus, 1962; Reid et al., 1983; Castro et al., 1990; Vernon, 1990; Sylvester, 1998), and (2) because the mingling process is clearly displayed at a few locations elsewhere in the region as described above, as well as in other high-level Sierra Nevadan plutons (e.g., Reid et al., 1983; Frost and Mahood, 1987; Barbarin, 1990, 2005; Coleman et al., 1995; Sisson et al., 1996), and as described elsewhere, especially by Wiebe (1991), Barbarin and Didier (1992), and Pitcher (1993), among many others. The presence of orbs with a microdiorite core having a partial rind of granodiorite (Fig. 9) indicates that mingling occurred before the formation of the orbicular shell, but it also indicates that some of the enclaves were not completely disassociated from their granodiorite host when the orbicules formed.

The felsic orbicules are evidence that discrete infusion of melt followed hybridization of
the mafic enclaves. The rounded shapes of the mafic enclaves and the tangential layering in the orbicules imply that the orbicular structures formed in the magmatic state. The irregular, polygonal shape of the rare hornfelsic inclusions implies that they were solids, that they obtained their shapes by fracture, and that they retained their shapes even when entrained in the granodiorite magma.

Nucleation of the orbicules occurred directly on the margins of solid enclave and hornfels cores. The contact between the orbicules and the quartz monzodiorite matrix is invariably sharp, which indicates an abrupt, in situ change in the conditions of crystallization. It is especially noteworthy that the orbicules lack dispersed crystals having the shape, size, and distribution of those in the quartz monzodiorite matrix or granodiorite of the pluton, indicating that orbicule formation was a discrete event in the interval between enclave formation and matrix crystallization.

The sharp outer contact of the orbicules indicates that both orbicular and nonorbicular enclaves and inclusions were coherent and mutually separable before their incorporation in the quartz monzodiorite matrix. Some of the orbicules are merged (Fig. 8), indicating they were plastic enough to agglutinate during the time of orbicule formation. The K-feldspar and/or quartz rings within the orbicules (Figs. 10 and 12) indicate compositional fluctuations of felsic melt in the pipe, probably due to fluctuations in temperature and pressure. The orbicules cannot have formed by metasomatic reaction between their microdioritic cores and the quartz monzodiorite matrix (Thompson and Giles, 1974; but see also Enz et al., 1979), because the orbicules are equally developed around hornfels.

In order for orbicules to form so nicely and neatly on just some of the enclaves, however, their spatial separation is required at their place of origin or during transport through the pipe, perhaps as a gas-driven fluidized mass, to a site where the pipe encountered a felsic melt. Direct evidence of such a gas-driven mechanism is lacking at the outcrop, but fluidization is commonly postulated to explain transport of fragmented rocks in pipes in shallow epizonal plutons (e.g., Platten, 1984; Burnham, 1985; Ross et al., 2002). The felsic melt was probably an aplite dike that supplied the mineral components for the orbicules.

The fourth event was infusion of quartz monzodiorite into the mixture of orbicular and nonorbicular enclaves and inclusions. Restriction of this heterogeneous mass to the confines of the pipe and plastic deformation of some the orbs suggest that the mixture was transported as a mobilized aggregate through the

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Figure 7. Hammer bridges the gap between two halves of a hornfels inclusion separated from its felsic orbicule by a rind of granodiorite; black feature in center of image is a shadow between the two halves.

Figure 8. Two mafic enclaves conjoined by a felsic orbicule. Pencil for scale. Photo by Amber Miniami.
host granodiorite. Schlieren along part of the pipe margin (Fig. 5) are local evidence of flow between the mass of enclaves in the pipe and the host granodiorite.

Although the orbs are not closely associated with comb-layered structures in the Lower Castle Creek pluton, they share enough features with well-developed orbs described elsewhere in the literature to suggest the processes of formation may be similar (Tom Sisson, 2006, written commun.). These shared features include: (1) a spatial concentration of preexisting mafic enclaves, such as provided by an enclave swarm; (2) a restricted size range of the mafic enclaves, probably due to mechanical sorting during flow; (3) coating of the enclave cores with an anomalous abundance of one or a few mineral phases; and (4) the presence of a rare metamorphic fragment in some of the enclave swarms, supporting mechanical concentration as a possible cause of the sorting observed in the pipe.

Concentration of the orbs to just part of the pipe demands discussion (Fig. 3). Moore and Lockwood (1973) noted that comb-layering and orbicular structures are largely restricted to structural traps along pluton walls into which upwardly migrating, “low density, solute-rich aqueous fluids” were channeled. Thus orbicular and nonorbicular mafic enclaves exist in close proximity in Lower Castle Creek pipe, but orbs evidently formed only in that part of the pipe where sufficient felsic fluids or melt were available. On the other hand, because the orbicular enclaves are generally larger than those lacking orbs, flow sorting or mechanical concentration may have occurred during transport in the pipe to their present position. Thus a sharp boundary between orbs and the host granodiorite, and the close proximity of orbicular and nonorbicular enclaves, cannot be due to an in situ change in the conditions of crystallization (Vernon, 1985). Alternatively, the orbicular and nonorbicular enclaves formed spatially and perhaps temporally separate from one another and then were joined as two separate intrusions in the pipe. Compelling field evidence is lacking to choose between the two alternatives.

Vernon (1985) argued cogently that both comb-layering and orbicular structures require the absence of nuclei in a melt, and that superheating is an effective way to destroy nuclei, as he maintained experiments show (e.g., Donaldson, 1977). He stated further that absence of nuclei also delays crystallization and allows a significant degree of undercooling to occur, which, in turn, forces development of compositional layering (Donaldson, 1977). Thus injection of a superheated melt into a pluton during

Figure 9. Felsic orbicule encloses mafic enclave together with its partial orbicule of granodiorite, all surrounded by quartz monzodiorite.

Figure 10. Detail of felsic orbicule with a thin, white layer of microcrystalline K-feldspar and quartz. Inner edge (top) of orbicule is against the mafic core; upper edge is against quartz monzodiorite matrix. Tangential mineral layering within orbicule is defined by discontinuous concentrations of biotite. Photo by Amber Miniami.
its late stages of crystallization may supply the components for orbicule formation. Undercooling would force crystallization of the melt’s components upon solid objects such as enclaves and inclusions, or on refractory crystals or megacrysts during a hiatus between superheating and the onset ofcomplete crystallization of the plutonic host (Vernon, 1985; Ort, 1992).

The initial superheating may have been supplied to a late-stage aplitic melt by upward infusion of a plume of still-molten quartz monzodiorite from the bottom of the cooling granodiorite pluton or by fluidization that provided the gas-drive for the enclaves during their transport up the pipe. The undercooling of the felsic melt and consequent deposition of the orbicules may have been occasioned by rapid ascent of the pipe contents to a regime of lower temperature and pressure, perhaps by an abrupt volcanic venting (see Ort, 1992). Then following formation of the orbs, quartz monzodiorite intruded and mobilized both the suspended orbs and nonorbicular enclaves and carried them farther upward in the pipe.

That the orbicules have a tangential fabric rather than the more common radial fabric may be due to the kinetics of epitaxial crystallization, a low degree of supersaturation, or to concentration gradients at the enclave margins. If the orbicules crystallized from an aqueous fluid (Moore and Lockwood, 1973; Donaldson, 1977) or from a superheated felsic melt such as aplite, then fluid concentrations in a partially molten system are controlled by local reactions between minerals and liquid. Concentration gradients in the liquid may move material to or away from the boundary from both sides of the boundary, not simply across it (Lundstrom et al., 2005). Thus water and/or K\textsubscript{2}O may concentrate at an enclave boundary, favor crystallization of biotite there, and provide a sink for any additional H\textsubscript{2}O or K\textsubscript{2}O in the system.

Assuming the enclaves represent hot, crystal-poor mafic magma (say 1050–1200 °C) that is injected by a cooler, felsic magma (say 750–850 °C), then significant thermal gradients on the order of 300–400 °C will exist initially, at least over a few centimeters or tens of centimeters between the enclaves and the felsic melt. Eventually the thermal gradients will flatten over geologically short times, depending on the geometry and frequency of injection of mafic magma to maintain high temperatures. In the meantime, a thermal gradient will set up around each hot mafic enclave, which then allows nonequilibrium Soret diffusion to occur in the surrounding mush, so that Si, K, Na, and, to a lesser extent, Al, all from a felsic melt or aqueous fluid, may concentrate around the enclaves, whereas Ca, Fe, Ti, and Mg move away.

Processes that probably cause enclaves to concentrate in swarms (“log jams” in the terminology of Tobisch et al., 1997, and illustrated but not described by Paterson, 2009, in his fig. 18c, p. 520) include convergent flow in fractures or pipes, velocity gradient sorting, and flow perturbations due to boundary irregularities such as overhangs in walls near the roof of the host pluton (Moore and Lockwood, 1973). The size of the Lower Castle Creek pipe is larger than most of those described elsewhere (e.g., Tobisch et al., 1997; Paterson, 2009) and may be unique in that regard. The question of how mafic enclaves accumulate in the first place, so as to be in a position to rise in a pipe and form swarms, is a topic of debate and continued study (e.g., Tobisch et al., 1997; Wiebe et al., 1997; Wiebe and Collins, 1998).

The orbicular rocks in this study evince a complex history of formation that requires an equally complex interpretation. Initial formation of mafic enclaves involved mingling of mafic magma and granodiorite deep in the granodiorite magma chamber. Different from all other mingled magma interactions in the Castle Creek plutons, however, is the addition of a third melt phase, a highly mobile, H\textsubscript{2}O-saturated felsic melt that ascended from depth and may have had the same source as neighboring aplite dikes. These aplites may represent a low-melt fraction generated during injection of late-stage basaltic melts into hot, nearly solid host granodiorite. Such an aplitic melt could be superheated and invade a swarm...
of mafic enclaves that were mechanically and spatially separated by gas-driven ascent in a pipe. During undercooling of the aplitic melt in a restricted part of the pipe, or in a separate mass of enclaves altogether, mafic enclaves and rare hornfels inclusions were nuclei for deposition of orbicules. If from an aqueous fluid, then deposition may have been facilitated by the Soret effect. The entire mass of enclaves, inclusions, and orbs were then intruded by quartz mafic enclave. Photo by Amber Miniami.

Figure 12. Irregularly-shaped felsic orbicule with internal thin layer of K-feldspar and quartz surrounding a mixed core of quartz monzonodiorite and almost completely hybridized mafic enclave. Photo by Amber Miniami.

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Polygenic origin of orbicular granodiorite


